CHAPTER 11

METERING PRINCIPLES AND PRACTICES

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GENERAL INTRODUCTION

The material which is presented in this chapter is confined to the theory and application of the induction watthour meter, demand meter, instrument transformers applied with these metering equipments, and meter accessories. Due to the number of induction watthour meters required in the electrical industry, considerable space is given to theory of the meters. Also, the theory is of additional importance because of the similarity of induction protective relays to the meters. However, emphasis is placed on application in preference to theory.

The entire revenue of all electrical power plants is derived from the customers served by the individual plant. All customers are billed on energy usage (kilowatt-hours); while the billing of industrial, commercial, and large residential customers may also include demand charges and power factor penalties. Measurement of the quantities, within the close tolerance established by regulating agencies, at a minimum cost is extremely important to the management of each plant and to the individual customer. The economics may be reflected in the rates charged by the utility management to the customer. Also, an error in a particular meter in excess of the established tolerance may represent a considerable sum of money.

Progress in engineering and research has resulted in the development of metering equipment which has laboratory accuracy under all normal operating conditions.[1,2] Also, by employing efficient quantity production methods and standardization, reliable watthour meters are produced and sold at remarkably low prices. An example is the comparison of the watthour meter with a wattmeter of comparable accuracy.

I. WATTHOUR METER—GENERAL

1. Requirements of a Watthour Meter

The registration of a watthour meter under all normal operating conditions is important to both the utility and the customer. It would be desirable to both parties for the registration to be 100% correct under all conditions. It is usually required by regulating agencies to be within ±1.0 per cent of 100% registration under specified tests. Under normal operating conditions, the meter may be subjected to variations in line voltage, frequency (including application of complex wave forms), load, load power factor, and temperature. It may also be subjected to abnormal conditions, such as surges due to lightning and system disturbances, and to vibration.[3] As a result of its maintained accuracy under both normal and abnormal conditions, the induction watthour meter may be referred to as a versatile, rugged instrument.

If the registration of a watthour meter is to be correct, the number of revolutions of the rotating disk, or rotor, N, must be proportional to energy, W. Where C_1 is a constant,

$$N = C_1 W \tag{1}$$

Instantaneous power, $p(t)$ at the points of entry of an electric circuit into a region is the rate at which electric energy is being transmitted by the circuit into the region and is given by

$$p(t) = \frac{dw}{dt} \tag{2a}$$

Conversely, energy is the integral with respect to time of power or

$$W = \int_0^t p(t)\, dt \tag{2b}$$

The active power, P, at the points of entry of an electric circuit is the time average of the values of instantaneous power, $p(t)$, when the average is taken over a cycle of alternating current. Hence,

$$P = \frac{1}{T} \int_0^T p(t)\, dt \tag{3}$$

where T is the period of one cycle of fundamental frequency, the total time of an integral number of cycles of fundamental frequency, or a period of time which is much greater than a period of fundamental frequency.

Generally, energy is proportional to the integral with respect to time of power, $p(t)$, or of active power, $P(t)$, because, in general, active power is time variant. Hence,

$$W = \int_0^t P(t)\, dt \tag{4a}$$

Then, from Equation (1)

$$N = C_1 \int_0^t P(t)\, dt \tag{4b}$$

For a steady load or constant active power, P, energy is proportional to time or

$$W = P\, t \tag{5a}$$

Then,

$$N = C_1\, P\, t \tag{5b}$$

The speed of the rotating disk of a watthour meter is the time rate of change of the revolutions of the disk. Therefore,

$$s = \frac{dN}{dt} = C_1 p(t) \tag{6}$$

where s is the speed of the disk.

For correct registration of the meter, the speed of the disk must be directly proportional to power. For repetitive time variant voltage and current, the average power is constant; hence, the average speed must be constant. Also, for a constant average speed, the average retarding torque and average driving torque must be equal and directly proportional to average power. Therefore, for correct registration of a meter, two requirements which must be satisfied are: 1) the speed must be directly proportional to average power, and 2) the retarding torque must be directly proportional to speed. If both requirements are satisfied, the average driving torque and average retarding torque are directly proportional to average power delivered to the load.

2. General Construction of an Induction Watthour Meter

An isometric view of a typical single-phase, induction watthour meter is shown in Fig. 1 to indicate general physical arrangement of the basic components. Four basic and essential mechanisms of a watthour meter are: 1) the driving mechanism, which is the electromagnet, 2) the retarding mechanism, which is two permanent magnets, 3) the register mechanism, which is geared to the rotating disk and registers the energy measurement by totalizing the number of revolutions of the disk, and 4) the rotor or rotating disk common to all mechanisms, which is essentially the coupling between the other mechanisms. All single-phase meters contain one of each of the above mechanisms. Polyphase watthour meters contain one or more of each of the mechanisms.

The electromagnet, which is usually referred to as the stator, consists of the magnetic core, the potential coil, the current coils, and the variable coils. Magnetic cores of modern meters have one potential pole and two current poles, with the potential and current poles located on opposite sides of the disk air gap. The potential and current coils are wound around the respective poles. Adjustable coils are placed in the face of the potential poles piece and around each of the current poles for calibration of the meter.

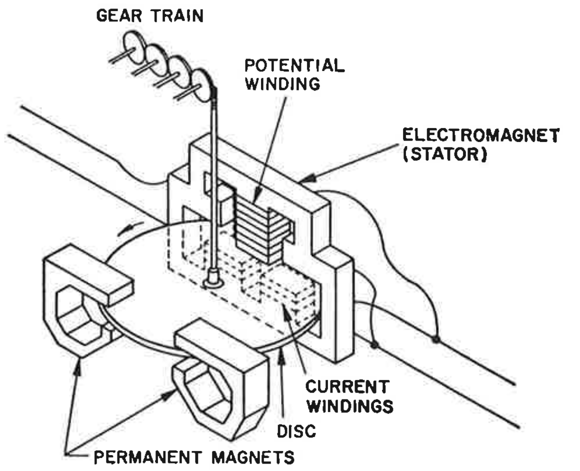


Fig. 1—Isometric view of single-phase, induction watthour meter.

The rotating element is a thin, stippled aluminum disk which is supported by bearings on the supporting frame and is free to rotate in a plane lying in the air gap between the faces of the potential and current poles. Two very small anti-creep holes are located, one on either side of the spindle. When passing through the potential flux field, the holes prevent the disk from creeping under no load conditions.

The permanent magnets are located on the opposite side of the spindle from the electromagnet and serve to introduce an intentional drag on the rotating disk, which is proportional to the speed of the disk. The permanent magnets are so arranged that poles of unlike polarities are on the same side of the disk and only a portion of the flux passes through the disk. Experience has shown that this arrangement produces the greatest drag because of the shunt paths for the eddy current.

The register mechanism consists of a gear reduction mechanism to which is fixed four or five pointers, and

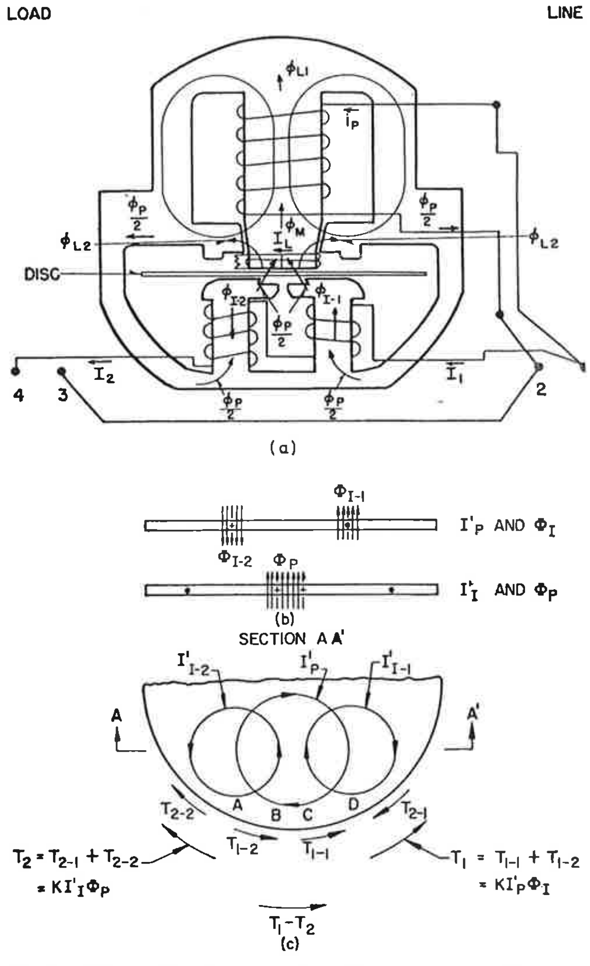


Fig. 2—Schematic diagram of watthour meter (a) Electromagnet and rotor, (b) Elevation section of disk, showing representations of paths of eddy currents due to potential and current flux, (c) Plan of disk showing interaction of eddy currents and fluxes.

which has a 10:1 reduction between adjacent pointers. The pointers indicate the cumulative number of revolutions of the rotor or the energy measurement. The registration is indicated in kilowatt-hours. The register mechanism is discussed further under "Meter Constants and Test Data."

II. WATTHOUR METER THEORY[3,4,5,6]

The approach taken in this analysis of an induction watthour meter seeks to analyze each mechanism in its particular function in the operation of the meter. A single-phase meter is analyzed here; however, the analysis is applicable to polyphase meters by considering each stator independently.

3. Electromagnet

A schematic diagram of the electromagnet (stator) and rotating disk are shown in Fig. 2. A sectional view of the disk is shown twice in Fig. 2(b) to indicate the eddy current paths in the disk due to the potential flux and the current flux. A partial plan view is shown in Fig. 2(c) to indicate the regions of interactions of the disk eddy currents and fluxes which produce driving torques. The positive direction for all quantities is shown by arrows. The positive direction of voltage drop in the potential circuit is shown by an arrow in the direction of voltage drop. A simplified vector diagram applicable to Fig. 2 is shown in Fig. 3.

The following notation is applicable to Figs. 2 and 3.

V = voltage applied to meter potential circuit

I = load current flowing in each meter current winding

θ = angle by which load current lags the applied voltage

Φ_{I-1} and Φ_{I-2} = effective flux normal to disk which is due to load current in current windings 1 and 2, respectively

Φ_p = effective flux normal to disk which is due to applied voltage, V

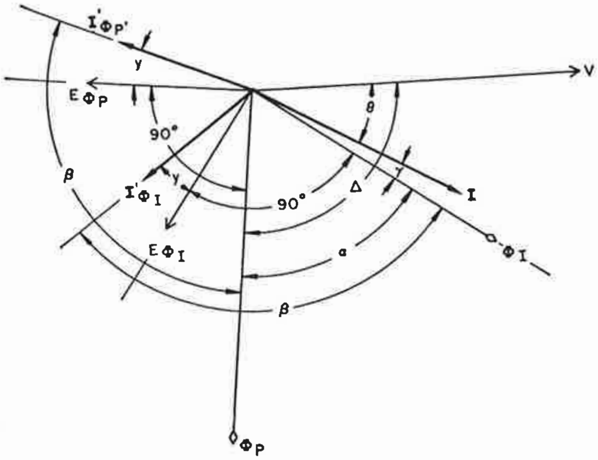


Fig. 3—Vector diagram of circuit shown in Fig. 2.

E_{Φ_p} = voltage induced in disk by change in I_p

E_{Φ_I} = voltage induced in disk by change in Φ_I

I'_{Φ_p} = eddy current in disk due to E_{Φ_p}

$I'_{\Phi I-1}$ and $I'_{\Phi I-2}$ = eddy current in disk due to E_{Φ_I}

y = impedance angle of disk, approximately 18°

α = angle by which Φ_{I-1} and Φ_{I-2} leads Φ_p

β = angle by which I'_{Φ_p} lags Φ_p and $I'_{\Phi I-1}$ lags Φ_{I-1}

Δ = angle by which Φ_p lags V

γ = angle by which Φ_{I-1} and Φ_{I-2} lag I

As can be seen from Figs. 2(b) and 2(c), three distinct fluxes and three corresponding eddy currents are present in the disk. Four points, A, B, C, and D, exist at which eddy currents flow in a flux other than the flux which causes the eddy currents. A torque is developed at each of the four points, due to the interaction of the eddy current and flux. The four torques developed are as follows:

At point A, I'_p and Φ_{I-2} produce torque T_{2-2} to the left (clockwise)

At point B, I'_{I-2} and Φ_p produce torque T_{1-2} to the right (counterclockwise)

At point C, I'_{I-1} and Φ_p produce torque T_{1-1} to the right (counterclockwise)

At point D, I'_p and Φ_{I-1} produce torque T_{2-1} to the right (clockwise)

An analysis of the interaction of the eddy currents and flux results in positive values of T_{1-1} and T_{1-2} and negative values of T_{2-1} and T_{2-2}. If symmetry, constant frequency, and sinusoids are assumed, the net average driving torque, T_N, is given by

$$T_N = K\Phi_p\Phi_I \cos y \sin(\Delta-\theta-\gamma) \tag{7}$$

where K = a constant of proportionality. If linear circuits are assumed, Φ_p is directly proportional to V and Φ_{I-1} and Φ_{I-2} are proportional to the load current, I. Then, for a constant frequency

$$T_N = CVI \sin\beta \sin\alpha \tag{8}$$

where

$$\alpha = (\Delta-\theta-\gamma)$$

and

$$\beta = 90° + y \text{ (constant for a particular meter)}$$

From Equation 8

$$T_N = C'VI \sin\alpha \tag{9}$$

where

$$C' = C \sin\beta$$

Since the power delivered to the load is $|V|\,|I| \cos\theta$, the driving torque is proportional to the load only if

$$\sin\alpha = \cos\theta \text{ or}$$
$$\sin(\Delta-\theta-\gamma) = \cos\theta$$

This relationship must hold at all power factors. Also, since $\sin(90-\theta) = \cos\theta$, $(\Delta-\gamma)$ must equal 90 degrees at all power factors. Due to core losses in both the potential and current circuits, the angle $(\Delta-\gamma)$ would be less than 90 degrees unless means are provided for increasing the angle by which Φ_p lags V. This is referred to as "lagging the meter" and is provided in all induction watthour meters by placing a closed-circuit coil, which is adjustable radially with respect to the disk, on the potential pole piece near the disk or in the face of the pole piece. The per cent registration as a function lagging error and power factor is given by

$$\% \text{ Reg} = (\cos\delta + \tan\theta \sin\delta + \frac{1-\cos\delta}{\cos\theta}) \times 100 \qquad (10)$$

where:

δ = angle of overlagging

θ = angle by which the load current lags the line voltage

In the derivation of Equation 10, it was assumed that the meter registers correctly at unity pf. The seriousness of a lagging error is shown in Fig. 4, which is a plot of Equation 10.

An error in lagging which might be negligible near unity pf becomes increasingly serious as the pf departs from unity. This factor is particularly important in reactive metering, because the voltage applied to the reactive meter lags the line voltage by 90 degrees. A high pf load appears as low pf load to the watthour meter used for reactive metering. If θ in Equation 10 is replaced by $(90° - \theta)$, the equation gives the per cent registration of a varhour meter, which is overlagged by δ and which has been calibrated as a watthour meter to register correctly at unity pf.

In testing a watthour meter to be applied as a reactive meter, the meter may be tested as a watthour meter with watthour potentials applied to the meter, or it may be tested as a reactive meter with the phase displacement transformers. This factor is emphasized in polyphase meter applications, because the power factor apparent to each stator may be considerably different from the system power factor. This condition is apt to exist in polyphase watthour and reactive metering applications. Although correct lagging of a watthour meter is particularly important in polyphase and reactive metering applications, it is of little concern in the application of modern meters which are permanently lagged.

A shading coil which is adjustable in a tangential direction with respect to the disk causes a flux which leads the potential mutual flux in time- and space-phase. This results in a rotating field across the disk and a voltage only driving torque in the direction of the shading coil from the normal center of the potential flux field. This is the light load adjustment.

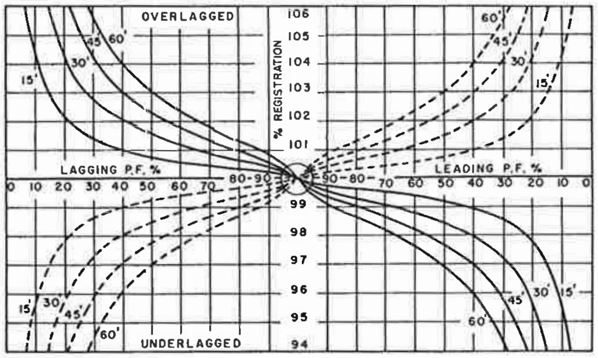


Fig. 4—Registration of watthour as a function of load power factor for various lagging errors. Meter calibrated to register correctly at 1.0 pf.

Torque Due To Alternating Fields—The retarding torque due to movement of the disk through the alternating flux fields accounts for about four and one-half per cent of the total retarding torque at full load. About four per cent is due to the potential or shunt field. The remaining one-half of one per cent is due to the current or series fields. The torque due to each field is proportional to the speed and to the square of the flux in each respective field, or is proportional to $(\phi^2_I + \phi_p^2)\, S$. The variation in the absolute value of torque due the potential flux is nearly proportional to speed, because the voltage and resulting potential flux do not vary widely. However, torque due to the alternating series (current) fields varies widely and results in low registration of the meter at excessive overloads. The overload range has been extended in modern meters by reducing the normal full load speed of the disk.[7]

Permanent Magnets—The purpose of the permanent magnets is to provide a retarding torque which is directly proportional to the speed of the disk and sufficiently large to overshadow the effects of undesirable characteristics of the unavoidable torques. Let Φ_R be the flux from the permanent magnets which cuts the disk and contributes to the retarding torque, and let S be the speed of the disk. The eddy currents induced in the disk are directly proportional to Φ_R and S. The resulting retarding torque by reaction of those eddy currents and Φ_R is directly proportional to $\Phi_R^2 S$. A reduction of one per cent in Φ_R results in an increase in S of two per cent for the same retarding torque, and a two per cent increase in registration. It is essential that Φ_R remain constant if the retarding torque provided by the permanent magnets is proportional to speed.

The value of Φ_R varies inversely with temperature, while the presence of strong fields due to surges has a demagnetizing effect on the permanent magnets. Therefore, means must be provided either to compensate for normal variations in Φ_R due to these factors or to protect the magnets from these factors.

Errors in registration due to changes in Φ_R caused by temperature changes are referred to as Class I Temperature Errors, or they are non-inductive temperature errors. These errors are independent of the power factor of the load being measured, as contrasted with Class II Temperature Error or inductive temperature errors, which are a function of the power factor of the load.[7]

4. Retarding Torque

In order for a meter to register correctly, the retarding torque must be directly proportional to the speed of the rotating disk. The retarding torque may be segregated into intentional and unavoidable torques.

The unavoidable retarding torque consists of bearing friction, friction in the gear train of the register mechanism, disk windage, and torque due to rotation of the disk in the alternating magnetic flux fields. Not one of these torques meets the necessary requirement of being directly proportional to speed. Consequently, these components are made as small as possible, partially neutralized by an additional driving torque, or overshadowed in their effort by a large retarding torque of the correct characteristic.

Friction Torque—Friction torque, which is nearly constant, is first made as small as possible. The register gear train and main or lower bearing are the sources of friction, of which the main bearing is the principal source. The friction in the gear train is made small by the use of precision-milled gearing. The three general types of main bearings used in watthour meter designs to reduce the friction at that point are: 1) a polished steel pivot which rotates in a sapphire cup jewel; 2) a polished steel ball which runs between two sapphire cup jewels; and 3) a magnetic suspension bearing in which the rotating disk is held in suspension by two concentric permanent magnets.[7]

The friction retarding torque which remains after careful design of the bearings and gear train is overcompensated for by an additional driving torque developed by shading coil action in the potential circuit of the meter.

Class I Temperature Compensation is provided by a temperature compensating shunt, which is placed on the magnets in such a way as to shunt a portion of the magnet flux from crossing the air gap. The permeability of the shunt varies inversely with temperature, so that as the temperature increases, the proportion of magnet flux which cuts the disk is increased sufficiently to hold the disk flux, Φ_R, constant.

Two designs are used in permanent magnets to reduce the demagnetizing effects of surges. There are: 1) the casting of the magnets from one of the new highly coercive magnetic alloys of aluminum, and 2) plating the magnets with a heavy coating of copper. The first design depends upon the magnet to resist demagnetization due to surges. In the second method, the copper plating shields the magnet by the action of the eddy currents induced in the copper plating by the high fields due to surges. A comparison of the relative effectiveness of the two methods is shown in Fig. 5.

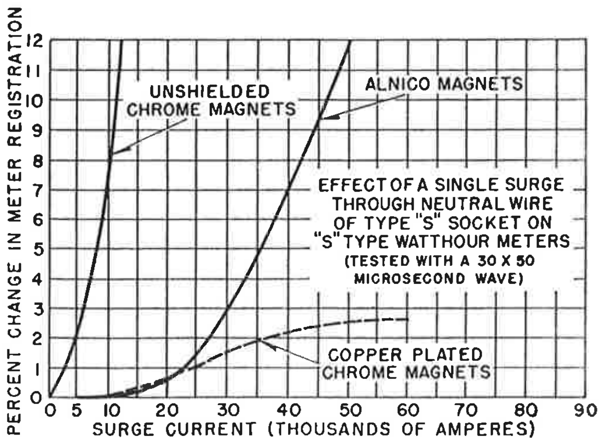


Fig. 5—Effectiveness of surge protection of meter permanent magnets.

5. The Register

The function of the register is to record the energy as measured by the meter. Essentially it indicates the total number of revolutions of the rotating element, each revolution of which is a measure of energy. It consists of a series of dials geared in a convenient relationship to each other and to the shaft of the rotating disk. The register is shown schematically in Fig. 6.

The gear ratio between adjacent dials shafts, 1, 2, 3, and 4 is one to ten, so that the energy measurements indicated by the respective dials are in units, tens, hundreds, and thousands of kilowatt-hours. The measurement of energy is that which is read from the dials for a direct reading meter or from some other convenient multiplier. The multipliers can result from the additional gear ratio between the shaft of the units dial and the shaft of the rotating element and/or the ratio of instrument transformers applied in the particular installation. It is apparent that a definite total gear ratio exists between the shaft of the rotating disk and the shaft of the "units" pointer for a particular meter having a specific dial multiplier.

The register is a complete and detachable unit driven by the shaft of the rotating element "f". The proper register to be applied with a particular meter depends upon the load being measured, which would determine the desired dial multiplier. Also, it may be required to replace the usual watthour meter register with a demand register, which would also indicate the maximum demand of the load. This is discussed further under section VI, "Demand Metering".

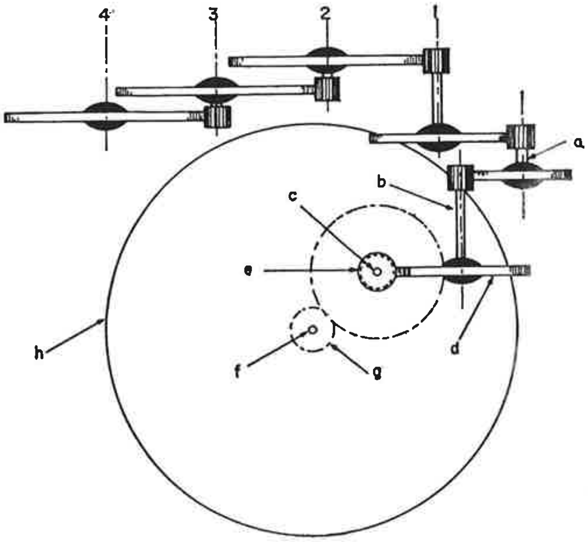


Fig. 6—Schematic view of watthour meter register.

1—First pointer shaft
2—Second pointer shaft
3—Third pointer shaft
4—Fourth pointer shaft
a—Shaft No. 3
b—Shaft No. 2
c—Shaft No. 1
d—Worm gear
e—Worm
f—Meter rotor shaft
g—Meter rotor pinion
h—Meter rotor (disk)

The essential difference in register designs of various meter manufacturers is in the selection of the point in the gear train at which the worm gear is applied. The indicating dials rotate in a vertical plane, while the disk rotates in a horizontal plane. Therefore, it is necessary to use a worm gear at some point because of this transition. Some manufacturers apply the worm gear at the first gear reduction, where the disk shaft meshes with the register.

III. METER PERFORMANCE, CHARACTERISTICS, AND RATINGS

6. Performance Under Variations in Service Conditions

Frequency—Deviation from rated frequency produces numerous effects in a watthour meter. This can be resolved into changes in currents and fluxes which produce torque. The effects are dependent upon the load current and the load pf. The resulting changes in absolute values (magnitudes) of torque-producing eddy currents and fluxes tend to balance one another out. Errors result from changes in phase relationships which are not balanced out. However, commercial system frequencies are sufficiently constant that the problem is not serious.

7. Wave Form[10, 11]

In the analysis and application of the induction watthour meter, sinusoidal voltages, fluxes, and currents are usually assumed. Under distorted wave forms, which can be broken down into fundamentals and harmonics, the analysis is applicable if it is realized that the final driving torque is the summation of driving torques due to the various harmonics. A particular harmonic in the flux wave reacts only with the same harmonic in the eddy current wave to produce a driving torque. However, it should be realized that all harmonics of the fluxes are effective in the retarding torques, due to the disk's moving through the alternating fields. It should be realized that the applied voltage and the torque producing potential flux are not necessarily of the same wave forms. Also, the disk eddy currents and the flux causing these eddy currents may not be of the same wave form. On commercial systems, the voltage wave forms are usually sufficiently sinusoidal to be considered as such. However, in energy measurements in non-linear circuits, the current wave form may be sufficiently distorted to be a source of error. This fact should be considered in the measurements in non-linear and rectifier circuits.

Voltage—A deviation in applied voltage affects the saturation and losses of the potential circuits, the lagging of the meter, the driving torque produced by the potential shading coil, and the retarding torque due to movement of the disk in the potential alternating flux. The net effect in meter registration is dependent upon the relative effects on each torque. The retarding torque is proportional to the square of the potential flux, which in turn is proportional to voltage. An increase in voltage results in an increase in losses and a decrease in lagging. The driving torque due to the shading coil is also proportional to the square of the voltage. A ten per cent change in voltage results in less than 0.8 per cent error in registration, while 2.5 to 30 per cent overvoltages result in less than 1.0 per cent error in registration. Greater than 30 per cent overvoltages may cause serious inaccuracies. However, system voltages do not normally deviate sufficiently from rated voltage to cause serious errors.

The operation of a 240-volt meter at 277 volts is of particular interest in the metering of services which are fed from 265/460-volt network systems. The full-load registration of a modern 240-volt meter, when subjected to abnormally wide variations in applied voltage, is shown in Fig. 7. The meter had previously been calibrated to register correctly at the rated voltage of 240 volts. Although the change in registration with applied voltage is greater when metering unity pf loads, registration is within the usual tolerances over a wide range of applied voltage. The characteristics indicate that a meter calibrated at 240 volts can be applied at 277 volts with satisfactory accuracy; however, the meter might creep at the higher voltage and require resetting of the light load adjustment. Other factors might require application of transformer rated meters at the higher voltage.

Temperature—In modern watthour meters, compensation is provided for Class I and Class II temperature errors.[8] No compensation is provided for variations in disk temperature; however, such variations would have little effect, since the disk is involved in both driving and retarding torques. A modern temperature-compensated watthour meter will usually provide satisfactory registration within required tolerances from −10°F to 125°F. Ambient temperatures outside this range may justify special consideration.

Summary of Performance Characteristics—Typical performance characteristics of a watthour meter are shown in Fig. 8; however, the characteristic of a particular meter may deviate from those shown.

8. Ratings of Watthour Meters

At the present, two areas of rating watthour meters for application purposes exist. A third area of rating is in the design of meter. The two areas of rating for application purposes are the preferred or available ratings and the standard ratings. The preferred ratings have been established by the needs of the industry, which is

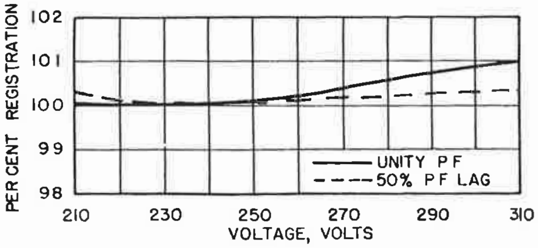


Fig. 7—Registration-voltage characteristic of watthour meter over abnormally wide range of voltage.

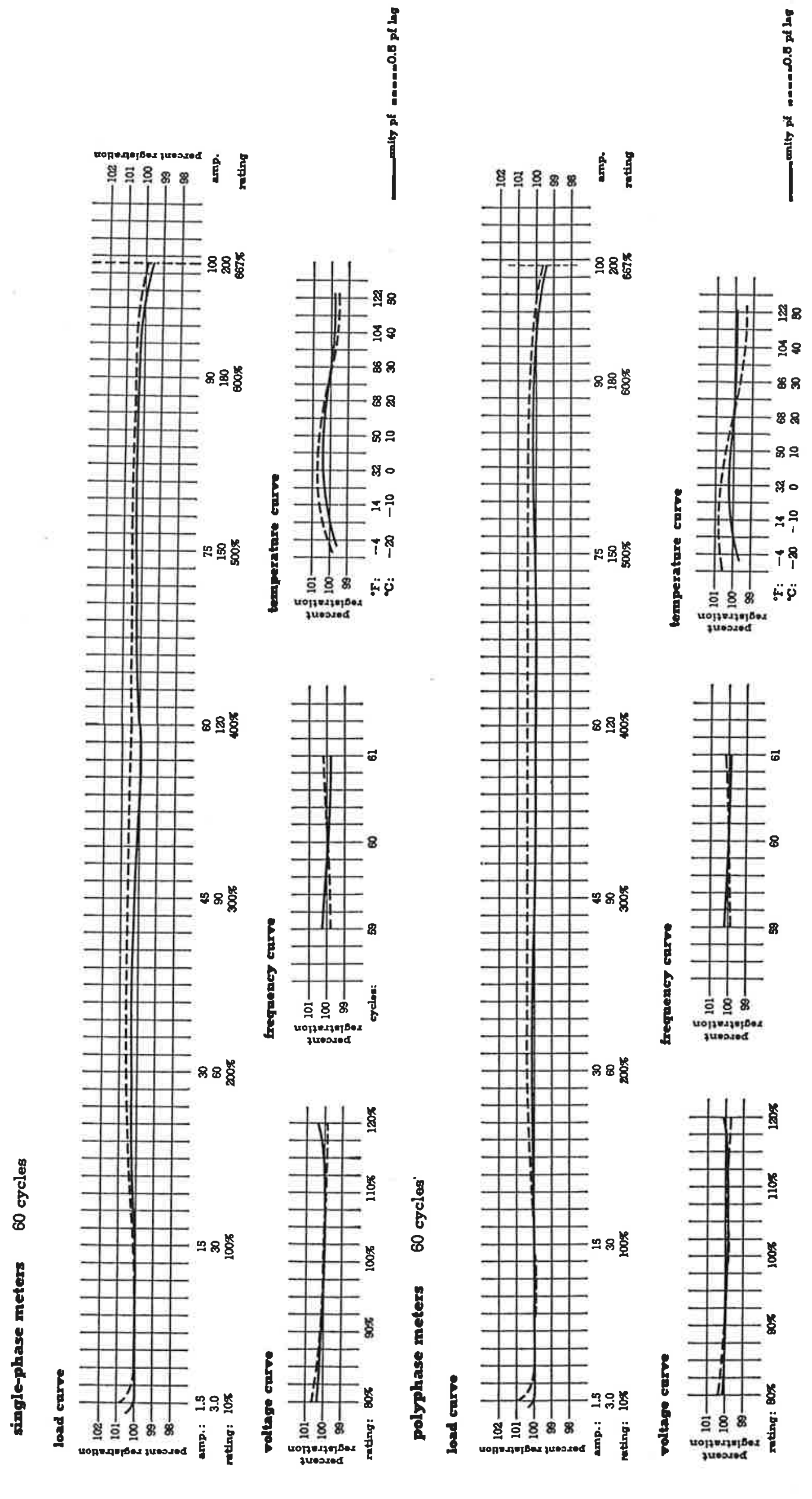


Fig. 8—Typical characteristics of induction watthour meter.

the basis for standards. However, only the single-phase, detachable, and bottom-connected meters have been standardized.[12]

The usual ratings applied to a meter are voltage, current, and frequency. So for a system frequency, the meters are rated in voltage and current to agree with the load being metered. For design purposes, each stator is also rated in kilowatts. The voltage, current, and kw rating of single stator meters agree with the respective load quantities. However, this does not generally apply to polyphase meters.

Ratings of polyphase meters require special considerations. For a specific polyphase watthour meter, the same voltage and current ratings do not necessarily apply to all stators. However, the kw ratings of all stators are usually equal. This is necessary since the watthour constant, K_h, applies to any or all stators. For application purposes, a polyphase meter is given a voltage and current rating. Since the stators are rated equally in kw and equal voltages are not necessarily applied to each stator, the voltage and current rating of a stator may differ from the respective ratings of the meter. This condition exists in the two-stator meters for application on three-phase, four-wire wye systems, and for meters applied to three-phase, four-wire delta systems.

The voltage rating of a meter for a particular application depends upon the type of system from which the load to be metered is served. For self-contained meters applied on a three-phase, three-wire system, the meter is rated at line-to-line voltage. For metering a load served from a three-phase, four-wire wye system, the meter is rated at line-to-neutral voltage. A meter rated at line-to-line voltage is applied on three-phase, four-wire delta systems.

Preferred Ratings—The preferred or available ratings of meters for applications to various systems are shown in Table I.

Standard Ratings—Single-phase, detachable and bottom-connected watthour meters are given in AEIC-EEI-NEMA Standards for Watthour Meters.

Standard Voltage and Frequency Ratings—The standard voltage ratings are 120, 240, and 480 volts. The standard frequency rating is 60 cps.

Standard Current Ratings—Two standard current ratings are applicable to each meter.[12] The Class (CL) designation of a watthour meter denotes the maximum of the load range in amperes. The standard class ratings are 10 (for transformer rated meters), 100, and 200. The Test Current (TA) rating of a meter corresponds with the value of current at which the watthour meter is calibrated for operation over its load range. The TA rating corresponds with the current rating of watthour meters not covered by the existing standards, and the current rating of single-phase meters according to methods applied prior to standardizing the ratings. The standard TA ratings of single-phase, detachable and bottom-connected watthour meters are:

Class 10—2.5 amperes
Class 100—15 amperes
Class 200—50 or 30 amperes.

Other values of current may be recommended as a base test current by a manufacturer.

IV. WATTHOUR METER APPLICATIONS[4,5,14,15]

In this discussion on meter applications, it is assumed that each meter stator has been adjusted to read correctly; i.e., the driving torque is proportional to power delivered to the load, and the speed is always proportional to power. Having made this assumption, it is unnecessary to include "time" in the equation applying to the application.

Also, the scalar or dot product of vectors is used here in preference to trigonometric functions for simplicity in the analysis of the connections of a particular meter and the resulting registration.[5] The quantities applied to a watthour meter, voltage, and current, can be represented on vector diagrams as co-planor vectors, vectors rotating at a fixed frequency in a common plane, or phasors. The scalar or dot product is equally applicable to phasors.

9. A Scalar or Dot Product of Phasors (Vectors)[5,16]

The dot product of two phasors, V and I, is defined as $V\cdot I$.

$$V\cdot I\equiv|V|\,|I|\cos\theta$$

where $|V|$ = the absolute value of the voltage phasor, V
$|I|$ = the absolute value of the current phasor, I
θ = the angle between the two phasors, V and I

For this analysis of watthour meter applications,

V = the phasor voltage drop in the load in a positive direction. It is also the voltage applied to the potential element of the watthour.
I = the phasor current into the load in a positive direction and through the meter in a positive direction to produce forward torque in the meter.
$|V|$ = the rms or effective value of V
$|I|$ = the rms or effective value of I
θ = the phase angle by which I lags V

The quantities V and I are assumed to be sinusoidally time variant at the same frequency.

APPLICABILITY OF DOT PRODUCT TO LAWS OF ALGEBRA

Commutative Law

$$V\cdot I=|V|\,|I|\,\cos\theta \qquad \text{(a)}$$
$$V\cdot I=|I|\,|V|\,\cos\theta \qquad \text{(b) (11)}$$
$$\therefore V\cdot I=I\cdot V \qquad \text{(c)}$$

Distributive Law

Assume three phasors V, I_1, and I_2 as shown in Fig. 9

$$(I_1+I_2)\cdot V=(OB)\ V \qquad \text{(a)}$$

Since $OB=OA+AB$,

$$(I_1+I_2)\cdot V=(OA+AB)\ V=(OA)\ V+(AB)\ V \qquad \text{(b) (12)}$$

but

$$I_1\cdot V=(OA)\ V \qquad \text{(c)}$$

and

$$I_2\cdot V=(AB)\ V \qquad \text{(d)}$$
$$\therefore (I_1+I_2)\cdot V=I_1\cdot V+I_2\cdot V \qquad \text{(e)}$$

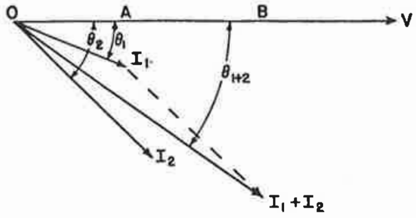


Fig. 9—Vector diagram for showing applicability of a dot product to the distributive law of algebra.

Assume four phasors V_1, V_2, I_1, and I_2 as shown in Fig. 10.

By the Commutative Law

$$(V_1+V_2)\cdot(I_1+I_2)=(I_1+I_2)\cdot(V_1+V_2) \quad \text{(a)}$$

By the Distributive Law

$$(V_1+V_2)\cdot(I_1+I_2)=(V_1+V_2)\cdot I_1 + (V_1+V_2)\cdot I_2 \quad \text{(b)} \qquad (13)$$

and

$$(V_1+V_2)\cdot I_1=V_1\cdot I_1+V_2\cdot I_1 \quad \text{(c)}$$

Similarly

$$(V_1+V_2)\cdot I_2=V_1\cdot I_2+V_2\cdot I_2 \quad \text{(d)}$$

$$\therefore (V_1+V_2)\cdot(I_1+I_2)=V_1\cdot I_1+V_1\cdot I_2+V_2\cdot I_1+V_2\cdot I_2 \quad \text{(e)}$$

10. Blondel's Theorem

Blondel's Theorem applies to the measurement of power flowing into a network of any number of wires, with no restrictions on the number of phases or wires or the balance of load distribution among the phases. It is stated as follows: "If energy is supplied to a network through a wire, the total power in the system is given by the algebraic sum of the readings of n wattmeters, so arranged that each of the n wires contains one current coil, the corresponding potential coil being connected between that wire and a point on the system that is common to all the potential circuits. If this circuit point is on one of the n wires and coincides with the point of attachment of the potential lead to that wire, only n-1 wattmeters are required.

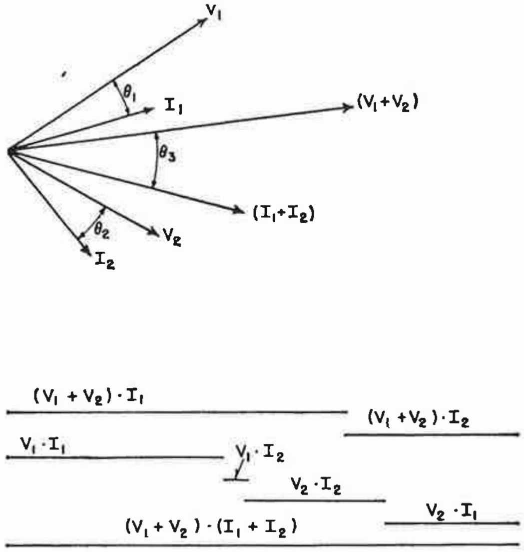


Fig. 10—Vector diagram for showing applicability of a dot product to the cumulative and distributive laws of algebra.

"The receiving and generating circuits may be arranged in any desired manner, and no assumption is made as to the way in which the voltage and currents vary."[17]

Applying this theorem, the minimum number of single-stator, two-wire meters with which energy delivered to a service on n wires can be accurately measured under general conditions is n-1.

11. Application Data

In the analyses presented here for the various meter connections, *VI* is defined as and understood to indicate a dot or scalar product of the two phasors, unless it is expressly written as otherwise.

The analyses of connections are given for the general case, or any condition of power factor, voltage balance, or load balance. Generally unbalanced loading is assumed. The condition of generally unbalanced voltages, and the special condition of balanced voltages, are both considered in each case.

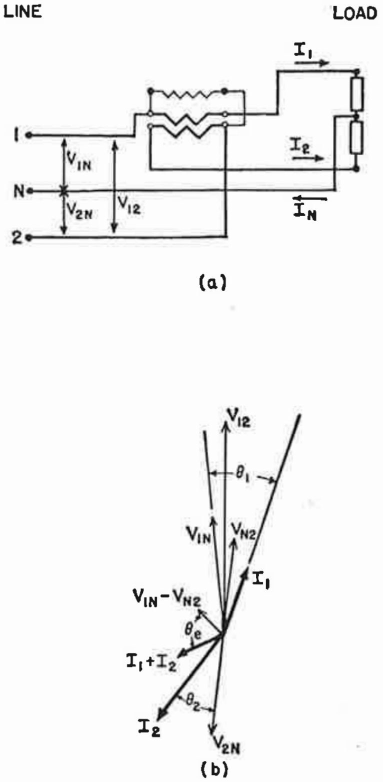


Fig. 11—Metering a single-phase, three-wire circuit (a) Circuit diagram of connections, (b) Vector diagram.

Table 1A—Preferred Ratings of Induction Watthour Meters

Application No.	Circuit Application		Rating of Meter Type	Voltage Rating of Meter	Test Current Rating of Meter	Type of Meter	Westinghouse Designation		Number of Stators	Types of Stators	Voltage Rating of Stators	Voltage Applied to Stators	Remarks
	Type of Circuit	Nominal Voltage					Socket	Bottom Connected					
1	1-ϕ, 2-wire	E	SC	E	15	1	DS	DA	1	2-wire	E	E	
			SC	E/2E	15	1	DS		1	2–3-wire	E	E	Universal meter. Potential windings in parallel and use one current winding only.
			TR	E	2.5	1	DS	DA	1	2-wire	E	E	
2	1-ϕ, 3-wire	E/2E	SC	2E	15	1	DA	DA	1	3-wire	2E	2E	Applicable to 1-ϕ, 3-wire systems with balanced L-N voltages.
			SC	2E	30	1	DS	DA	1	3-wire	2E	2E	
			SC	2E	50	1			1	3-wire	2E	2E	
			SC	E/2E	15	1	DS		1	2–3-wire	2E	2E	
			TR	2E	2.5	1	DS	DA	1	2-wire	2E	2E	Universal meter. Potential windings in series and use both current windings (one in series with each line (not neutral) conductor). Applicable to 1–3-wire systems with balanced 1-N voltages. Use one 2-wire stator meter on one 3-wire CT or with two 2-wire CT's. secondaries in series or one 3-wire stator meter with two 2-wire CT's connected to corresponding current coil meter. Using CT's only.
			SC	E	15	5	DS-5	DA-5	2	2-wire	E	E	Applicable to 1-ϕ, 3-wire systems with unbalanced L-N voltages. Terminals provided for neutral connection to potential windings.
			TR	E	2.5	2	DSP-2	DAP-2	2	2-wire	E	E	Applicable to 1-ϕ, 3-wire systems with unbalanced L-N voltages. Using two 2-wire CT's only.
3	2-ϕ, 3-wire (Network)	E/E_1Y	SC	E	15	5	DS-5	DA-5	2	2-wire	E	E	For 265/460Y networks meter with stators rated at 240 volts is suitable.
			SC	E	30	5	DS-5	DA-5	2	2-wire	E	E	Meter has terminal for connection of each potential winding to neutral.
			SC	E	50	5			2	2-wire	E	E	
			TR	E	2.5	2	DSP-2	DAP-2	2	2-wire	E	E	Secondaries of CT's must also be grounded. Two stator meter with all its windings isolated is suitable for any application requiring a 2-stator, a transformed rated meter, using CT's only.
4	3-ϕ, 3-wire wye or delta.	$E_{(L-L)}$	SC	E	15	2	DSP-2	DAP-2	2	2-wire	E	E	
			SC		30	2	DSP-2	DAP-2	2	2-wire	E	E	
			SC		50	2							
			TR	E	2.5	2	DSP-2	DAP-2	2	2-wire	E	E	Using two 2-wire CT's only
			TR	120	2.5	2	DSP-2	DAP-2	2	2-wire	120	120	Using E/120 PT's and CT's
5	3-ϕ, 4-wire wye	E/E_1Y	SC	E	15	8	DSP-8	DAP-8	2	3-wire	E	E	So called "2½ stator" or "Z" connected meter applicable to system with balanced 3-ϕ, L-N voltages. For 265/460Y networks, meter with stators rated at 240 volts are suitable; alternative is to apply 120 meters with two 265/120-volt potential transformers.
			SC	E	50	8			2	3-wire	E	E	
			TR	E	2.5	2	DSP-2	DAP-2	2	3-wire	E	E	Using CT's only. Remarks for SC meter also applicable
			TR	120	2.5	2	DSP-2	DAP-2	2	3-wire	120	120	Using E/120 potential transformers and CT's. Usual application to transmission circuits. Remarks for SC "Z" connected meters are also applicable.
			SC	E	5	3	CS-3	DA-3	3	2-wire	E	E	Applicable for systems with unbalance and 3-ϕ, L-N voltages.
			SC	E	15	3	CS-3	DA-3	3	2-wire	E	E	
			SC	E	50	3	CS-3	DA-3	3	2-wire	E	E	
			TR	E	2.5	3	CS-3	DA-3	3	2-wire	E	E	Applicable to systems with unbalanced 3-ϕ, L-N voltages. Using CT's only.
				E	5.0	3	CS-3	DA-3	3	2-wire	E	E	
			TR	120	2.5	3	CS-3	DA-3	3	2-wire	120	120	Applicable to systems with unbalanced 3-ϕ, L-N voltages using E/120 PT's; also using CT's.
					5.0	3	CS-3	DA-3	3	2-wire	120	120	
6	3-ϕ, 4-wire delta	3-W,3-ϕ,E; 3-W,1-ϕ, (E/2)/E	SC	E	15	7	DSP-7	DAP-7	2	2-wire	E	.867E	Applicable to systems with balanced L-N voltages on 3-wire 1-ϕ circuit.
										3-wire	E	E	
					50	7				2-wire	E	.867E	
						7	DSP-7	DAP-7	2	3-wire	E	E	
			TR	E	2.5	2	DSP-2	DAP-2	2	2-wire	E	.867E	Applicable to systems with balanced L-N voltages on 1-ϕ, 3-wire circuit (7) Type meter requires three 2-wire CT's, one 2-wire CT and one 3-wire CT (or two 2-wire CT's equivalent) required for (2) meter.
										2-wire	E	E	
			SC	E	5	9	CS-9	CA-9	3	2–2-wire	E/2	E/2	Applicable to systems with unbalanced L-N voltages on 1-ϕ, 3-wire circuit.
										2-wire	E	.867E	
					15	9							
					25	9							
			TR	E	2.5	9	CS-9	CA-9	3	2–2-wire	E/2	E/2	Applicable to systems with unbalanced L-N voltages on 1-ϕ, 3-wire circuit and 3 CT's of equal rating.
										2-wire	E	.867E	

Table 1A (cont'd)—Preferred Ratings of Induction Watthour Meters

Application No.	Circuit Application: Type of Circuit	Circuit Application: Nominal Voltage	Rating of Meter Type	Voltage Rating of Meter	Test Current Rating of Meter	Type of Meter	Westinghouse Designation: Socket	Westinghouse Designation: Bottom Connected	Number of Stators	Types of Stators	Voltage Rating of Stators	Voltage Applied to Stators	Remarks
7	Totalizing 1-φ, 2-wire, and 3-φ, 3-wire service	1-φ E₁ 3-φ E	SC	1-φ E/2	15	4	CS-4	CA-4	3	2-wire	E/2	E/2	
				3-φ E	7.5					2–2-wire	E	E	
				1-φ E/2	50	4	CS-4	CA-4		2–2-wire	E	E	
				3-φ E	25					2–2-wire	E	E	
				1-φ E	15	4	CS-4	CA-4	3	2-wire	E	E	
				3-φ E	15					2–2-wire	E	E	
				1-φ E	50					2–2-wire	E	E	
				3-φ E	50					2–2-wire	E	E	
			TR	1-φ E/2	5	4	CS-4	CA-4	3	2-wire	E/2	E/2	Uses CT's only. Uses three–2-wire CT's (one for 1φ ckt. and two for 3-φ ckts.).
				3-φ E	2.5					2–2-wire	E	E	
				1-φ E	5	4	CS-4	CA-4	3	2-wire	E	E	
				3-φ E	5					2–2-wire	E	E	
8	Totalizing 1-φ, & 3-φ, 3-wire service	1-φ (E/2)/E 3-φ E	SC	1-φ (E/2)/E	15	6	CS-6	CA-6	3	3-wire	(E/2)/E	E	
				3-φ E	15					2–2-wire	E	E	
					50	6	CS-6	CA-6					
					50								
			TR	1-φ (E/2)/E	5	6	CS-6	CA-6	3	3-wire	E/2	E	Use CT's only. Uses two 2-wire CT's on 1-φ ckt. and two 2-wire CT's for 3-φ ckt.; alternate is to use a three 2-wire stator meter (similar to CS-4 or CA-4) and one 3-wire CT on 1-φ ckt. and two 2-wire CT's on 3-φ ckt.; second alternate is to use a three 2-wire stator meter (similar to CS-3) with three PT's, one 3-wire CT and two 2-wire CT's.
				3-φ E	5					2–2-wire	E	E	
		1-φ (E/2)/E 3-φ 2E	SC	1-φ (E/2)/E	15	6	CS-6	CA-6	3	3-wire	(E/2)/E	E	
				3-φ 2E	7.5					2–2-wire	2E	2E	
					50	6	CS-6	CA-6	3	2–2-wire	(E/2)/E	E	
					25					2–2-wire	2E	2E	
			TR	1-φ (E/2)/E	5	6	CS-6	CA-6	3	3-wire	(E/2)/E		Remarks applicable to TR meter on 1-φ E₂/E, 2-φ E application above also applicable.
				3-φ 2E	2.5					2–2-wire	2E	2E	
9	2-φ, 5-wire		SC	E	15	10	CS-10	CA-10	2	2–3-wire	E	E	Each stator is similar to 3-wire stator used on 1-φ (E/2)/E system. Circuit is essentially two 1-φ systems with common neutral.
					50								
			TR	E	2.5	10	CS-10	CA-10	2	2–3-wire	E	E	CT's only. Used with four 2-wire CT's. A two 2-wire stator meter similar to (DS-2 or DA-2) can be applied with two 3-wire CT's.

Table 1B—Preferred Voltage Ratings of Induction Watthour Meters

Application # Table 1A

1		2		3		4		5		6		7				8				9	
E		2E		E		E		E		E		E									
SC	TR	SC	TR	SC	TR	SC	TR	SC	TR	SC	TR	SC		TR		SC		TR		SC	TR
												1-φ	3-φ	1-φ	3-φ	1-φ	3-φ	1-φ	3-φ		
120	120	240	240	120	120	120	120	120	120	240	240	240	240	240	240	120/240	240	120/240	240	240	240
240	240			240	240	240	240	240	240			480	240	480	240	120/240	480	120/240	480		
				480	480	480	480	480	480			480	480	480	480						
				600	600	600	600	600	600												

E = Nominal voltage of circuit to which the meter is applied.
SC = Self-contained meter.
TR = Transformer-rated meter.

It is assumed in each application that in the meter being considered, each stator has been adjusted and registers correctly the dot product of voltage and current applied to each stator. Only voltages and currents available for metering are shown in diagrams. Since the meter stators have been assumed to register correctly, the factor of "time" has been omitted from the analyses for simplicity.

Single-Phase, Two-Wire Meter—No analysis is necessary for this application, because this is the basic stator or meter considered under watthour meter theory. Also, it has been assumed that the stator has been calibrated for correct registration.

Single-Phase, Three-Wire Circuit—For ordinary commercial and residential loads, the single-phase, three-wire, self-contained meter is used, although some loads may require transformer-rated meters. The meter is connected as shown in Fig. 11(a). In this meter, the two coils on the individual pole pieces are connected opposing each other for positive direction of currents into the loads. The corresponding vector diagram is shown in Fig. 11(b).

Analysis of measurement obtained in single-stator, three-wire meter:

Power delivered to the load is

$$\begin{aligned} P_t &= V_{1N}I_1 + V_{2N}I_2 && \text{(a)} \\ &= V_{1N}I_1 - V_{N2}I_2 && \end{aligned} \quad (14)$$

For balanced voltages

$$V_{1N} = V_{N2} = \frac{V_{12}}{2}$$

Then,

$$\begin{aligned} P_t &= V_{1N}I_1 - V_{1N}I_2 && \text{(a)} \\ &= V_{1N}\ (I_1 - I_2) && \text{(b)} \\ &= \frac{V_{12}}{2}(I_1 - I_2) && \text{(c)} \end{aligned}$$

Let the power measured by the meter be P_m. Then,

$$P_m = V_{12}\left(\frac{I_1 - I_2}{2}\right)$$

Division by "2" and "$-$" sign are necessary, since the three-wire meter has two half-winding current coils of opposite polarity for positive direction of current into the load.

If the voltages to neutral are balanced, the meter registers correctly regardless of any unbalance in load or difference in load power factors. However, since the possibility of voltage unbalance exists, the error in registration which may occur is of interest.[18] Let P_e be the difference between P_t, the true power delivered to the load, and P_m, the power as measured by the meter. Then

$$\begin{aligned} P_e &= P_t - P_m && \text{(a)} \\ &= \tfrac{1}{2}\ (V_{1N} - V_{N2})\ (I_1 + I_2) && \text{(b)} \end{aligned} \quad (16)$$

P_e is one-half the dot product of the phasors $(V_{1N} - V_{N2})$ and $I_1 + I_2$). This expression is of limited usefulness because the unbalance phasors and their phase relationship are not generally known. However, an analysis of the fundamental accuracy of the meter shows that its acceptance is well founded and the error is usually negligible. Where the error due to voltage unbalance is objectionable, a two-stator meter or two single-stator two-wire meters are required to obtain correct registration. Connections for these applications are shown in Fig. 12(a) and Fig. 12(b).

A three-wire single-phase service which requires current transformers can be metered with either a two-wire, single-stator meter or a three-wire single-stator meter. The diagrams of connections for metering a single-phase, three-wire service which requires current transformation are shown in Fig. 13. A three-wire meter requires two current transformers. A two-wire meter can be applied with two current transformers; however, a special three-winding current transformer, which is usually more economical, is available for metering three-wire, single-phase service with a two-wire meter.

A combination self-contained, two-wire, three-wire, single-phase meter is suitable for application on a 120-volt, two-wire service or on a 240-volt, three-wire service. The current coils are similar to those in a three-wire meter. The potential winding is split into two identical windings, which are connected in parallel for 120-volt, two-wire service, and in series for 240-volt, three-wire service. Both current coils are used for three-wire metering. For two-wire service, only one current coil is used; the other coil is disconnected and bridged. The meter watthour constant is the same for both the

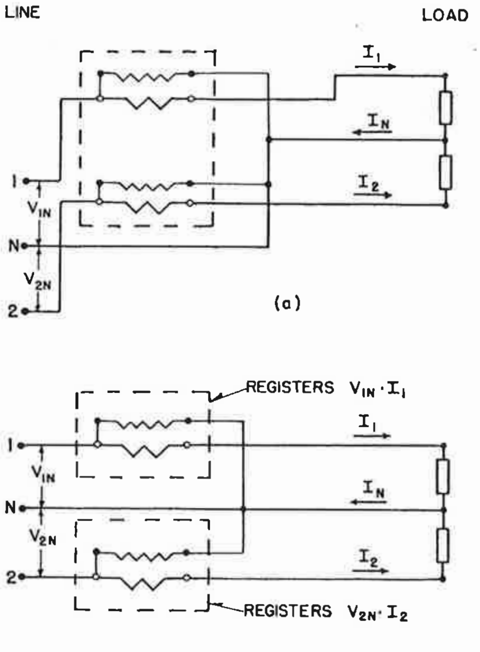
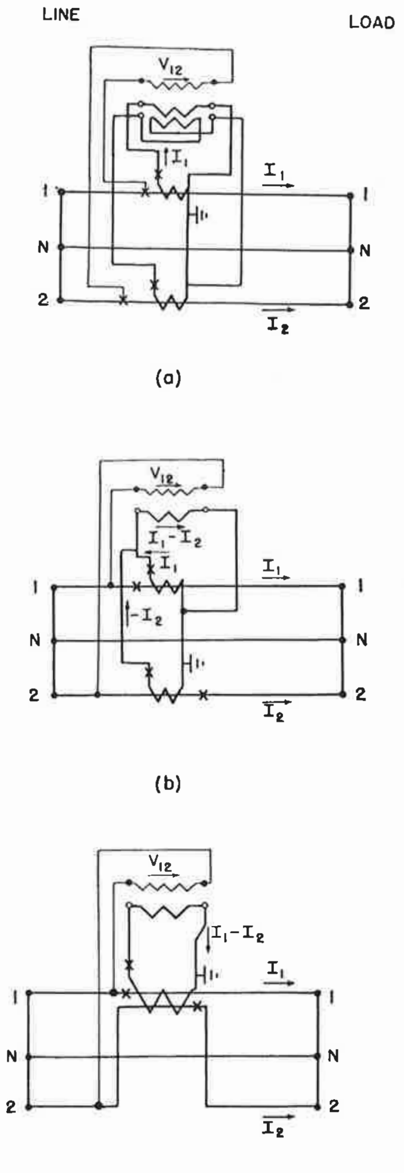


Fig. 12—Diagrams of connections for metering a single-phase, three-wire service where line-to-neutral voltages are unbalanced. (a) Using a two-stator meter, (b) Using two single-stator meters.



(a)

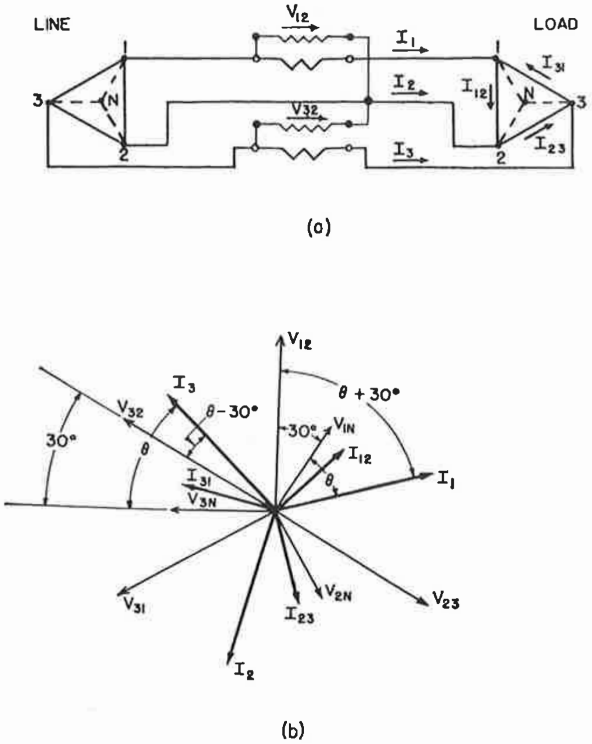
(b)

(c)

Fig. 13—Diagram of connections of transformer rated single-phase, three-wire meter. (a) Three-wire meter and two two-wire CT's (b) Two-wire meter and two two-wire CT's, (c) Two-wire meter and three-wire CT.

120-volt and 240-volt connections, because the potential flux is essentially the same for either connection.

Three-Phase, Three-Wire Circuit—According to Blondel's Theorem, a three-phase, three-wire circuit requires two meters of a two-stator meter for measurement of energy. The circuit diagram for measurement of energy (or power) in either a three-phase, three-wire delta or wye circuit is shown in Fig. 14(a). The load might be any one of these types of circuits. Hence, the delta load is indicated by solid lines; dotted lines indicate alternate loads. The metering shown in Fig. 14(a) may be either a



(a)

(b)

Fig. 14—Metering a three-phase, three-wire circuit, (a) diagram of connections, (b) vector diagram.

two-stator meter or two single-stator meters. Note that a meter current coil is in each of two-phase conductors, and that the potential coils are connected between the conductor containing the related current coil and the phase conductor which does not contain a current coil. Such a connection is required in order for the energy measurement to be made with n-1 meters or stators.

The vector diagram for Fig. 14(a) is shown in Fig. 14(b). Delta currents, indicated by double subscripts, are not applicable to the wye circuit.

Analysis of the applicability of the circuit represented by the diagram shown in Fig. 14(a) to three-phase, 3-wire circuits is as follows: The phasors are as shown on the vector diagrams of Fig. 14(b).

(1) For Delta

$$
\begin{aligned}
I_1 &= I_{12} - I_{31} && \text{(a)}\\
I_2 &= I_{23} - I_{12} && \text{(b)}\\
I_3 &= I_{31} - I_{23} && \text{(c)} \quad (17)\\
V_{12} + V_{23} + V_{31} &= 0 \text{ and } I_1 + I_2 + I_3 = 0 && \text{(d)}
\end{aligned}
$$

$$
\begin{aligned}
P &= V_{12}\, I_{12} + V_{23}\, I_{23} + V_{31}\, I_{31} && \text{(a)}\\
P &= V_{12}\, I_{12} - V_{32}\, I_{23} - (V_{12} - V_{32})\, I_{31} && \text{(b)}\\
P &= V_{12}\, (I_{12} - I_{31}) + V_{32}\, (I_{31} - I_{23}) && \text{(c)} \quad (18)\\
P &= V_{12}\, I_1 + V_{32}\, I_3 = \text{Meter Registration} && \text{(d)}
\end{aligned}
$$

(2) For Wye

$$
\begin{aligned}
P &= V_{1N}\, I_1 + V_{2N}\, I_2 + V_{3N}\, I_3 && \text{(a)}\\
P &= V_{1N}\, I_1 - V_{2N}\, (I_1 + I_3) + V_{3N}\, I_3 && \text{(b)} \quad (19)\\
&= (V_{1N} - V_{2N})\, I_1 + (V_{3N} - V_{2N})\, I_3 && \text{(c)}\\
&= V_{12}\, I_1 + V_{32}\, I_3
\end{aligned}
$$

Two-Phase, Three-Wire Network Circuits—According to Blondel's Theorem, the two-phase, three-wire network service requires either a two-stator meter or two single-stator meters, as shown in Fig. 15(a). The vector diagram is shown in Fig. 15(b) .Attention is directed to some peculiarities in the metering of a two-phase, three-wire network service. It has been shown that a two-stator meter registers correctly when applied on a three-wire, three-phase circuit, if line-to-line potentials are applied to the meter. It registers equally well on a two-phase, three-wire neutral service fed from a three-phase, four-wire wye system, if line-to-neutral potentials are applied to the meter. Then each stator measures the load on the respective phase to which it is connected. The analysis of the applicability of the network meter follows:

$$P_1 = V_{1N} \cdot I_1 \text{ and } P_2 = V_{2N} \cdot I_2 \qquad \text{(a)} \qquad (20)$$
$$P = P_1 + P_2 = V_{1N} I_1 + V_{2N} I_2 \qquad \text{(b)}$$

For line-to-line loads, the registration on each stator is as follows:

$$\text{Stator \#1, } P_1 = V_{1N} \cdot I \qquad \text{(a)} \qquad (21)$$
$$\text{Stator \#2, } P_2 = V_{2N} \cdot I_2$$

But for line-to-line loads, $I_2 = -I_1$.

Then, $P_2 = V_{2N} I_1$

The net registration is given by

$$P = P_1 + P_2 \qquad \text{(a)}$$
$$P = (V_{1N} - V_{2N}) I_1 \qquad \text{(b)} \qquad (22)$$
$$P = V_{12} \cdot I_1$$

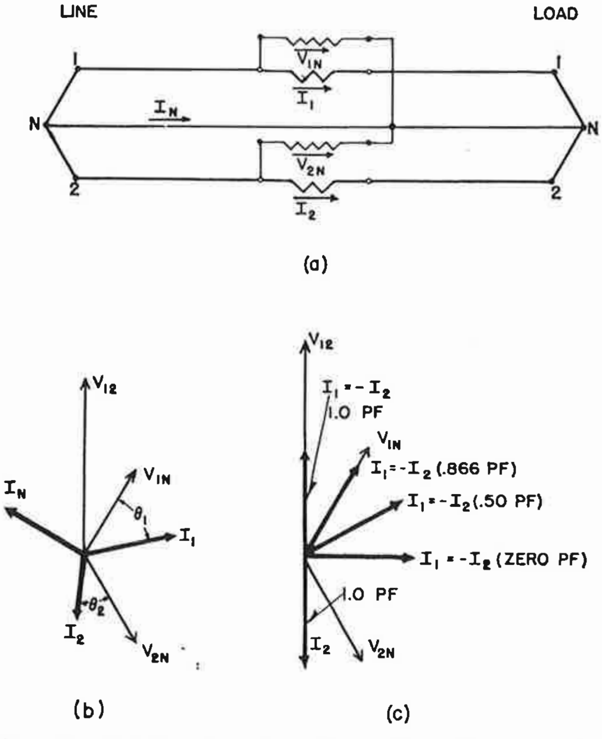


Fig. 15—Metering two-phase, three-wire network circuit, (a) Diagram of connections, (b) Vector diagram, balanced system voltages, unbalanced load, (c) Vector diagram for metering line-to-line loads, balanced system voltages.

Since the true power to the load is $V_{12} \cdot I_1$, the two-stator meter also registers correctly on measurement of line-to-line loads.

The essential differences in the standard two-stator, three-phase, three-wire meter and the network meter are in the terminal connections and in the voltage ratings. The standard two-stator meter usually has completely separate potential and current circuits; therefore, it has eight terminals. The network meter is arranged so that the two potential circuits are connected to a common terminal. The other terminal of each potential circuit is common with a terminal of the respective related current coil. A greater difference in the standard two-stator and network meters is in the voltage ratings of each type and meter. The voltage rating for application to three-phase, three-wire circuits is line-to-line voltage. However, the network meter is rated for line-to-neutral voltage. The network meter is applicable to three-phase, three-wire circuits if the nominal circuit line-to-line voltage is equal to the rated voltage of the meter.

Transformer-rated, three-wire meters for two-phase and three-phase circuits are usually the standard two-stator meter, because meters having completely separate potential and current circuits would be required. The secondary circuits at the current transformers must be grounded; however, line-to-line potential may be applied to the stators, so that no potential terminal can be grounded. The current transformers cannot be grounded when a network meter is used. For reasons of economy and simplicity, a two-stator network meter is recommended where it is applicable in metering three-phase, three-wire circuits.

Attention is directed to the rather interesting peculiarities in metering of two-phase, three-wire network services. These peculiarities are: 1) the action of a two-stator meter when metering line-to-line load on a two-phase, three-wire network service by means of a two-stator meter, and 2) the accuracies of a single-phase, three-wire meter when applied to two-phase, three-wire network circuits.

The measurement of line-to-line loads in a two-stator meter are considered first. The condition of the measurement of line-to-line load should not be confused with the measurement of identical line-to-neutral loads. The two conditions are entirely different. For equal line-to-neutral loads, each load is measured on the proper stator. However, in measurement of line-to-line loads, the torque developed by each stator or the measurement of energy on each stator of a network meter is a function of the phase angle between the phase voltage and the corresponding phase current or line current. The energy consumption in line-to-line loads is a function of the phase angle between line-to-line voltage and phase or line current. This results in a variation in the distribution of driving torque between the meter stators with load power factors. Fig. 15(c) is the vector diagram for line-to-line loads taken from a two-phase, three-wire neutral service. With the aid of Fig. 15(c), the variation in driving torque distribution with load pf can be analyzed.

Although a single-stator, three-wire meter correctly registers line-to-line network loads, the meter does not register correctly for line-to-neutral loads. The diagram of the circuit considered here is shown in Fig. 16. The vector diagrams for various line-to-neutral load power factors are shown in Fig. 17. Since neither V_{1N} nor V_{N2} is equal to $V_{12}/2$, and I_2 is not equal to $-I_1$, the single-stator, three-wire meter does not register correctly. As an example, consider the vector diagram shown in Fig. 17(a), which is for a unity power factor line-to-neutral load on phase "1".

$$\left.\begin{aligned}\text{True Power} &= V_{1N}\cdot I_1 && \text{(a)}\\ &= V_{1N}I_1 \text{ at unity pf.} && \text{(b)}\end{aligned}\right\}\quad(23)$$

$$\left.\begin{aligned}\text{Meter registers} = P_m &= V_{12}\cdot\frac{I_1}{2} && \text{(a)}\\ P_m &= \frac{V_{12}I_1\cos 30°}{2} && \text{(b)}\\ P_m &= \frac{\sqrt{3}V_{1N}I_1}{2}\,\frac{\sqrt{3}}{2} && \text{(c)}\\ P_m &= .75V_{1N}I_1 && \text{(d)}\end{aligned}\right\}\quad(24)$$

The registration on the meter is 75 per cent. A similar reasoning may be applied to the other load power factors and the following results obtained:

Load Between	Power Factor	Per Cent of Correct Registration
1-N	100%	75%
1-N	86.6% lag	50%
1-N	50.0% lag	0
2-N	100%	75%
2-N	86.6% lag	100%
2-N	59.0% lag	150%

For identical line-to-neutral loads on the two phases, the single-stator, three-wire meter registration is correct only at zero pf and is 75 per cent correct at all other power factors. This can be seen from an analysis of Fig. 18. Balanced line-to-neutral voltages are assumed.

Three-Phase, Four-Wire Wye—According to Blondel's Theorem, a three (n-1) stator meter is required for accurately metering a three-phase, four-wire wye service. However, if the voltages are balanced, the metering is simplified, and the "Z" connection of a two and one-half stator meter is applicable with equal accuracy. For most applications, the voltages are sufficiently balanced to make this assumption valid. This factor is particular-

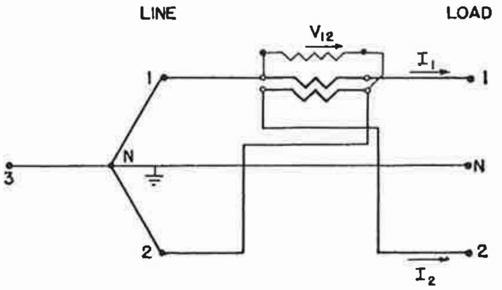


Fig. 16—Diagram of connections for incorrect metering of two-phase, three-wire network circuit with a single-stator, three-wire meter.

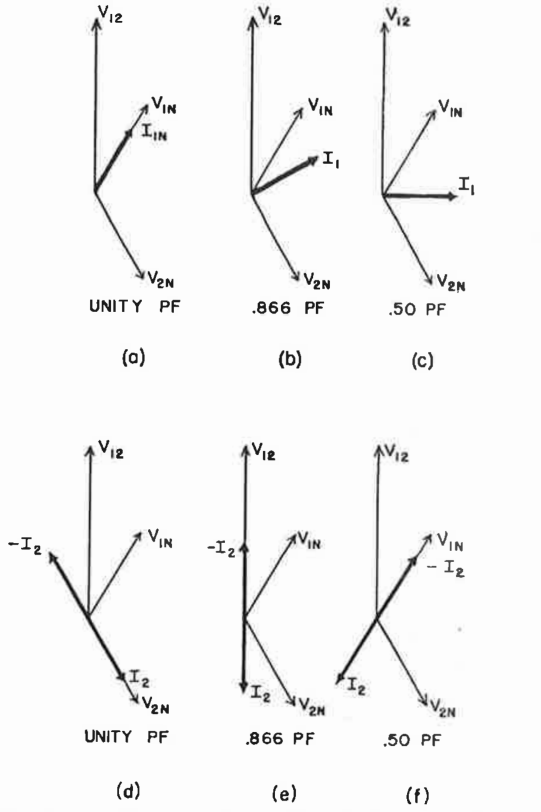


Fig. 17—Vector diagrams for various load power factors for metering line-to-neutral loads on two-phase, three-wire network circuit with a single-stator, three-wire meter.

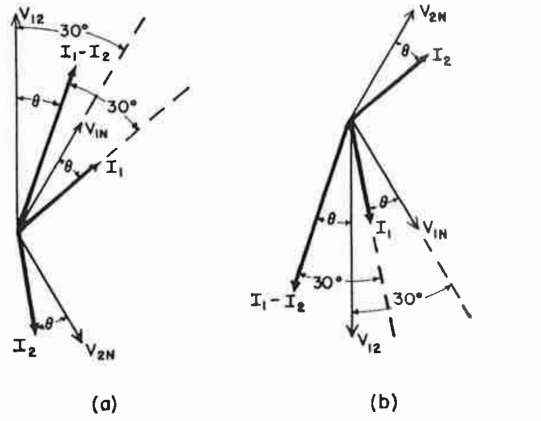


Fig. 18—Vector diagram for metering identical line-to-neutral loads on a two-phase, three-wire network circuit with a single-stator, three-wire meter, (a) Phase sequence 1-2-3, (b) Phase sequence 1-3-2.

$$\begin{aligned}\text{True Power} &= V_{1N}I_1 + V_{2N}I_2\\ &= 2V_{1N}I_1\cos\theta\\ \text{Measure Power} &= \tfrac{1}{2}V_{12}(I_1-I_2)\\ &= \frac{\sqrt{3}\,V_{1N}\sqrt{3}\,I_1\cos\theta}{2}\end{aligned}$$

$$\frac{\text{Measure Power}}{\text{True Power}} = .75$$

ly important in the measurement of energy on three-phase, four-wire wye systems which require potential transformers. If the voltages are balanced, only two potential transformers are required for the energy metering. Although the factor is important when low voltage systems are considered, it becomes increasingly important at the higher voltages, due to the increased cost of the potential transformers. The circuit diagram for metering three-phase, four-wire, wye service by a three-stator meter is shown in Fig. 19(a). The circuit diagram for use of the 2½ stator meter is shown in Fig. 19(b). The vector diagram is shown in Fig. 19(c).

Analysis of measurement of three-phase, four-wire, wye circuit shown in Figure 19 is as follows:

$$\text{True Power} = P_T = V_{1N}I_1 + V_{2N}I_2 + V_{3N}I_3 \qquad (24)$$

if the voltages are balanced,

$$\begin{array}{lll} V_{1N} + V_{2N} + V_{3N} = O & \text{(a)} & \\ P_T = V_{1N}I_1 + V_{2N}I_2 - (V_{1N} + V_{2N})I_3 & \text{(b)} & (25) \\ \quad = V_{1N}(I_1 - I_3) + V_{2N}(I_2 - I_3) & \text{(c)} & \end{array}$$

The 2½ stator or "Z"-connected meter is comprised of two single-phase, three-wire stators driving a common shaft. The current coil in each stator is divided evenly into two windings. One current winding on each stator carries the current of the phase, the voltage of which is applied to the potential coil, while the other current winding of that stator carries the negative of the current of the phase in which the potential is not measured.

Since the current windings on each stator are split into two half-windings and are wound with opposite polarity, the power measurement on a "Z"-connected meter is given by

$$\begin{array}{lll} P_M = V_{1N}(I_1 - I_3) + V_{2N}(I_2 - I_3) & \text{(a)} & \\ \quad = V_{1N}I_1 + V_{2N}I_2 - (V_{1N} + V_{2N})I_3 & \text{(b)} & (26) \end{array}$$

This measurement is correct for balanced line-to-neutral voltages. However, the measurement indicated on the meter is as given by Equation 26, regardless of the voltage unbalance. The true power into a three-phase, four-wire, wye circuit is given by Equation 24.

The vector diagram for metering the circuit with a 2½ stator meter under conditions of generally unbalanced voltages is shown in Fig. 20. The error, P_e, in the measurement of power, or the registration of a 2½ stator meter for a condition of unbalanced line-to-neutral voltages is given by

$$\begin{array}{lll} P_e = P_T - P_M & \text{(a)} & \\ P_e = (V_{1N} + V_{2N} + V_{3N})I_3 & \text{(b)} & (27) \\ P_e = V_R I_3 & \text{(c)} & \end{array}$$

where

$$V_R = V_{1N} + V_{2N} + V_{3N}$$

Therefore, no error occurs from application of a 2½ stator meter on three-phase, four-wire wye system if: (1) the residual voltage to neutral is zero, which occurs if the voltages-to-neutral are unbalanced; (2) the current in the "Z" connected current coils (I_3 above) is zero; and (3) the residual voltage-to-neutral and the current in the "Z" connected current coils are in quadrature time phase. For applications in which any one of these conditions hold, a 2½ stator meter registers with the same accuracy obtained with a three-stator meter.

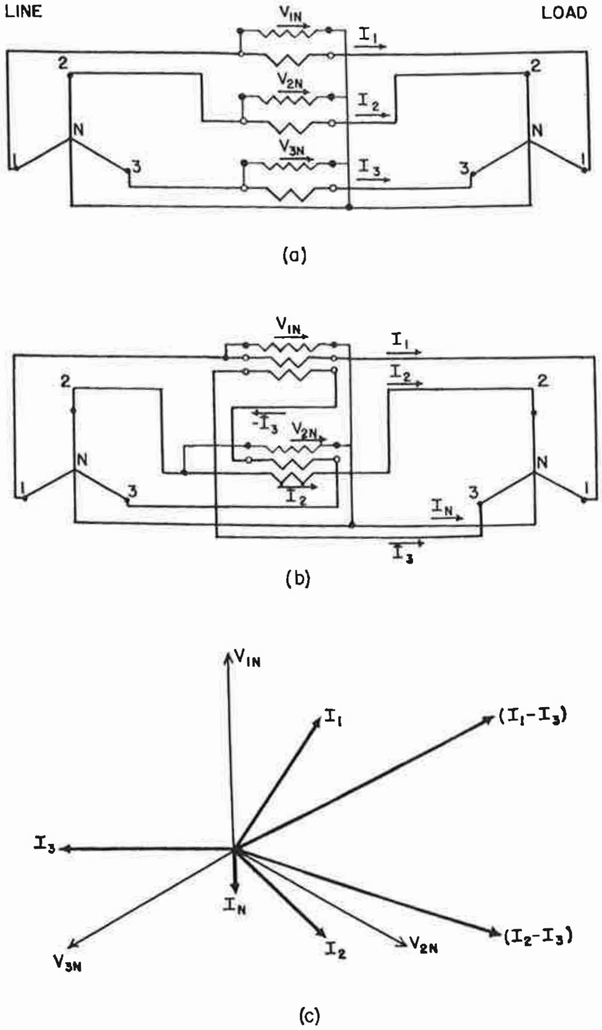


Fig. 19—Metering of three-phase, four-wire wye circuit, (a) Diagram of connections for using a three-stator meter, (b) Diagram of connections for using a two-stator, "Z" connected meter, (c) Vector diagram.

The error in a 2½ stator meter occurs in the measurement of load on the phase on which the potential is not applied to the meter. The meter registers correctly the loads on the phases of which both potential and current are applied to the meter.

Some effects of unbalanced voltages on the accuracy of a 2½ stator meter can be seen from Fig. 21. It is assumed that V_{3N} is not applied to the meter. In Fig. 21(a), $-(V_{1N}+V_{2N})$ is in phase with but not equal to V_{3N}. In Fig. 21(b), $-(V_{1N}+V_{2N})$ is equal in magnitude only to V_{3N}. Observe Fig. 21(a) and suppose that if, E_{3N}, is 1.0 per cent lower than $-(V_{1N}+V_{2N})$. Phases "one" and "two" are registered correctly and the measurement on phase "three" will be one per cent high. The

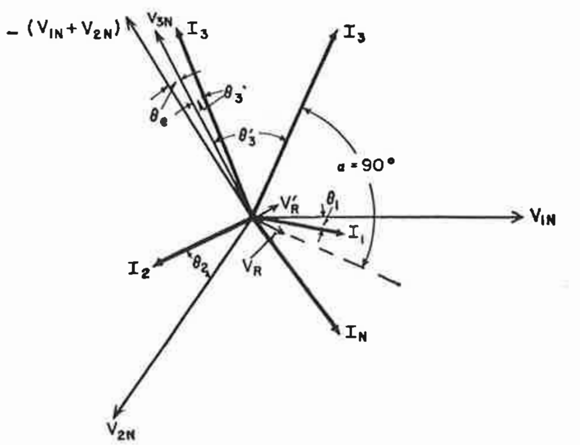


Fig. 20—Vector diagram of circuit for metering a three-phase, four-wire wye circuit with two-stator "Z" connected meter under conditions of generally unbalanced voltages showing factors in error of meter.

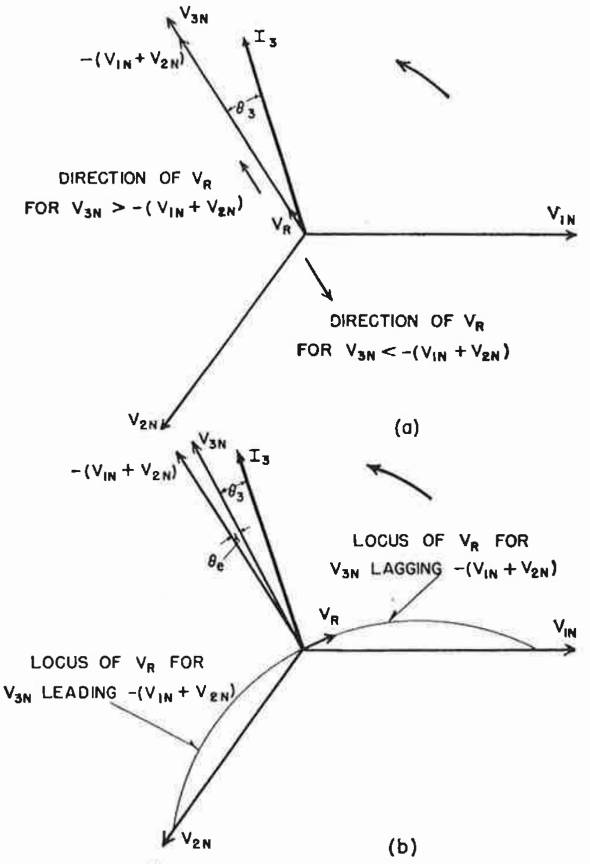


Fig. 21—Vector diagram circuit for metering a three-phase, four-wire wye circuit with "Z" connected meter for analyzing error under various load conditions, (a) $-(V_{1N}+V_{2N})$ in phase with but not equal to V_{3N}, (b) $-(V_{1N}+V_{2N})$ equal in absolute value only to V_{3N}.

total error will then depend on the distribution of the load. The meter registration will be (1) 0.3 per cent high if the load is balanced; (2) one per cent high if only phase "three" is loaded; and (3) correct if the load on phase "three" is zero. For V_{3N} equal in magnitude only to $-(V_{1N}+V_{2N})$, no appreciable error results for load power factor near unity. For load power factor near 50 per cent, an error of 15 minutes [the angle between V_{3N} and $-(V_{1N}+V_{2N})$] will result in the following errors: (1) .75 per cent if only phase "three" is loaded; (2) .25 per cent if the load is balanced; and (3) no error if the load on phase "three" is zero.

Three-Phase, Four-Wire, Delta—The circuit diagrams showing the metering of a three-phase four-wire delta circuit are shown in Fig. 22. The circuit shown in Fig. 22(a) uses a two-stator meter, which has one three-wire stator and one two-wire stator. The circuit shown in Fig. 22(b) uses a meter having three two-wire stators. The circuit is suitable for combined single-phase, three-wire and three-phase, three-wire service. The analysis of metering this type of load is simplified by considering the three-phase and single-phase loads separately, and then superimposing these loads for consideration of the combined load. No assumption is made regarding the balance of load in either the three-phase or single-phase circuits, or the relative magnitudes of the single-phase and total three-phase loads. In order to be generally applicable, unbalanced voltages-to-neutral on

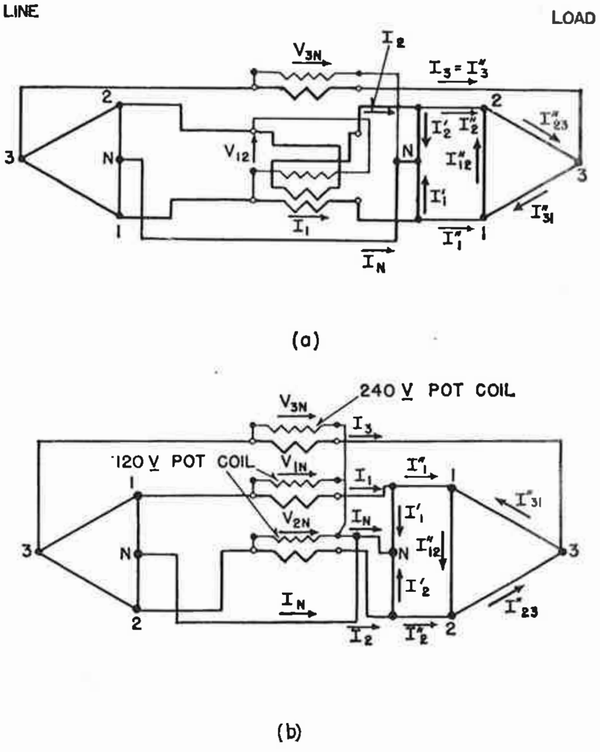
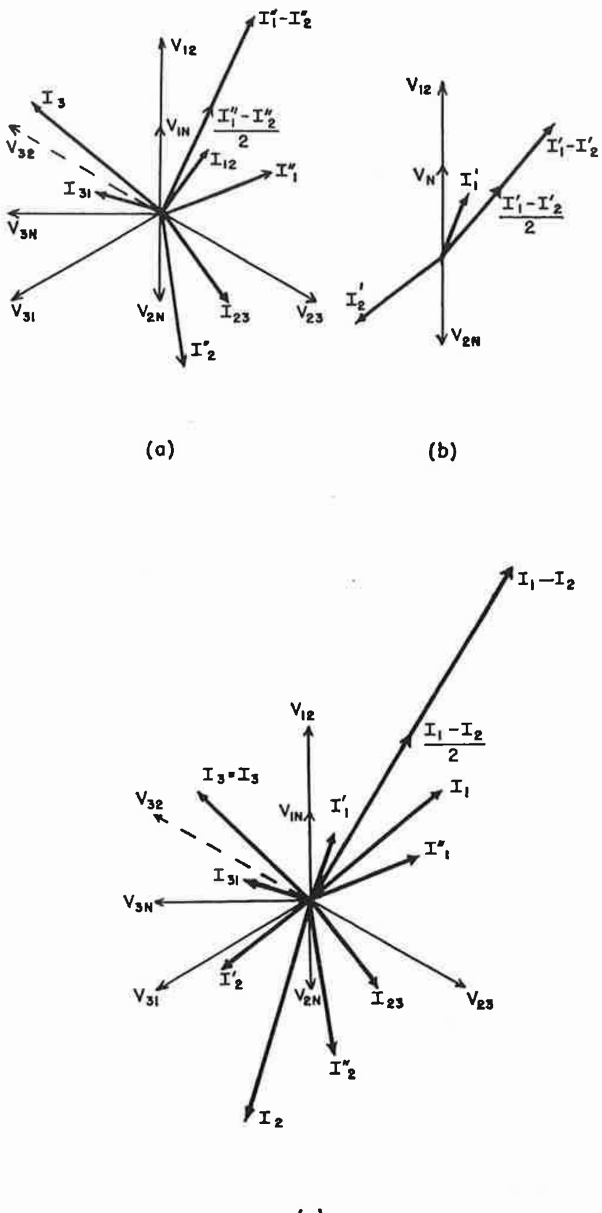


Fig. 22—Diagram of connections for metering a three-phase, four-wire delta circuit with a (a) Two-stator meter, (b) Three-stator meter.

the single-phase load is assumed. The accuracy of the metering of the three-phase, three-wire delta loads is not dependent upon balanced line-to-line voltages; however, balanced three-phase voltages are assumed.

The vector diagrams of circuits for metering three-phase, four-wire delta loads are shown in Fig. 23(a). This diagram is similar to the diagram shown in Fig. 14(b), for the three-phase, three-wire circuit. The vector diagram for the single-phase, three-wire load is shown in Fig. 23(b), which is the same diagram shown in Fig. 11(b) for the single-phase, three-wire meter. The vector diagram for the combined single-phase and three-phase loads is shown in Fig. 23(a). This is a composite diagram in which Fig. 23 (a) is superimposed on Fig. 23(b). Single-prime I's indicate single-phase currents; double-prime I's indicate three-phase currents; and the unprimed, single subscript I's indicate the combined single-phase and three-phase currents.



(a) (b)

(c)

Fig. 23—Vector diagrams for circuit for metering a three-phase, four-wire delta circuit (a) Three-phase load only, (b) Single-phase load only, (c) Combined single- and three-phase loads.

This type of load can be metered by either a two-stator meter, a three-stator meter, or the equivalent of either. A two-stator meter has one two-wire, stator and one three-wire stator driving a common shaft. A three-stator meter has three two-wire stators which drive a common shaft. The choice of the type of meter to use in a particular application depends upon the balance of the voltages on the three-wire (lighting) phase.

The analysis of the single-phase, three-wire meter previously made is equally applicable here. The accuracy in metering only the three-phase loads need be considered here.

Let P''_{T3} = power delivered to the three-phase load.

$$P''_{T3} = V_{12}I''_1 + V_{32}I''_3 \qquad \text{(a)}$$

But

$$V_{32} = V_{3N} + V_{N2}$$

and

$$V_{12} = V_{1N} + V_{N2}$$

Then (28)

$$P''_{T3} = (V_{1N} + V_{N2})I_1'' + (V_{3N} + V_{N2})I''_3 \qquad \text{(b)}$$
$$= V_{1N}I''_1 + V_{N2}(I_1'' + I''_3) + V_{3N}I''_3$$

But

$$I''_1 + I''_3 = -I''_2 \qquad \text{(c)}$$

Therefore

$$P''_{T3} = V_{1N}I''_1 - V_{N2}I''_2 + V_{3N}I''_3 \qquad \text{(d)}$$

If the line-to-neutral voltages are balanced,

$$V_{1N} = V_{N2} = \frac{V_{12}}{2}$$

$$P''_{T3} = \frac{V_{12}}{2}(I''_1 - I''_2) + V_{3N}I''_3 \qquad \text{(a)}$$

(29)

$$= \frac{(V_{1N} + V_{N2})}{2}(I''_1 - I''_2) + V_{3N}I''_3 \qquad \text{(b)}$$

Let P''_M = three-phase power measured on 2-stator, three-phase, four-wire, delta meter.

P''_{T3} = true power delivered to three-phase load

P''_{M-3} = three-phase power measured on three-wire stator

P''_{M-2} = three-phase power measured on two-wire stator

$P''_{M-3} = \frac{V_{12}}{2}(I''_1 - I''_2)$, because three-wire stator is composed of two one-half windings of opposing polarities.

$P''_{M-2} = V_{3N}I''_3$

Let $P''_e = P''_{T3} - P''_M$ = Error in registration of three-phase power

Then

$$P''_e = \tfrac{1}{2}(V_{1N} - V_{N2})(I''_1 + I''_2) \qquad (30)$$

The error, P''_e, is one-half the dot product of the voltage difference, $(V_{1N} - V_{N2})$ and the current sum, $(I''_1 + I''_2)$ where all quantities, including the difference and sum, are phasors. Reference to Equation 16 shows that the error in measurement of three-phase power is of the same form as the expression for the error in the single-phase, three-wire meter.

The error in the registration of three-phase load expressed in watts, has little meaning itself. The error expressed as percentage of the true value is more significant. It is of interest to consider the phasor $(V_{1N} - V_{N2})$ as being either in phase with or 180° out of phase with V_{12} and in quadrature with V_{3N}, and expressed as a percentage of normal line-to-line and to consider balanced three-phase loads only are considered. Then, in per unit,

$$\left.\begin{aligned} P''_e &= \frac{P''_e}{P_{T3}} && \text{(a)} \\ P''_e &= \tfrac{1}{2} V_u \frac{(-\tan\theta)}{\sqrt{3}} && \text{(b)} \end{aligned}\right\} \quad (31)$$

where $V_u = \frac{(V_{1N} - V_{N2})}{V_{12}}$

V_u = the voltage unbalance to neutral in per unit of normal line-to-line voltage.

θ = angle by which phase current lags phase voltage.

The vector diagram for a balanced three-phase load on a three-phase, four-wire delta system is shown in Fig. 24. The variation in error with load power factor can be analyzed with the aid of Fig. 24 and Equation 31. A one per cent unbalance in line-to-neutral voltage results in no error for unity power factor load. As the power factor decreases, tan θ increases at an increasing rate. At 50 per cent power factor, a voltage unbalance of one per cent results in an error in registration of one-half of one per cent. As the power factor approaches zero, the phasor $(I''_1 + I''_2)$ approaches in phase with the voltage unbalance. The true power becomes zero and the percentage error in the power registration increases without limit. When the error is objectionable, a three-stator meter is used.

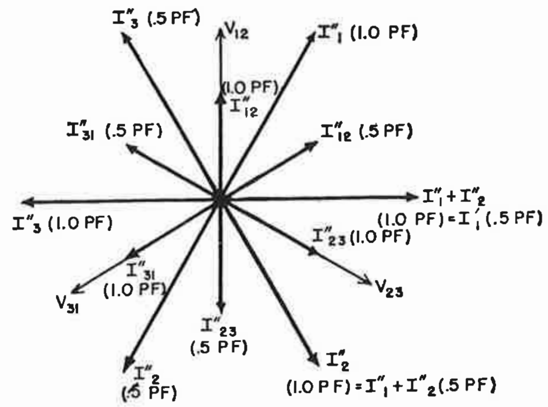


Fig. 24—Vector diagram for balanced three-phase loads at various load power factors for analyzing variation with load power factor of apparent power factor as seen by meter stators.

Two-Phase, Four-Wire—A two-phase, four-wire circuit consists essentially of two single-phase, two-wire systems in which the applied voltages are 90° apart. Such a circuit can, therefore, be metered with a two-stator meter, which is composed of two two-wire stators.

The circuit diagram showing the metering of a two-phase, four-wire circuit with a two-stator meter is shown in Fig. 25(a). The vector diagram is also shown in

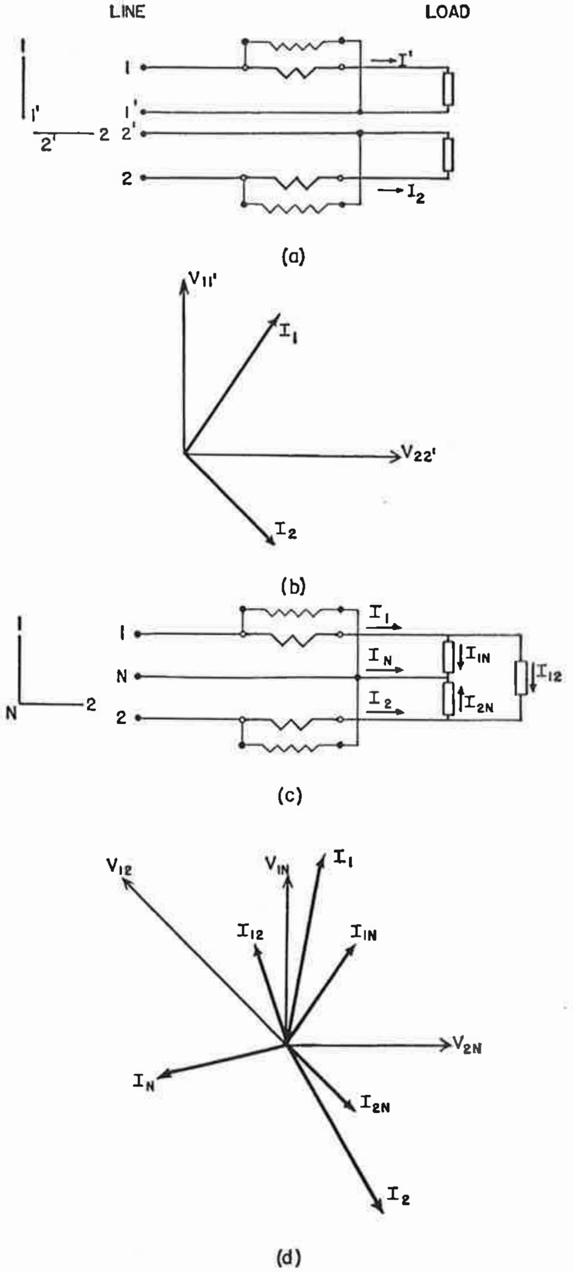


Fig. 25—(a) Diagram of connections for metering a two-phase, four-wire circuit, (b) Vector diagram of (a), (c) Diagram of connections for metering a two-phase, three-wire circuit (b) Vector diagram of (c).

Fig. 25(b). Metering of two-phase, four-wire service is essentially the totalizing of two two-wire services which are fed from separate sources in which the applied voltages are 90 degrees out of phase. The restriction on the circuit shown in Fig. 25(a) for accurate metering is that no load may be connected between the conductors which contain current coils. This restriction can be removed by connecting at both ends the conductors which do not contain current coils. Then it becomes a two-phase, three-wire circuit as shown in Fig. 25(c). The vector diagram for the two-phase three-wire circuit is shown in Fig. 25(d). It is similar to the two-phase three-wire network circuit except that the voltages are 90 degrees, rather than 120 degrees, out of phase.

Analysis of the accuracy of metering a three-phase, three-wire circuit as shown in Fig. 25d is as follows:

(True Power) $P_T = V_{1N}I_{1N} + V_{2N}I_{2N} + V_{12}I_{12}$ (a) (32)

$P_T = V_{1N}(I_{1N} + I_{12}) + V_{2N}(I_{2N} - I_{12})$ (b)

$P_T = V_{1N}I_1 + V_{2N}I_2$ (c)

$P_M = V_{1N}I_1 + V_{2N}I_2$;

∴ the meter registers correctly (d)

Where P_T = True Power

P_M = Measured Power

Two-Phase, Five-Wire—A two-phase, five-wire system is essentially two single-phase, three-wire systems in which the line-to-line applied voltages are 90 degrees out of phase and which have a common neutral. Loads on this type of system can be metered with two single-phase, three-wire meters or four single-phase, two-wire meters, or the multi-stator meter equivalents. The diagram of connections for metering two-phase, five-wire loads by means of two single-phase, three-wire meters is shown in Fig. 26.

The dependency of accuracy upon balanced voltages of a three-wire stator in metering a three-wire, single-phase service is also applicable to metering a two-phase, five-wire circuit. Four two-wire stators will give correct registration, independent of the balance of the line-to-neutral voltages. However, usually the voltages are sufficiently balanced that the circuit can be metered with sufficient accuracy by a meter having two three-wire stators.

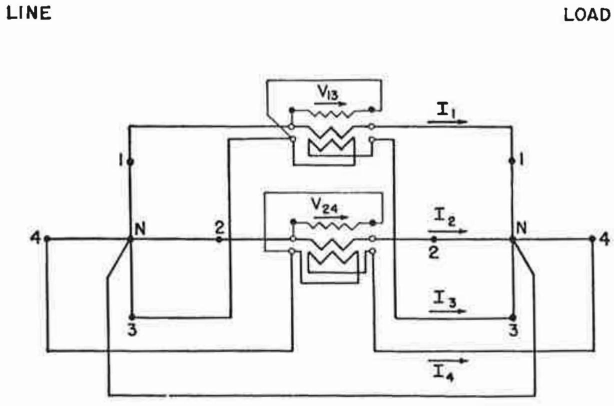


Fig. 26—Diagram of connections for metering a two-phase, five-wire circuit using two three-wire stators.

Also, all of the various methods of applying transformer rated meters to three-wire single-phase services apply equally well to each stator of a two-stator five-wire meter.

Six-Phase, Six-Wire—A six-phase, six-wire system is essentially three three-wire single-phase systems having a common neutral point which is not brought out, and in which the applied voltages to the respective phases are 120 degrees apart. Each single-phase, three-wire load can be metered by a three-wire stator, with the accuracy dependent upon balanced voltages to the same degree as in the single-phase, three-wire circuit. The diagram of connections used for metering such a system is shown in Fig. 27.

Analysis of the accuracy of the circuit shown in Fig. 27 is as follows: (33)

$P_T = V_{1N}I_1 + V_{2N}I_2 + V_{3N}I_3 + V_{4N}I_4 + V_{5N}I_5 + V_{6N}I_6$

If the voltages applied to the respective stators are balanced with respect to neutral,

$$V_{1N} = V_{N4} = \frac{V_{14}}{2};\ V_{2N} = V_{N5} = \frac{V_{25}}{2};\ V_{3N} = V_{N6} = \frac{V_{36}}{2}$$

$$P_T = \frac{V_{14}}{2}(I_1 - I_4) + \frac{V_{25}}{2}(I_2 - I_5) + \frac{V_{36}}{2}(I_3 - I_6) \qquad (34)$$

Where P_T = True Power

The three stator, six-wire meter registers this value. The meter connected as shown in Fig. 27, therefore, accurately meters the load, provided the voltages are balanced according to the restriction stated above. Each stator is subject to the same errors due to unbalanced line-to-neutral voltages to which a single-phase, three-wire meter would be subjected under the same unbalance.

The metering is essentially the totalizing of three single-phase, three-wire services in which the applied line-to-line voltages are 120 degrees apart.

Totalizing Metering for Single-Phase and Three-Phase Circuits—The combined energy consumption of a single-phase circuit and of a three-phase circuit can be measured on a totalizing meter. The meter consists of the stators which are normally required for metering the single-phase and three-phase circuits independently; however, the stators drive a common shaft. The meter usually applied to totalize a two-wire, single-phase circuit and a three-phase, three-wire circuit has three two-wire stators. The meter for totalizing energy measurement on a single-phase, three-wire circuit and on a three-phase, three-wire circuit consists of a three-wire

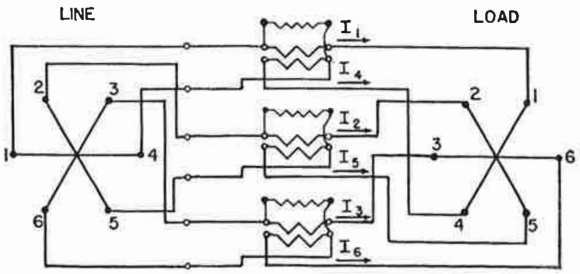


Fig. 27—Diagram of connections for metering a six-phase, six-wire circuit using three three-wire stators.

Table 2—Watthour Meter Socket Selector Guide

Socket	Wiring Data					Watthour Meter Application★									
						1 phase, 2 or 3 wire		1, 2, 3 phase, 3 wire		3 phase, 4 wire Y		3 phase, 4 wire∆		2 phase, 5 wire	totalizing 1-3 phase
Series	Type □	No. of Jaws	Type of Terminals	Wire size, maxi-mum	amp ♦ maxi-mum	Self Con-tained	trans-former Type■	Self Con-tained	Trans-former type■	Self Con-tained	Trans-former Type■	Self Con-tained	Trans-former Type■	Self Contained and Transformer Type■	
Round Sockets	SE	4	set-screw	#1	100	S	....	....	....	....	....	....	....	....	....
	SE-5	5	set-screw	#1	100	S	....	S-5	....	....	....	....	....	....	....
	SE-6	6	set-screw	#1	100	S	....	....	....	....	....	....	....	....	....
	S	4	bus	#0	100	S	....	....	....	....	....	....	....	....	....
	S-5	5	bus(4) screw(1)	#0	100	....	S	S-5	....	....	....	....	....	....	....
	S-6	6	bus(4) screw(2)	#0	100	....	S	....	....	....	....	....	....	....	....
Ring Sockets	S	4	bus (line side only)	#0	100	S	....	....	....	....	....	....	....	....	....
	S-2	8	set-screw	#2	100	....	....	S-2	S-2	....	S-2‡	....	S-2⊙	S-2✚	....
	S-3	13	set-screw	#2	100	....	....	....	....	....	S-3, S-8	....	S-7	....	....
	S-5	5	bus (line side only)	#0	100	....	S	S-5	....	....	....	....	....	....	....
	S-6	6	bus (line side only)	#2	100	....	S	S-5	....	....	....	....	....	....	....
	S-8	7	set-screw	#2	100	....	....	....	....	S-3, S-8	....	S-7, S-9	....	....	....
	S-9	14	set-screw	#2	100	....	....	....	....	....	....	....	S-9	....	S-4
	S-10	15	set-screw	#2	100	....	....	....	....	....	....	....	....	S-10	S-6
Trough Sockets	ST-2	8	set-screw semi-floating	#2 #4/0	100 140	....	....	S-2	S-2	....	S-2‡	....	S-2⊙	S-2✚	....
	ST-3	13	set-screw	#2	100	....	....	....	....	....	S-3, S-8	....	S-7	....	....
	ST-5	5	semi-floating	#4/0	140	....	....	S-5	....	....	....	....	....	....	....
	ST-8	7	set-screw semi-floating	#2 #4/0	100 140	....	....	....	....	S-3, S-8	....	S-7, S-9	....	....	....
	ST-9	14	set-screw semi-floating	#2 #4/0	100 140	....	....	....	....	....	....	....	S-9	....	S-4
	ST-10	15	set-screw semi-floating	#2 #4/0	100 140	....	....	....	....	....	....	....	....	S-10	S-6
High-Capacity Sockets	STL-4	4	heavy-duty	#4/0	160	S	....	S-5	....	....	....	....	....	....	....
	STL-5	5	heavy-duty	#4/0	160	S	....	S-5	....	....	....	....	....	....	....
	STG-4	4	heavy-duty	#4/0	200	S	....	S-5	....	....	....	....	....	....	....
	STG-5	5	heavy-duty	#4/0	200	S	....	S-5	....	....	....	....	....	....	....
	STU	4	heavy-duty	#4/0	200	S	....	....	....	....	....	....	....	....	....
	STU-5	5	heavy-duty	#4/0	175	....	....	S-5	....	....	....	....	....	....	....
	STU-8	7	heavy-duty	#4/0	175	....	....	....	....	S-3, S-8	....	S-7, S-9	....	....	....
Transocket Sockets			transformers no. rating												
	STS	6	2 200 amp	500 mcm	400	....	S	....	....	....	....	....	....	....	....
		5	2 400 amp+	500 mcm	400	....	S	....	....	....	....	....	....	....	....
	STS-2	8	2 200 amp	500 mcm	400	....	....	....	S-2	....	....	....	....	....	....
	STS-3	13	3 200 amp	500 mcm	400	....	....	....	....	....	S-3	....	S-7	....	....
	STS-7	8	2 400 amp+ 1 200 amp	500 mcm	400	....	....	....	....	....	....	....	S-2	....	....
	STS-8	13	3 200 amp	500 mcm	400	....	....	....	....	....	S-8	....	....	....	....
		8	3 200 amp✠	500 mcm	400	....	....	....	....	....	S-2	....	....	....	....
	STS-9	14	3 200 amp	500 mcm	400	....	....	....	....	....	....	....	S-9	....	....
Trans-A-Mount Mountings	STA	..	2 200 amp	500 mcm	400	....	A	....	....	....	....	....	....	....	....
	STA-2	..	2 200 amp	500 mcm	400	....	....	....	A-2	....	....	....	....	....	....
	STA-3	..	3 200 amp	500 mcm	400	....	....	....	....	....	A-3	....	A-9	....	....
	STA-7	..	2 400 amp+ 1 200 amp	500 mcm	400	....	....	....	....	....	....	....	A-2	....	....
	STA-8	..	3 200 amp	500 mcm	400	....	....	....	....	....	A-8	....	....	....	....
	STA-9	..	3 200 amp	500 mcm	400	....	....	....	....	....	....	....	A-7	....	....

Demand Meter Application

Westinghouse socket-type demand meters (series DSW, DSH, QDS, etc.) employ the same sockets as their corresponding watthour meter types.

Westinghouse bottom-connected thermal demand meters (series CAH, KCA, QCA, etc.) require special styles of Trans-A-mount mountings: Indicating demand meters (series CA-W) employ the same Trans-A-mount as their equivalent series DA meters.

Notes

□Westinghouse designation.

★For further application information including wiring diagrams, see Fig. 28, 29, 30, and 31.

♦Maximum current rating based on 55°C temperature rise above a maximum ambient of 35°C in current coil of meter listed when socket is wired with maximum-size conductors.

■All sockets used with instrument transformers must have circuit-closing devices.

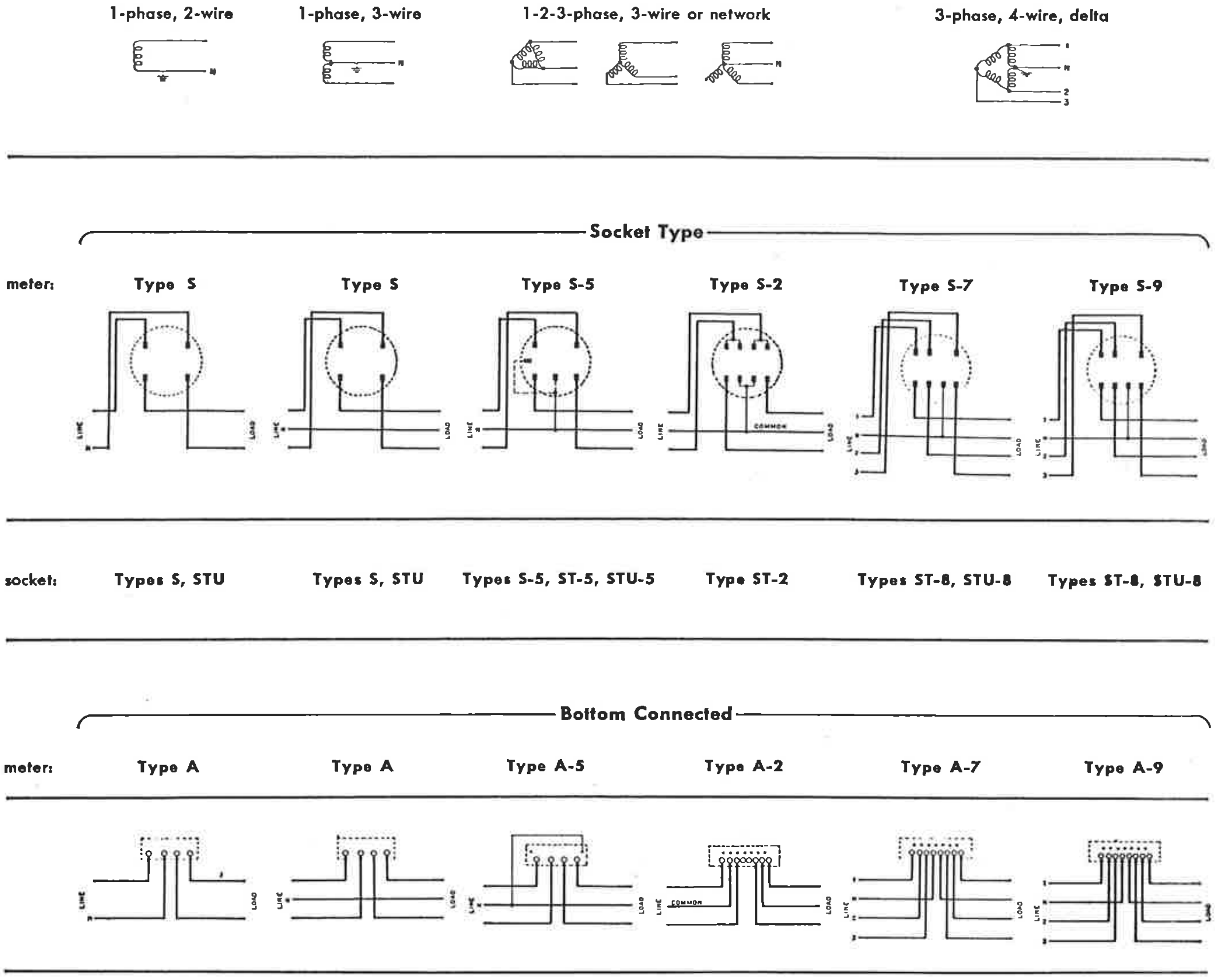
+STS (5 terminal, STS-7 and STA-7: 400-amp current transformers have secondaries connected in parallel to serve as one 200 5 3-wire current transformer.

✠STS-8 (for S-2): current transformer secondaries are connected in delta.

‡S-2 transformer-type for 3-phase, 4-wire Y; current transformer secondaries must be connected in delta.

⊙S-2 transformer-type for 3-phase, 4-wire∆: use with one 2-wire and one 3-wire current transformers.

✚S-2 for 2-phase, 5-wire service: use transformer type only with two 3-wire current transformers.



Type S combination 2-3-wire meter can also be used.

Type S combination 2-3-wire meter can also be used.

Most commonly used and most economical for this service. Type S-5 features optional fifth terminal arrangement.

S-2 meter can also be used for 2-phase, 4-wire. Special A-2 meter with 8 terminals required for 2-phase, 4-wire.

Contains one 2-wire and one 3-wire current coil. Suitable for all 3-phase, 4-wire △ loads except where extreme voltage unbalance may require a 3-stator meter, S-9.

Three-stator meter for use where line-to-neutral voltages are unbalanced. Needs special test setup because one stator has 240-volt potential coil; other two are 120-volt.

Fig. 28—Circuit Connections for self-contained socket (detachable) type and bottom connected meters.

Continued on next page

stator applied to the single-phase circuit and two two-wire stators applied to the three-phase circuit. The accuracy is the same as would be obtained by using separate meters in the single-phase and three-phase circuits.

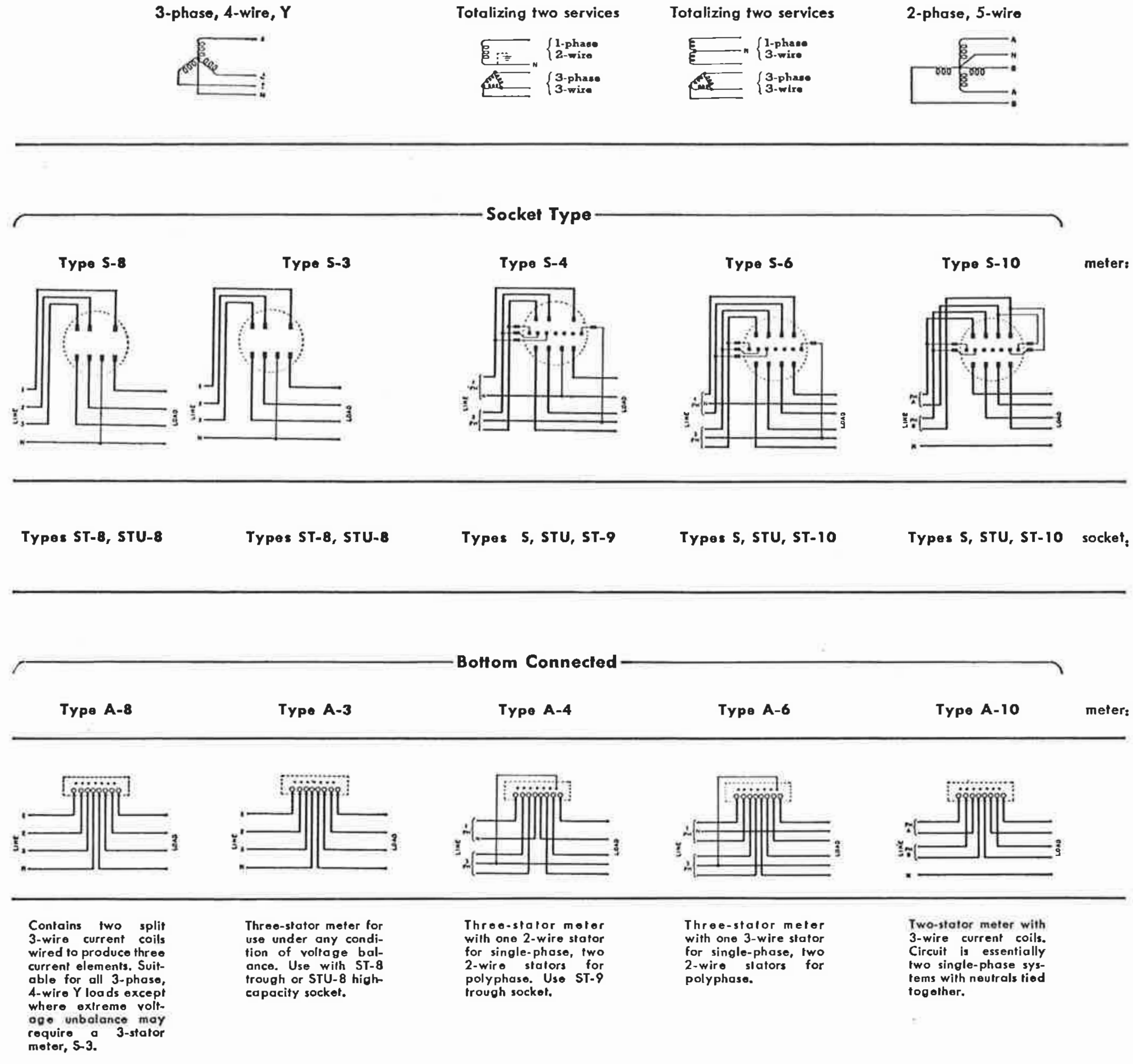
The energy to the three-phase circuits is metered correctly. However, the accuracy of the metering in the single-phase three-wire circuit is dependent upon the balance of the line-to-neutral voltages in that circuit. The voltage rating of each stator corresponds with voltage at the circuit which it is applied.

Summarizing Watthour Meter Applications—The application of watthour meters to the various types of circuits is summarized in Figs. 28 and 29. The circuit connections for self-contained meters in socket type and bottom connected are shown in Fig. 28. Corresponding circuit connections for transformer rated meters are shown in Fig. 29.

The internal wiring diagrams for socket-type and bottom-connected self-contained and transformer-rated meters are shown in Fig. 30.

12. Installation of Watthour Meters

The specifications for the location and other watthour meter installation requirements are established by the utility or other owner of the meter. However, the safety code provides that certain safety measures be taken in



Contains two split 3-wire current coils wired to produce three current elements. Suitable for all 3-phase, 4-wire Y loads except where extreme voltage unbalance may require a 3-stator meter, S-3.

Three-stator meter for use under any condition of voltage balance. Use with ST-8 trough or STU-8 high-capacity socket.

Three-stator meter with one 2-wire stator for single-phase, two 2-wire stators for polyphase. Use ST-9 trough socket.

Three-stator meter with one 3-wire stator for single-phase, two 2-wire stators for polyphase.

Two-stator meter with 3-wire current coils. Circuit is essentially two single-phase systems with neutrals tied together.

Fig. 28—continued

the installation of circuits to the meter.

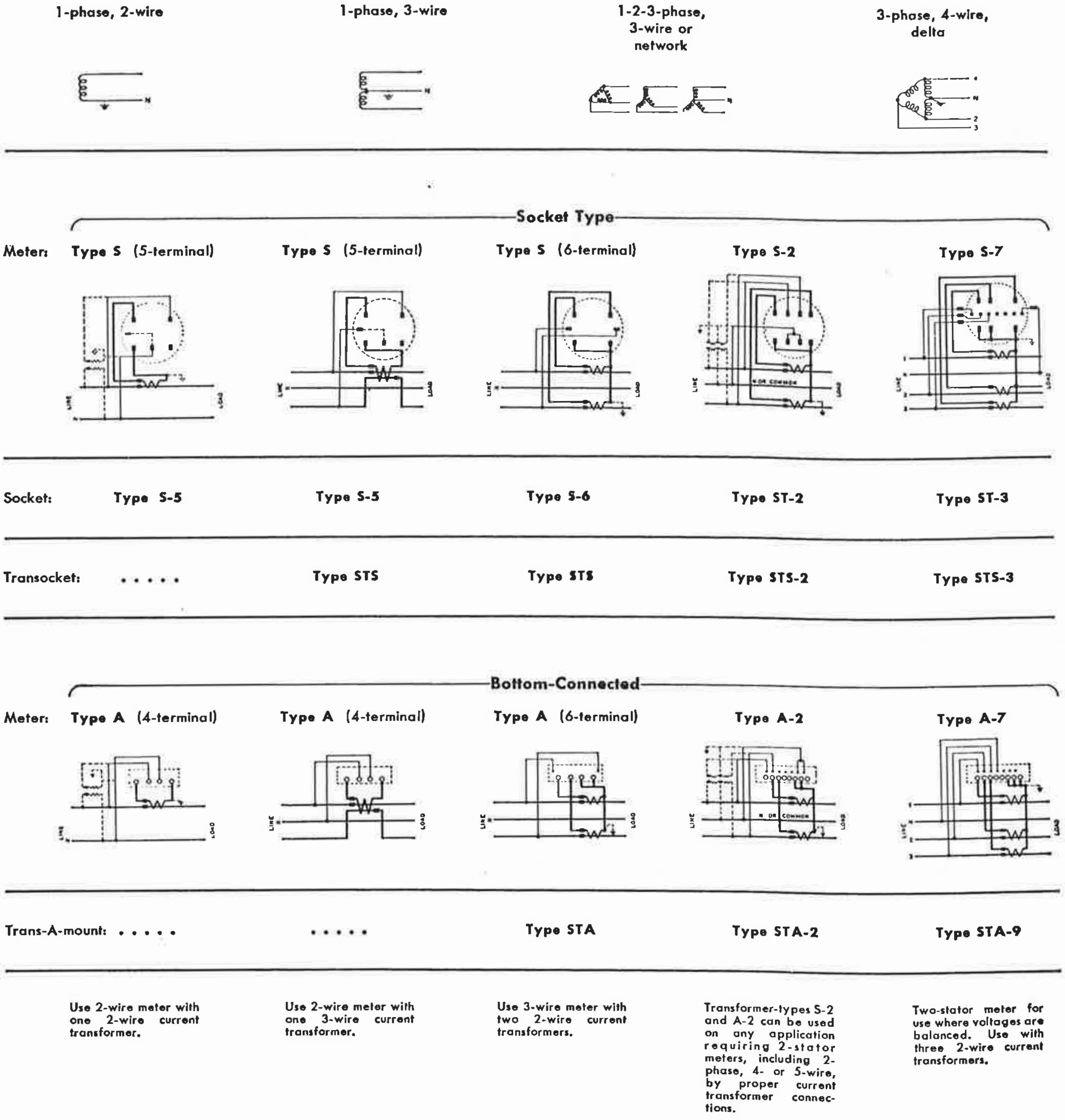
Socket and mountings with built-in current transformers for detachable and bottom-connected meters are also available. Westinghouse sockets with current transformers are designated as Transockets. Corresponding mountings for bottom-connected meters are designated as Trans-A-Mounts.

Various available sockets, Transockets or Trans-A-Mounts for application with the various detachable and transformer-rated, bottom-connected meters are given in Table 2.

The terminals arrangement in detachable (socket-type) and bottom-connected watthour meters have been standardized. The standard terminal arrangements for these types of meters are shown in Fig. 31. For the terminal arrangement in switchboard meters, reference is made to the manufacturer's literature as may be required.

13. Metering Reactive Voltampere-Hours [13, 19,20,21]

Metering of reactive voltampere-hours is of particular importance to the utility where the rate schedule contains a power factor clause which provides the manner in which load power factor influences the charges for electric service. The manner in which load power factor is included in the rate schedule varies with utilities, but



Use 2-wire meter with one 2-wire current transformer.

Use 2-wire meter with one 3-wire current transformer.

Use 3-wire meter with two 2-wire current transformers.

Transformer-types S-2 and A-2 can be used on any application requiring 2-stator meters, including 2-phase, 4- or 5-wire, by proper current transformer connections.

Two-stator meter for use where voltages are balanced. Use with three 2-wire current transformers.

Fig. 29—Circuit connections for transformer-rated meters.

Continued on next page

it generally affects a measurement of quantities necessary for determining the charge. In some rate schedules, the power factor clause is based upon the average monthly power factor. Another manner provides for a reactive voltampere demand charge. Usually, the power factor clause applies to the larger industrial or power customers. The metering of services to such customers includes both energy (watthour) meters and reactive power (varhour) meters.

The reactive power metering is usually done by a

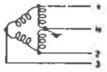
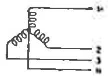
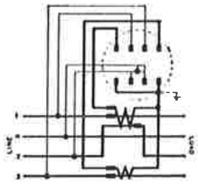
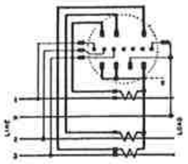
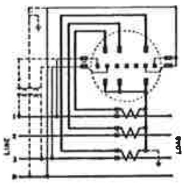
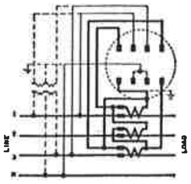
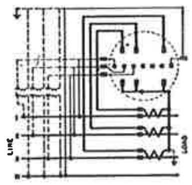
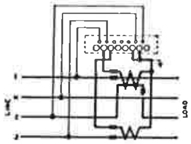
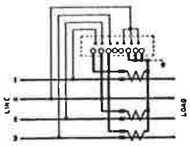
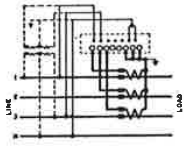
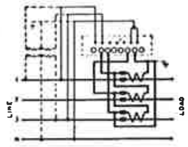
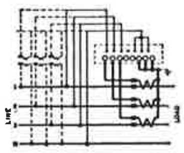
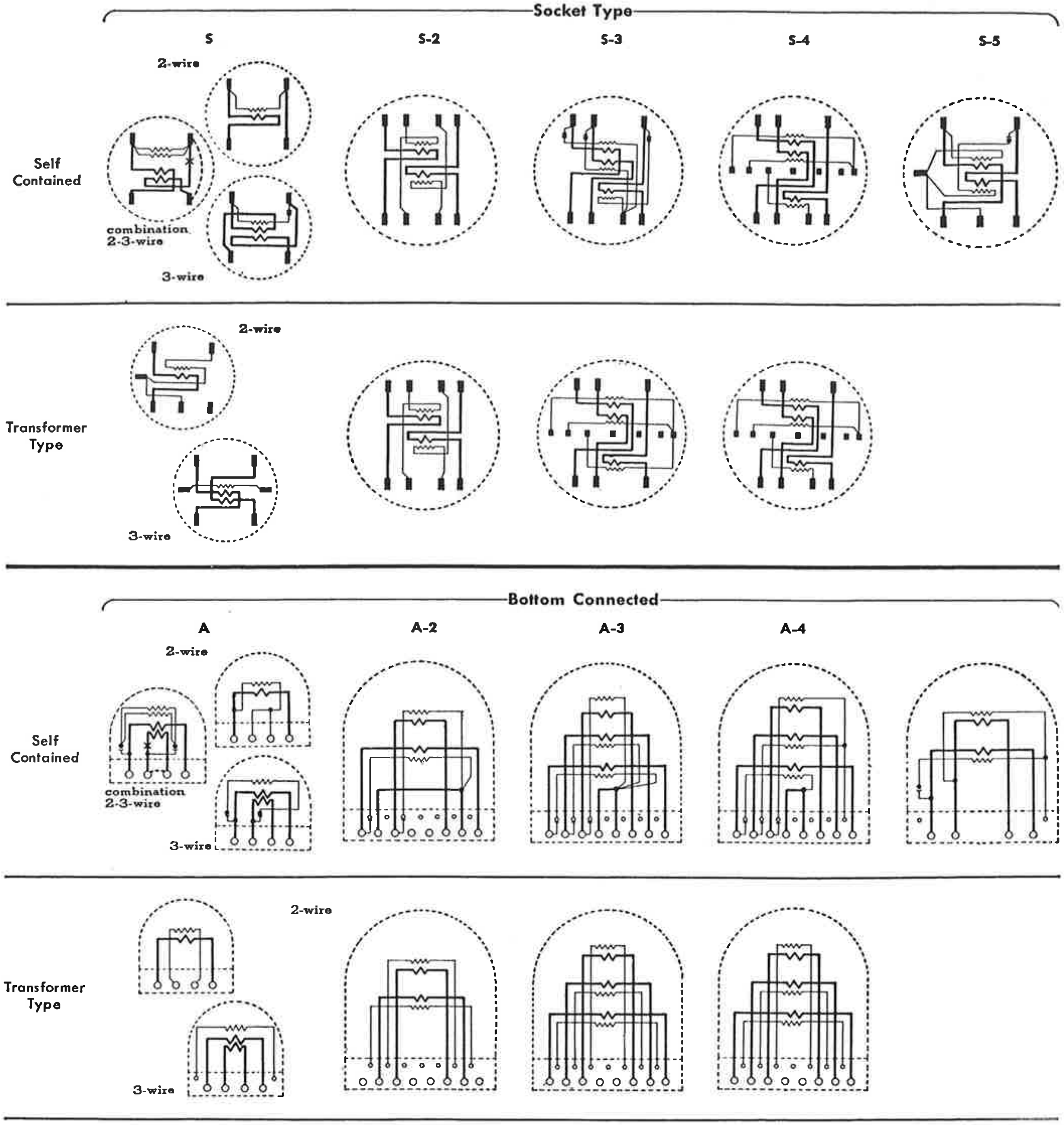
3-phase, 4-wire, delta		3-phase, 4-wire, Y			
					
		Socket Type			
Type S-2	Type S-9	Type S-8	Type S-2	Type S-3	Meters
					
Type ST-2	Type ST-9	Type ST-3	Type ST-2	Type ST-3	Sockets
Type STS-7	Type STS-9	Type STS-8	Type STS-8	Type STS-3	Transockets
		Bottom-Connected			
Type A-2	Type A-9	Type A-8	Type A-2	Type A-3	Meters
					
Type STA-7	Type STA-3	Type STA-8	. . . . .	. . . . .	
Two-stator meter for use where voltages are balanced. Requires one 2-wire and one 3-wire current transformer.	Three-stator meter for use under any condition of voltage balance. Needs special test set-up because one stator has 240 volt potential coil; other two are 120 volt. Used with three current transformers of equal ratio. Not suitable for potential transformers.	Two-and-one half stator meter for use where voltages are balanced. Use with three 2-wire current transformers.	Two-stator meter for use where voltages are balanced. Use with three 2-wire current transformers, secondaries connected in delta.	Three-stator meter for use where voltages are unbalanced. Use with three 2-wire current transformers, secondaries connected in wye.	

Fig. 29—continued

watthour meter to which a voltage which is equal to and lagging quadrature with the system voltage is applied to the potential circuits. The speed of the rotating disk of such a meter is proportional to reactive power in the positive direction. The registration of the meter in a specific time interval is proportional to the average reactive power during that interval. A demand register on such a meter indicates the maximum reactive demand during the period such as the billing period. Similarly, the registration of a watthour meter in a specific



Notes

Standard single-phase meter. Combination 2-3-wire self-contained meters come wired for 2-wire, 120 volt, with potential coils in parallel and one current coil disconnected and bridged. Self-contained 6-terminal A (not shown) is like transformer type.

Standard 2-stator meter. S-2 self-contained and transformer-type and A-2 transformer-type can be used as wired on 1, 2, or 3-phase service. A-2 self-contained must be ordered with 8 terminals for 2-phase, 4-wire.

Standard 3-stator meter. S-3 self-contained and transformer-type and A-3 self-contained have one side of each potential coil tied together. A-3 transformer-type has all potential leads brought out separately.

Three-stator meter for totalizing 3-phase, 3-wire and 1-phase, 2-wire from separate sources. Two stators for polyphase load have one side of each potential coil tied together except on A-4 transformer type. Third stator for single-phase is separate.

Standard 2-stator 3-wire network meter. Internally similar to S-2 and A-2 meters. Terminal-arrangements similar to single-phase S and A.

Fig. 30—Internal wiring diagrams for socket-type and bottom connected and transformer-rated meters.

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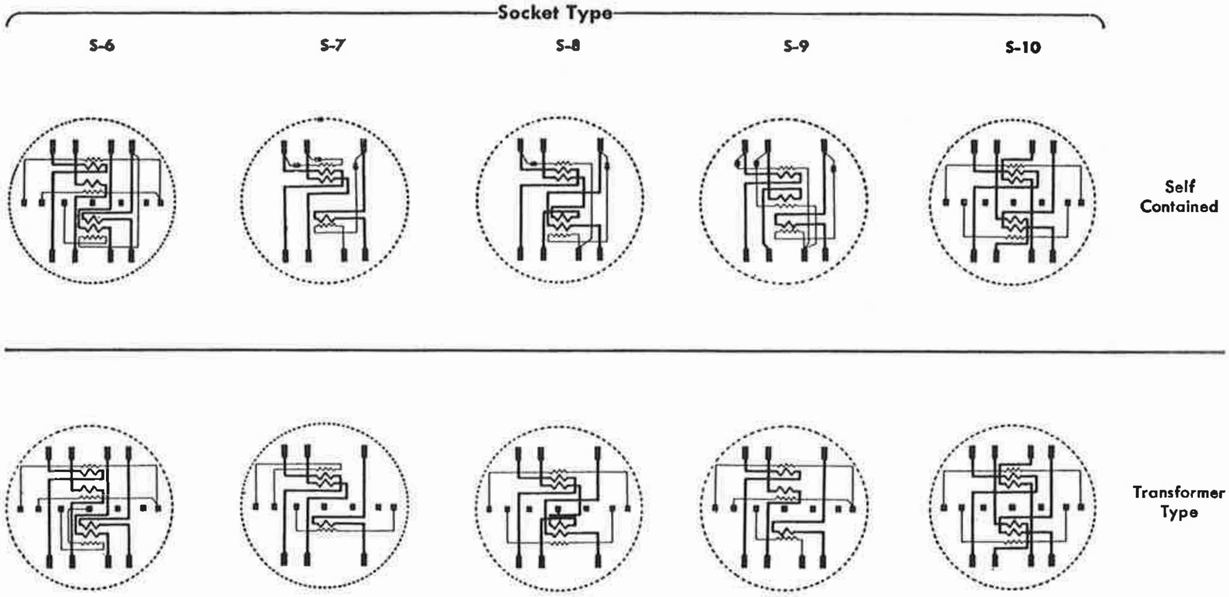
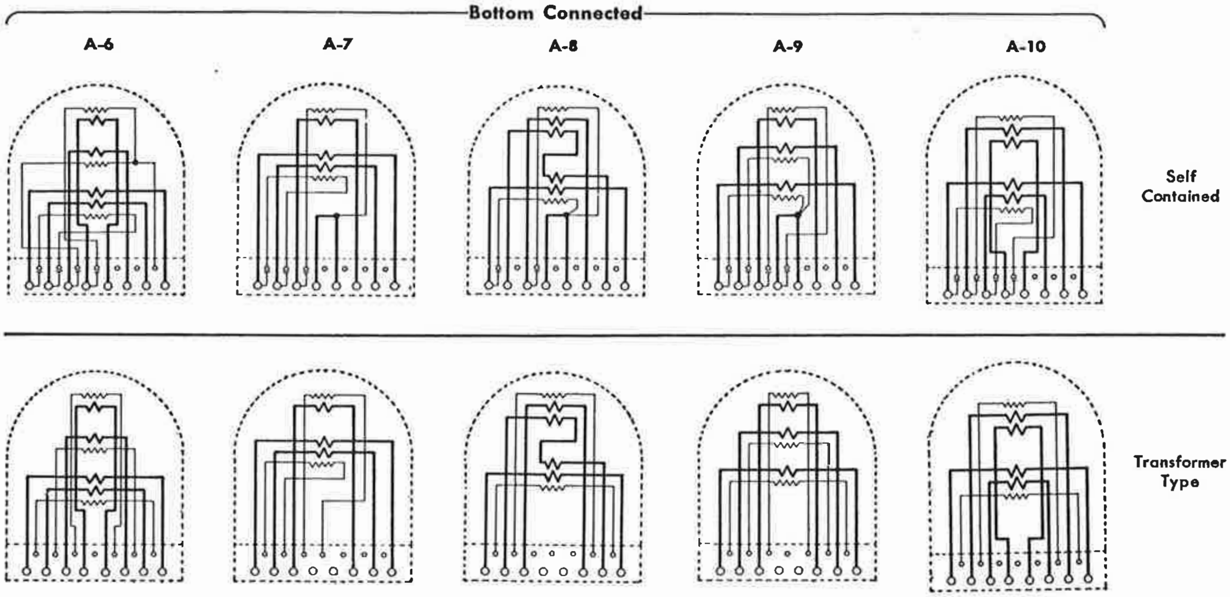




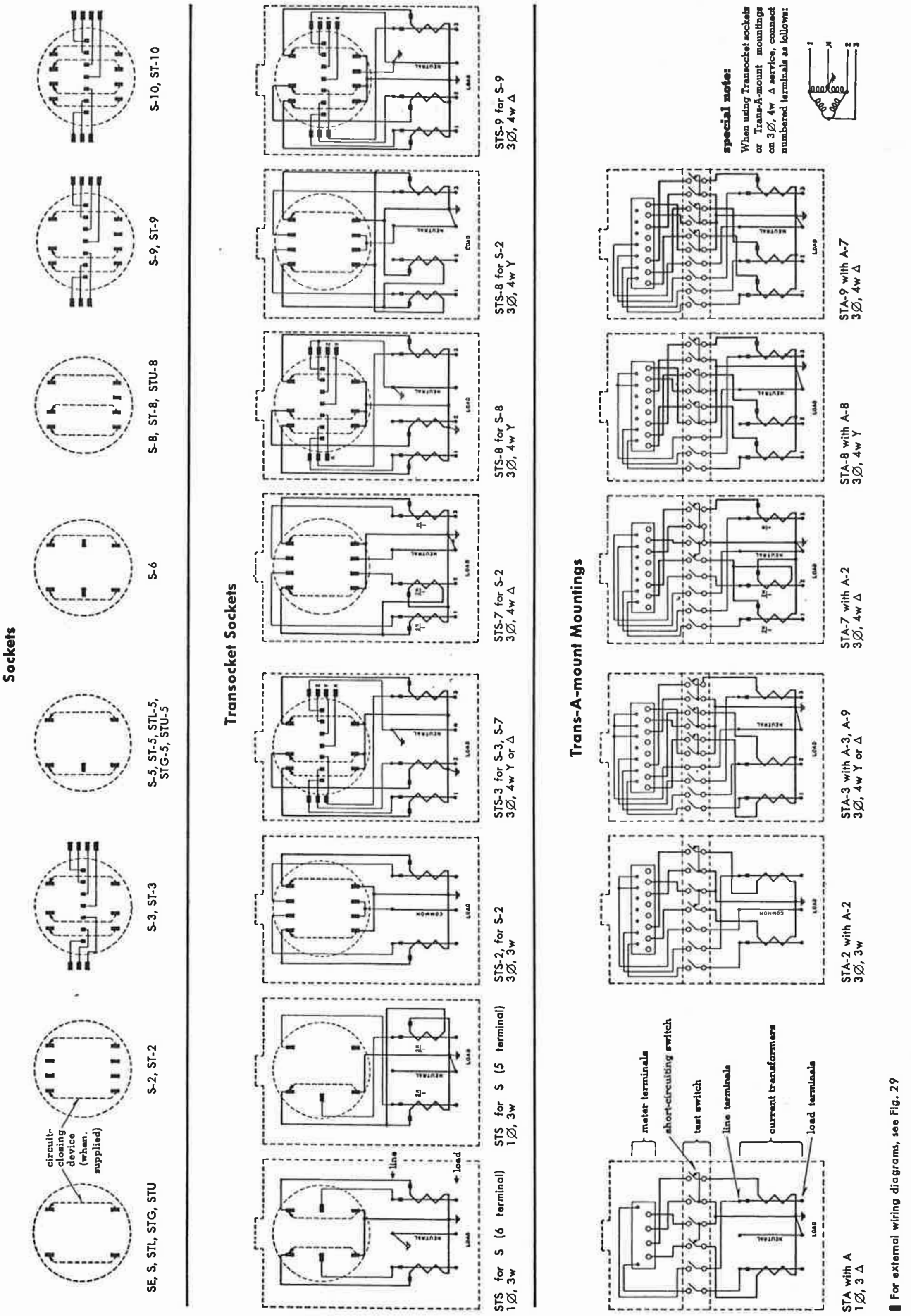
Three-stator meter for totalizing 3-phase, 3-wire and 1-phase, 3-wire from separate sources. Similar to S-4 and A-4 except single-phase element has 3-wire electromagnet. Slightly different terminal arrangements from S-4 or A-4.

Two-stator meter for 3-phase, 4-wire, delta service. One stator has 2-wire, 240-volt electromagnet; other has 3-wire, 240-volt electromagnet.

Two and one-half stator meter for 3-phase, 4-wire Y service. Meter has two stator with 3-wire current coils. One half of each current coil is tied together to form in effect a third current stator.

Three-stator meter for 3-phase, 4-wire delta service. Two stators have 120-volt potential coils; third stator has 240-volt potential coil. Current windings of 120-volt coils have twice current rating of 240-volt coil to make watt ratings of stators equal.

Two-stator meter for 2-phase, 5-wire service. Each electromagnet has 3-wire current winding.



special note:
When using Transocket sockets or Trans-A-mount mountings on 3Ø, 4w Δ service, connect numbered terminals as follows:

■ For external wiring diagrams, see Fig. 29

Fig. 31—Terminal arrangement of sockets and mounts for transformer-rated meters.

interval is proportional to the average active power during that interval. Therefore, the average load power factor for the period can be determined from the reactive kilovoltampere-hour and kilowatthour registrations for the period. The average power factor is given by

$$(F_P)_{avg} = \cos\left(\tan^{-1}\frac{\text{varhours}}{\text{watthours}}\right)$$

For correct registration of the varhours, the voltage applied to the potential circuit must be equal in absolute value to the voltage applied to the watthour meter, and in lagging quadrature with that voltage. The circuit voltage is shifted by 90 degrees in the lagging direction before it is applied to the varhour meter. The corresponding current coils of the watthour and varhour meters are connected in series. The manner in which the voltage is shifted for reactive metering is dependent upon the type of system. This discussion is restricted to methods of obtaining the required phase shift and the equipment available.

Two-Phase Systems—Reactive metering in a two-phase system is simpler than it is in either the single-phase or three-phase systems. Since the phase voltages are displaced by 90 degrees, no phase shifting equipment is required. The watthour and varhour meters in a two-phase service are connected as shown in Fig. 32. This is referred as cross-phasing. The accuracy of the reactive meter is dependent upon the phase voltages being equal and 90 degrees out of phase.

Three-Phase Systems—Shifting of system voltage for reactive metering in a three-phase system is done in phase-shifting transformers. They consist of small autotransformers with taps so arranged that voltages equal to and lagging the line voltage by 90 degrees are obtainable. In order for phase-shifting transformers to be applicable, it is necessary that the meter potential terminals be independent of the current terminals.

The various types of Westinghouse phase-shifting transformers available and the system application and voltage rating of each are shown in Table 3. The accuracy of the transformers may be checked by applying rated voltages from a system of balanced voltages to the transformers and measuring voltage between various tops as shown in Table 4.

The internal wiring diagrams of the various types of transformers and the taps from which quadrature voltages are obtained are shown in Fig. 33. The phase shifts shown result if the applied voltages are from a system of balanced voltages of the sequence 1-2-3. Unbalances in system voltages result in errors in the phase shift.

External and internal wiring diagrams of a Type K-5 transformer for application to various types of systems are shown in Fig. 34. The connections to potential circuits only of the watthour and varhour meters are shown. The corresponding meter current elements are connected in series.

Single-Phase Systems—The 90-degree phase shift necessary for reactive metering on single-phase services is obtained by connecting a resistor capacitor series network in series with the potential circuit of the watthour (varhour) meter with which it is applied. The resistor is variable, since the network must be calibrated individually for the meter with which it is to be used. The Westinghouse Type K-1 compensator is a resistor capacitor network for obtaining the 90-degree phase shift required for single-phase reactive metering.

V. DEMAND METERING

The demand of an installation or system is the load at the receiving terminals averaged over a specified interval of time. Demand is expressed in suitable units of the load commodity. The load may be real power, reactive power, apparent power, or current, and may be expressed in kilowatts, reactive voltamperes, voltamperes, or amperes, respectively. The most common demand intervals used in commercial metering are 15 minutes and 30 minutes, although other intervals such as 5 minutes or 60 minutes have been used in some cases.

Similarly, the maximum demand of an installation is the greatest of all demands which have occurred during a given period of time. The period of time during which the maximum demand is usually desired is the month or the billing period. Of course, the maximum demands for longer periods, such as a year, can be determined from the maximum demands of each of a group of periods, such as a month, which make up the longer period. The maximum demand is determined by measurement, according to specifications, over a definitely prescribed time interval.

14. Types and Classes of Demand Meters

Classes—Demand meters may be classified according to the manner in which demand is measured and according to the presentation of the measurements such as: [8,22]

Class I —curve-drawing or recording demand meters
Class II —integrated- or block interval-demand meters
Class III—lagged-demand meters

Recording Demand Meter—The designation of Class I indicates only the manner of presentation of the measurement and does not indicate the manner of the measurement, i.e., integrated or lagged demand. In the recording meter, a permanent record is made of the demands measured during the period of the record. The demands may be recorded on a paper strip chart, on printed or punched paper tape, or on magnetic tape. Usually, a recording demand meter is considered as a demand meter which uses a strip chart and in which the stylus is advanced across the paper chart at a rate proportional to the watthour. The chart is driven continuously by a clock mechanism. A meter in which the measurement is printed on a tape is usually referred to as a printometer. Magnetic or punched tape recorders are relatively recent developments in which the measured demand is recorded on magnetic or punched tape, from which the data are extracted by auxiliary devices for correlation on data processing machines.

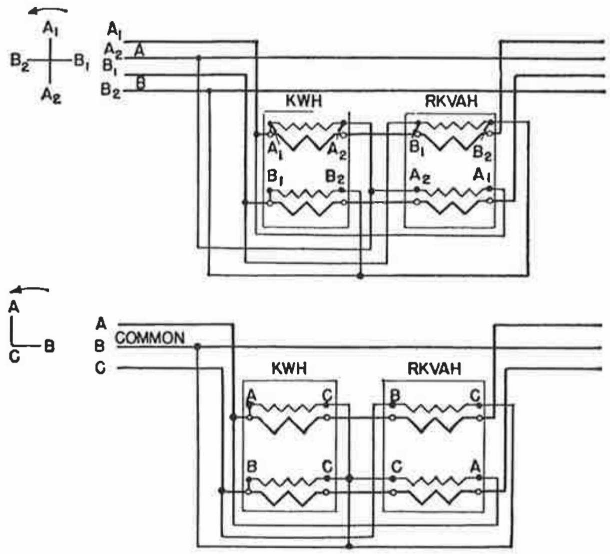


Fig. 32—Diagram of connections for reactive metering on two-phase systems.

Indicating Demand Meter—An indicating demand meter or register is a demand meter which is equipped with a scale over which a friction pointer is advanced to indicate maximum-demand. The indicating demand meters may be of the integrated demand (Class II) or of the lagged demand (Class III).

Cumulative Demand Meter—A cumulative demand meter or register is an indicating demand meter in which the accumulated total of maximum demands during the preceding periods is indicated during the period after the meter has been reset and before it is reset again. The maximum demand for any one period is equal to or proportional to the difference between the accumulated readings before and after reset. The accumulated maximum demands are presented on a group of dials and pointers similar to those on the watthour meter. The cumulative demand meter or register is of the integrated-demand (Class II) type.

Table 3—Application Chart for Westinghouse Phase-Shift Compensators

Phase Shifting Transformers for Varhour Metering

Service	Meter—No. of Elements	Phase Shifting Transformer
3-phase, 3-wire	2	K-3
	2	K-5
3-wire network	2	K-5
3-phase, 4-wire, delta	2	K-7
	2	K-5
	3	K-9
	3	K-5
3-phase, 4-wire, wye	2½	K-4
		K-5
	3	K-4
		K-5

Table 4—Tests for Ascertaining the Accuracy of Phase-Shift Compensators of Table 3

120 Volt* Phase-Shifting Transformers

	Apply 100 Volts to Terminal	57.7 Volts should be voltage across	115.5 Volts should be voltage across
Type K-3	1–2 3–2	4–2 7–2	6–2 5–2
Type K-4	1–0 2–0 3–0	6–0 4–0 5–0	. . . .
Type K-5	1–2 . . . 3–2 . . .	4–2 8–2 7–2 9–2	6–2 . . . 5–2 . . .
Type K-7	1–4 3–6	. . . . . .	1–2 5–6
Type K-9	1–6 3–0	. . . 4–0	1–2 5–0

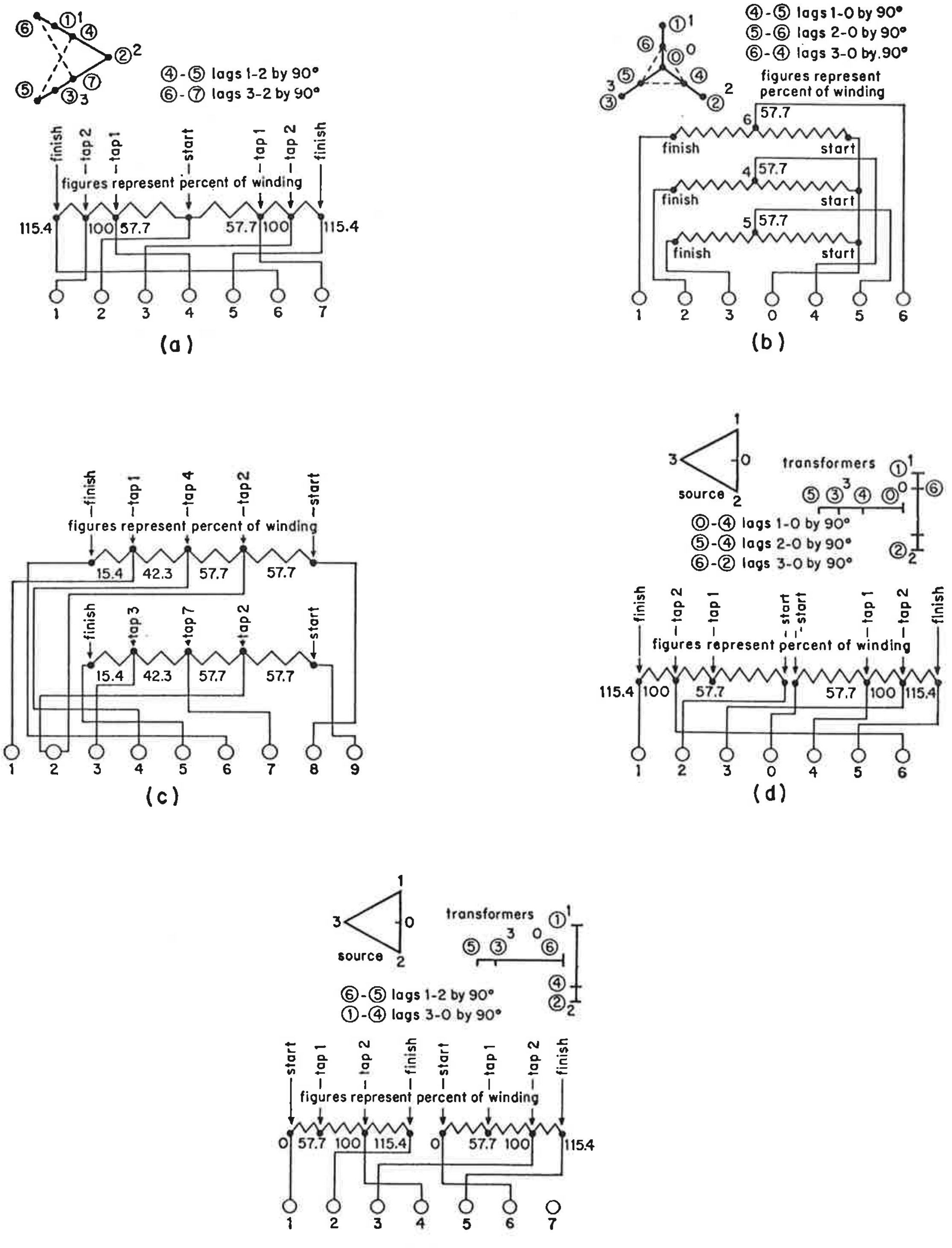
*For 240-Volt transformers double the given voltage values.

Integrated-Demand Meter (Block Interval Demand Meter)—An integrated demand meter is one which indicates or records the demand obtained through integration. The integration is performed over specific demand interval periods. That is, the period during which demands at specific intervals are measured is blocked into discrete periods, the duration of each of which is the prescribed demand interval.

Lagged-Demand Meter (Exponential or Logarithmic Demand Meter)—A lagged-demand meter is one in which the response of the meter element is subject to a characteristic time lag by either mechanical or thermal means. The presentation on such a meter is sometimes referred to as an exponential or logarithmic demand, since the response of the meter as a function of time is an exponential function of the quantity being measured. Usually the lagged-demand meter has a pointer pusher and a maximum-demand pointer which indicates the maximum deflection of the pointer pusher. The pointer pusher indicates the demand over the previous demand interval. Lagged-demand meters are equivalent in their action to an ordinary indicating wattmeter, in which the damping is highly accentuated, resulting in a time lag.

15. Theory and Application of Demand Meters

Integrated-Demand Meters—The integrated-demand principle is applied on both the indicating and cumulative-demand meters. The principle difference in the meters is in the presentation of the data. In fact, both meters are usually watthour meters with special registers for measuring both maximum demand and energy consumption. Integrating demand registers are shown in Fig. 35. The indicating demand register has two hands. One hand, the pointer pusher, moves at a rate proportional to the energy consumption; therefore, its total movement in a given interval is proportional to



(a) (b) (c) (d) (e)

Fig. 33—Internal wiring diagrams of various types of phase-displacement transformers for reactive metering on three-phase systems showing taps from which quadrature voltages are obtained.
(a) Type K-3, (b) Type K-4, (c) Type K-5, (d) Type K-7, (e) Type K-9.

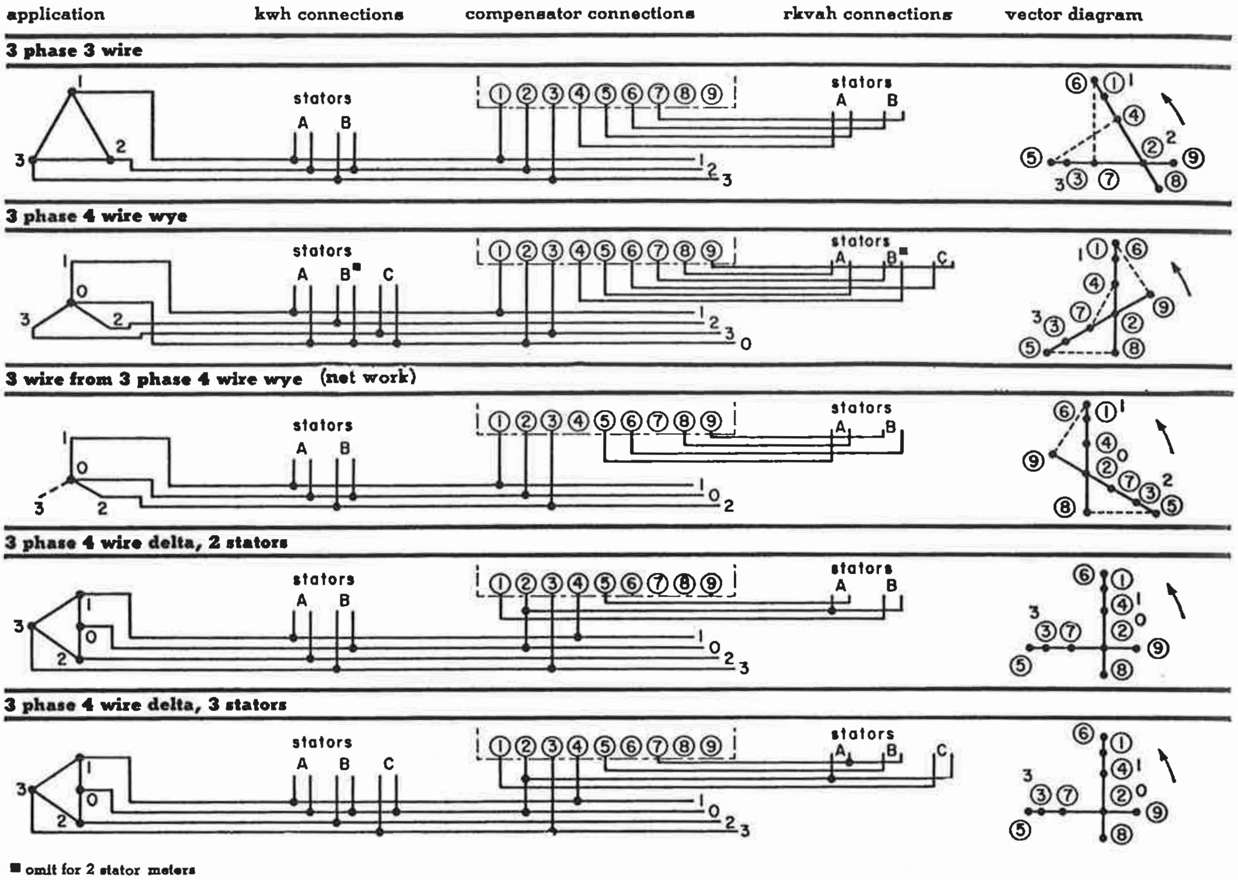


Fig. 34—External and internal wiring diagrams for application of a type K-5 phase displacement transformer for reactive metering on various types of systems.

the demand occurring in that interval. It resets to zero at the end of each interval. The second hand, the maximum demand pointer, is moved by the pointer pusher, and indicates the maximum demand which has occurred since the last resetting of the friction pointer to zero.

In the cumulative-demand register, the registration is on a set of dials similar to those on the watthour meter register. The maximum which has occurred since the last resetting of the register is stored within the register. A test dial indicates the approximate maximum demand since the last reset. When the meter is reset, the demand register dials change setting by the value of the maximum demand stored within the register, and the test dial resets to zero. The maximum demand is the difference in the readings of the demand register before and after resetting. The cumulative-demand register can be read to more significant figures than can be read on the indicating demand register. Being a more expensive register, cumulative-demand register is applied on larger loads where the added accuracy can be justified.

Lagged Demand Meter or Register (Thermal Demand)[23, 24, 25]—In an indicating lagged-demand meter, the demand indicated by the pointer pusher is the demand over the interval just preceding the time at which it is read. The friction pointer then indicates the maximum demand over any interval of a specific duration in the period, rather than over discrete block intervals. Due to this factor, peak splitting is not possible with the lagged demand meter.

Although the demand interval in an integrated demand meter is the period over which the load is integrated to determine the demand or average load during the interval, the demand interval of a thermally lagged meter is not so clearly defined. The demand interval of a thermal demand meter is considered as the time required for a meter to indicate 90 per cent of the full value of a constant load suddenly applied. This definition has been selected, because it provides an indication which is in close agreement with that obtained by an integrated demand meter with an equal demand interval. The interval of most thermal demand meters is 15 or 30 minutes.

The indication vs. time characteristic of a thermally lagged demand meter which has a demand interval of fifteen minutes is shown in Fig. 36. The characteristic

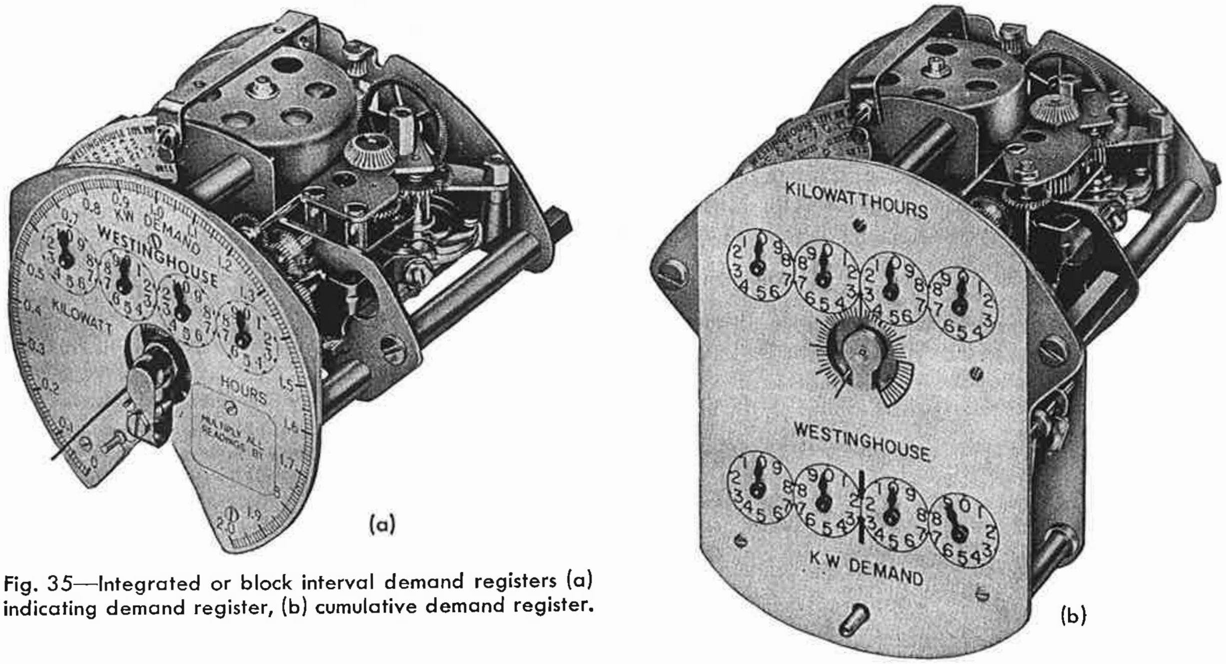


Fig. 35—Integrated or block interval demand registers (a) indicating demand register, (b) cumulative demand register.

shown is the response of the meter when a constant load is suddenly applied. The equation response vs. time characteristic has the form

$$d = D\ (1 - e^{-kt}) \tag{63}$$

where

d = deflection at any time after applying the load from a previous no-load state.

D = maximum deflection of the meter

$1/k$ = the time-constant of the meter; the time required for the meter to reach its final value if it continues to increase at the initial rate; it is also the time for the deflection to reach 63 per cent of its final value.

t = time after suddenly applying load

Either of two principles may be used to damp or lag a meter. These are thermal and mechanical. Only the principle of thermally lagging meters is applied to an appreciable extent in modern lagged-demand meters; therefore, only thermally lagged-demand meters are considered here.

The thermal element is essentially a thermal storage wattmeter which has a thermal (deflection vs. time) characteristic similar to the exponential or heating curve of electrical equipment. However, the characteristic of the meter may not correspond precisely with those of the electrical equipment, due to the variations of the thermal time constants of different types of equipment. The thermal time constants of a thermal-demand meter having a 15-minute interval approximates the thermal time constant of copper conductors, if there is no appreciable dissipation of heat to the environment of the conductor. For example, a fifteen minute thermal demand meter indicates 63 per cent of its final value in 6.5 minutes after a constant load is suddenly applied, while the copper gradient in an oil-filled distribution transformer will reach its final value in from 5 to 8 minutes if there is no heat dissipation to surrounding oil. However, due to heat absorption of heat by the oil, the time is greater, since the top oil temperature will reach its final value in from 3.5 to 5.5 hours if there is no heat dissipation to surrounding air. The rate of heat absorption by the oil diminishes with time. Therefore, the characteristic of a thermal-demand meter approaches the characteristic of a conductor, but it deviates considerably from the characteristic of an oil-filled transformer.

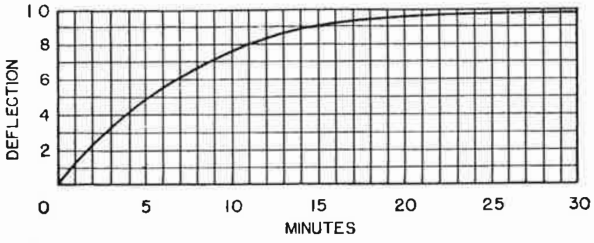


Fig. 36—Response characteristic of thermal demand meter.

Thermal Kilowatt Demand Meter—The diagram of the basic circuit of a single-phase, thermal kilowatt demand meter is shown in Fig. 37. The bimetal springs, which are wound in opposite directions, are connected to the shaft which carries the pusher pointer. The torque developed in each bi-metal spring is proportional to the temperature rise above ambient in the spring. The net torque to the shaft is proportional to the differential temperature rise of the two springs. The bi-metal springs may be either directly heated by an electric current passing through the spring or indirectly heated by resistors with an electric current. The indirectly heated design is considered here.

The heater units are connected in series across a potential transformer; therefore, a current I_E, proportional to line voltage, circulates through the heater units in the positive direction shown. Also, a current proportional to load current passes through each heater unit. The positive direction of load current is opposite directions in the heater units. The net current in heater A is $(I_E+\frac{I}{2})$. The components of currents in each heater are phasor values. Since power applied to the respective heater units ls proportional to the square of the current in each, the power dissipated in the heaters is given by

$$\text{For Heater } A \quad I_E^2 P_a = \left[I_E^2 + I_E I + \left(\frac{I}{2}\right)^2 \right] R \quad \text{(a)}$$

$$\text{(35)}$$

$$\text{For Heater } B \quad I_E^2 P_b = \left[I_E^2 - I_E I + \left(\frac{I}{2}\right)^2 \right] R \quad \text{(b)}$$

The net torque, T_N, to the shaft is proportional to the difference in power applied to the respective heater units and is given by

$$T_N = C_1(P_a - P_b) = C_2(EI) \quad \text{(a)}$$

where C_1 and C_2 are constants and (36)

$$C_2 EI \equiv C_2 \, |E| \, |I| \cos \theta \quad \text{(b)}$$

Therefore, the net torque developed is proportional to the kilowatts delivered to the load being metered.

The polyphase thermal kilowatt demand meters are similar in operation to the single-phase meter, except for the number of elements used. Two heaters and one potential transformer comprise each element. The bi-metal coil springs of the elements are ganged to one shaft to indicate the total kilowatt demands of the polyphase circuit. Separate potential and current transformers are used for the thermal units in polyphase meters.

Thermal Ampere Demand Meters[26]—The thermal ampere demand meter is similar to the kilowatt demand meters, except that it contains only the current bi-metal coil spring. Although the ampere demand meter is operated by current only, it is usually calibrated in kva. The calibration assumes constant voltage at the meter.

A phase-shifting network is applied in polyphase ampere demand meters in order to develop heating in one heater unit which is proportional to the total demand of polyphase circuit. The circuit diagram of a three-phase three-wire ampere-demand meter is shown in Fig. 38(a.) The vector diagram is shown in Fig. 38(b.) The polyphase thermal ampere-demand is dependent upon balanced system voltage for correct indication, but it is not dependent upon balanced currents.

Thermal KVA-Demand Meter[25, 27]—The thermal kva-demand meter which is available only in a polyphase meter is essentially a voltage compensated ampere-demand meter. A second heater unit and bi-metal coil spring is added to correct the indication for a variation in system voltage. The basic arrangement of such a meter is shown in Fig. 39. The potential bi-metal spring is coupled through a linkage to the complete current bi-metal assembly to cause recalibration at the meter for changes in applied voltage. The thermal kva demand meter is also dependent upon balanced voltages for current indication. Due to the added expense of the kva demand meter over the ampere demand meter, it is applied only when abnormal variations in voltage levels justify a more accurate and more expensive meter.

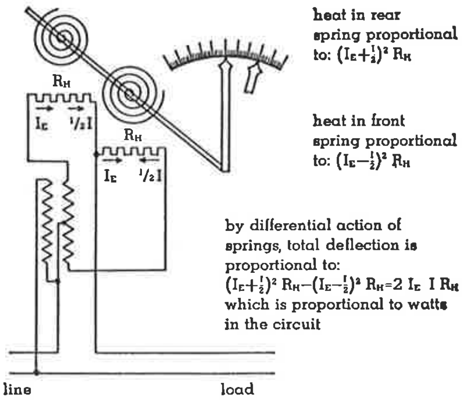


Fig. 37—Diagram of basic circuit of thermal kw demand meter.

Combination Thermal Demand-Watthour Meters—Combination thermal demand and watthour meters are available in which the thermal demand meter and a standard induction watthour meter are assembled as a unit. Internal current transformers are used in all meters. The current transformers may supply the watthour meters electromagnet as well as the thermal elements. For single-phase kilowatt demand meters, the watthour meter electromagnet potential coil also serves as the primary of the potential transformers. Separate current and potential transformers are used for the thermal elements of polyphase thermal demand meters.

A considerable variation in price prevails between the corresponding types of combination thermal-demand-watthour meters. The combination thermal kw demand watthour and thermal ampere-demand-watthour me-

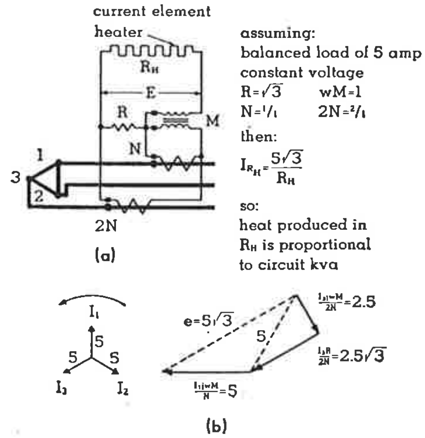


Fig. 38—Thermal ampere-demand meter, (a) Basic circuit, (b) Vector diagram.

ters are comparable in price. However, the cost of the thermal kva-demand-watthour meter is about twice the cost of corresponding thermal kw or ampere-demand-watthour meters.

The combination thermal demand-watthour meters are interchangeable in external connections with corresponding watthour meters.

Advantages of Thermal Demand Meters—The thermal-demand meter has certain advantages over the integrated-demand meter. The principal advantages are simplicity of operation and lower maintenance due to fewer moving parts. The danger of "peak splitting," which is possible with the integrated-demand meter, is eliminated in the thermal meter. This may not be of appreciable importance, since splitting of every peak in a period is unlikely. However, the load peaks are not necessarily repetitive.

Recording Demand Meters—In recording demand meters, the demand of each interval is permanently recorded for future reference. The demand may be recorded on strip charts, printed tape, punched tape, or magnetic tape.

Punched tape and magnetic tape recorders are relatively recent developments for application in load survey recorders. Such recording demand meters are for a special application and are discussed under that topic.

Most recording demand meters make use of strip chart recorders. Usually the recorder is applied with one or more watthour meters as a unit to register kilowatt hours, varhours, or kilovolt-ampere hours, and to record the integrated-demand in units of some quantity which has been integrated. More than one recorder may be applied in a meter where a continuous record of the demand of more than one commodity is desired.

Recording demand meters are available in various combinations of watthour meters, varhour meters, and recorders, from which the arrangement desired can be selected. The various combinations are:

1. Single watthour (or varhours) meters with recorders for recording kilowatt or kilovar reactive demand.
2. Duplex meters comprised of two watthour meters and individual recorders with a common timer and drive mechanism for metering in-out energy and kilowatt demand, metering energy and integral of reactive power (kvah) and recording demand of each.
3. Totalizing metering of two separate circuits, in which the total energy used is registered and the demand of the combined loads is recorded.
4. Duplex, totalizing or two circuits in which the total energy used and energy used in one circuit are registered separately; the demand of the combined circuits is also recorded.
5. Kva recording demand meters composed of a watthour and varhour meter, vector addition mechanism, for obtaining the vector sum of the integrals with respect to time of kilowatts and kilovars.

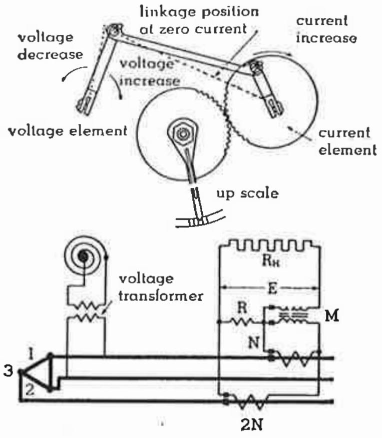


Fig. 39—Basic arrangement of thermal kva-demand meter.

KVA Demand Meter[28]—The vector addition kva demand meters are so unusual that they justify special consideration. By means of the fascinating vector addition ball mechanism, the rotation of watthour and varhour meters are added vectorally to provide a rotation, the speed of which is proportional to kva. The ball mechanism also provides the indicated load power factor. The output rotation of the ball mechanism is proportional to the integrated kva. It is totalized to give kvah registration and integrated kva demand. An analysis of the vector addition ball mechanism and the kva demand meter are given in references 14 and 28. The vector addition kva-demand meter is available in both indicating and recording demand meters, which are Westinghouse Types RK and RI, respectively. The Type RK and RI demand meters are shown in Fig. 40.

The measuring devices of the RK and RI meters are very similar. The principal differences are in the data presentation of integrated-kva demand of the quantities registered. Both meters contain a watthour meter and a varhour meter which supply the inputs to the vector addition ball mechanism. The data presented by the Type RK indicating kva-demand meter are (1) maximum integrated-kva demand, either (indicating or cumulative); (2) kwh registration; (3) kvah registration; and (4) power factor indication. The data obtained from the Type RI recording kva-demand meter are (1) recorded integrated kva demand; (2) recorded integrated-kw demand; (3) kwh registration; (4) kva hour registration; (5) kvar hour registration; and (6) indicated power factor.

Types RK and RI meters are available with both 2-stator and 3-stator watthour and varhour meters for application to various three-phase systems. The Type RI is also available with 4-stator watthour and varhour meters for totalizing two three-phase circuits.

Due to the unusual amount of data obtained from the kva-demand meters and the commensurate additional cost, the kva-demand meters are applied only where the additional data are required.

Relative Expense of Demand Meters—The relative expense for various types of demand meters can be seen from Fig. 41. Each bar represents a particular type or class of meter, although all types are for metering the same type of circuit. Since the recording meters are available only for polyphase meters, the meters represented by the particular bars are all polyphase meters. The indicating and cumulative demand registers are included for completeness.

VI. METER CONSTANTS AND TEST DATA

16. Meter Constants[8, 22]

The principal constants of a watthour meter are: (1) the register constants, (K_r); (2) the watthour constant (K_h); (3) Wattsecond constant or test constant (K_s); (4) the register ratio (R_r); and (5) the gear ratio (R_g). The definitions as given here have been extracted from American Standard Definition of Electrical Terms, Group 30, Instruments, Meters, and Meter Testing, ASA 642.30—1957.

Register Constant (K_r)—The register constant is the factor by which the register reading must be multiplied in order to provide proper consideration of the register, or gear ratio and of the instrument transformer ratios to obtain the registration in the desired units.

Watthour Constant (K_h)—The watthour constant of a watthour meter is the registration expressed in watthours corresponding to one revolution of the rotor.

Wattsecond Constant (K_s)—The wattsecond constant of a watthour meter is the registration in wattseconds corresponding to one revolution of the rotor.

Register Ratio (R_r)—The register ratio is the number of revolutions of the wheel meshing with the worm or pinion on the rotor for one revolution of the first dial.

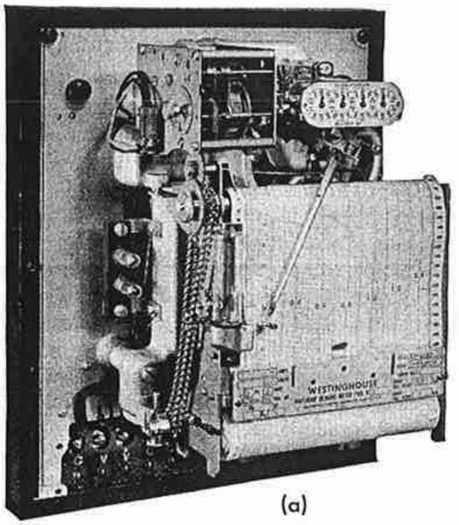
Gear Ratio (R_g)—The gear ratio is the number of revolutions of the rotor for one revolution of the first dial.

Relationships Between Meter Constants—The relationships between the watthour meter constants is given by the following:

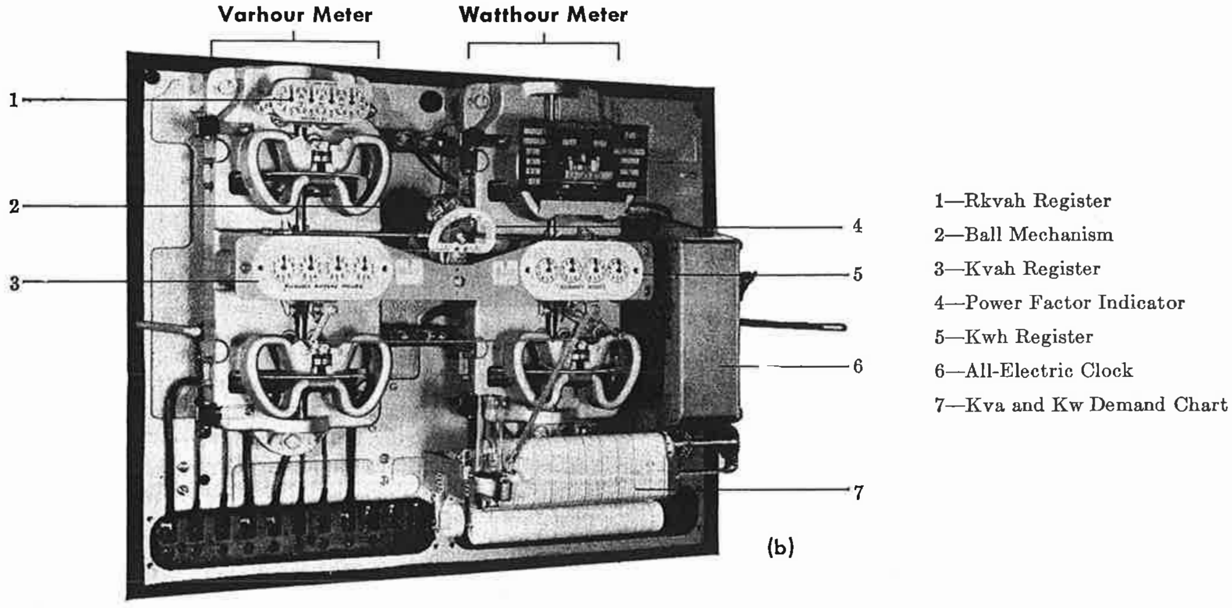
$$1)\ K_r = \text{register constant} = \frac{\text{Measured Kwh}}{\text{Registered Kwh}}$$

$$2)\ N = \text{Numerical value of one revolution of the first dial pointer (Usually } N=10)$$

$$3)\ K_h = \text{Watthour Constant} = \frac{\text{Watthours}}{\text{Rev of rotor}} = \frac{\text{Kwh}\times 1000}{\text{Rev of rotor}} = \frac{1000\times\text{Kw (rated full load or load}_x)}{60\times\text{rotor rpm (at rated full load or at load}_x)}$$



(a)



(b)

Fig. 40—Vector addition, integrated kva demand meters, (a) Type RK, (b) Type RI.

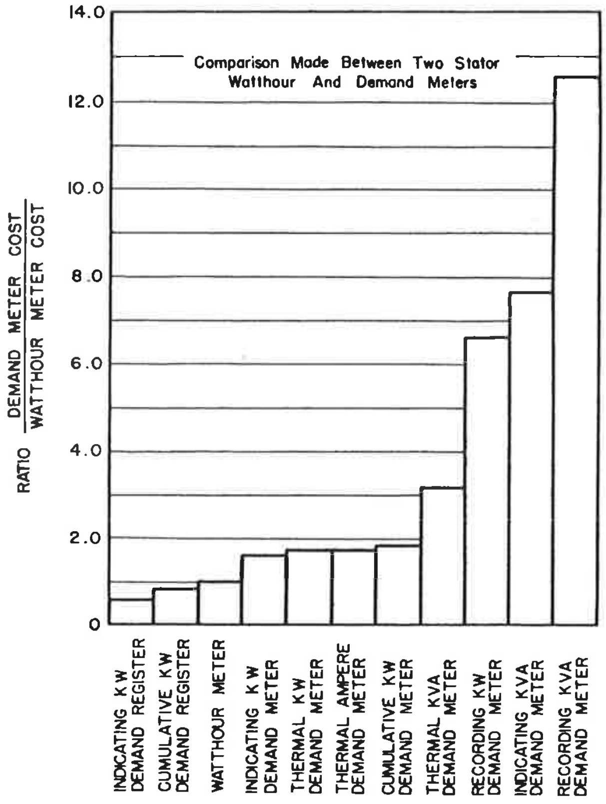


Fig. 41—Relative cost of demand meters.

4) K_s = Wattsecond constant or test constant

$$=\frac{\text{Wattseconds}}{\text{Rev of Rotor}}$$

$$=3600K_h$$

5) R_g = Gear ratio

$$=\frac{\text{Rev of rotor}}{\text{Rev of 1st dial pointer}}$$

6) R_r = Register Ratio

= The ratio of the number of revolutions meshing with the worm or pinion of the disk shaft to the number of revolutions of the first dial pointer.

7) $K_r=\frac{K_hR_g}{1000N}=\frac{K_hR_g}{10000}$ (Usually $N=10$)

17. Meter Testing

In order to register correctly the energy and reactive kilovar hours delivered to a load, the number of revolutions of the rotating disk of the meter must be proportional to the quantity being metered, and the number of revolutions of the disk must be accurately registered. Transformer rated meters must be calibrated for application with the particular instrument transformers. Usually transformers of high accuracies are applied, so that transformer errors may be neglected in calibration of the meter. Also, modern instrument transformers are not subject to changes in accuracy unless the transformer is mechanically injured. Testing of metering equipment, therefore, consists primarily of calibration of the watthour meters.

Testing a watthour meter consists of: (1) calibrating the meter so that the number of revolutions of the rotating disk is correct within the established tolerance for a given amount of energy delivered to the load, or that the speed of the disk is proportional to the load being measured; (2) the number of revolutions of the rotating disk is properly translated to the register, so that the energy delivered to the load is accurately registered on the watthour meter.

Testing of a demand meter consists of: (1) checking the interval of a block interval meter; (2) making usual tests on watthour meter with which the demand register is applied, except for lagged demand meters which are independent of the watthour meter; and (3) checking calibration of lagged-demand meters. In addition to the calibration check, testing a meter includes inspection of the meter and required repairs. After the repairs are made, the meter is calibrated.

Watthour meter tests may be classified as to: (1) the place of test, such as the laboratory or shop test or the field test (in customers' premises); (2) the time of the test, such as at or near the time of the installation, or periodic (routine); or (3) the reason for the test, as of customers' request, company (utility) request, referee (regulating agency), or test following repairs.[8]

Meter Test Methods[14, 29, 30]—Two fundamental methods are used to test meters by a user. First, a meter can be tested by using indicating instruments (watthour, voltmeter, and ammeter) and a stop watch. The energy delivered to a load can be computed if the time is accurately measured and the power transferred is held constant. The time required for a given number of revolutions of the disk is measured, and the watthour constant of meter is computed and compared with the nameplate value. The requirement of holding the load constant is an undesirable condition necessary for this method. The second and more widely used method of testing a watthour meter consists of comparing the responses of the meter under test (test meter) and a standard watthour meter (standard meter) when measuring the same load. Usually the measurements are made on a phantom load. Rated voltage is applied to the potential circuits, and current at a low voltage of a specified value and phase relationship with respect to potential circuit voltage is circulated through the current circuits of the two meters in series.

Two methods are used to compare the response of the standard and test meters. In the first method, known as portable standard meter method, the number of revolutions of the standard meter is compared with the number of revolutions of the test meter. In the second method, known as the stroboscopic method, the respective speeds of the rotating disks of the standard and test meters are compared; the test meter is adjusted until the disks of both meters rotate at the same speed. In order to make "as found" test, the stroboscopic method requires a variation (calibrated in per cent registration) in the voltage applied to the standard meter in order for both meters to rotate at the same speed.

The equipment required for the portable standard watthour meter method is less expensive than the equipment required for the stroboscopic method. However, the stroboscopic method is faster, since less time is required for comparing the relative speeds of the standard and test meters. The stroboscopic method of meter testing finds application in meter shops which do a large volume of meter testing. It is especially adaptable to gang testing. The method is not restricted to a particular type of meter, except that the marking or slotting of the disk is necessary. Disks of newer types of meters are marked for this purpose.

Meter test procedures are described in detail in literature available from manufacturers of test equipment. The procedure detailed usually applies to a particular test set. However, the procedure for testing of individual meters by use of the standard meter is fairly standard. A brief discussion of these tests is included here.

Individual Meter Test Procedure—As previously stated, the portable watthour meter test method consists essentially of comparing the number of revolutions at the test meter with the number of revolutions of a standard meter. The registration of a given meter is proportional to the number of revolutions. In order for a meter to register correctly, the gear ratio is dependent upon the watthour constant's being the values shown on the nameplate. Therefore, the registration is proportional to the watthour constant and the number of revolutions of the disk. This also applies to the standard meter. If the standard meter registers correctly, the registration of test meter is given by Equation 37

$$\% \text{ Reg} = \frac{k_h r}{K_h R} \times 100 \qquad (37)$$

where

k_h = the watthour constant of the meter under test

r = the number of revolutions of the meter under test

K_h = the watthour constant of the standard meter

R = the number of revolutions of standard meter

In comparing a test meter and a standard meter which have watthour constants of k_h and K_h, respectively, a definite ratio R_o/r exists for 100 per cent registration of the test meter. The ratio R_o/r is the ratio of the number of revolutions of standard meter to the number of revolutions of test meters, respectively. Conversely, for a given r, the standard meter will make R_o revolutions if the test meter registers correctly. Therefore, the registration of the test meter is given by Equation 38

$$\% \text{ Reg} = \frac{R_o}{R} \times 100 \qquad (38)$$

where R = the number of revolutions of standard meter in a test. Since R_o/R is very near unity, it is convenient to express the registration by Equation 39.

$$\% \text{ Reg} \approx \left(1 + \frac{R_o - R}{R_o}\right) \times 100 \qquad (39)$$

In order to simplify determining the registration of a meter, the standard meters are supplied with accuracy tables or comparison scales from which the registration can be easily determined. Each scale or table is based upon Equation 38 and is applicable for particular values of K_h, k_h, r and R. For an observed R, the registration is read from the table or scale.

Obviously, r must be an integer. It has been found that it is convenient if r for full load test is also a multiple of 5. Also, it has been the general practice to permit the test meter to rotate a sufficient number of revolutions, so that the standard meter will rotate at least ten revolutions in order to detect inaccuracies of a fraction of a per cent. It is convenient for application of Equation 39 that R_o be a multiple of 10.

Meter Tests[8]—The usual tests at which a single-phase meter is calibrated are: 1) Full load, unity power factor; 2) Full load, 50 per cent power factor; and 3) Light load (about 10 per cent of full load), unity power factor. For tests which are made on the customer's premises, the power factor test is usually omitted, because three-phase power for making the 50 per cent power factor test is not usually available.

Polyphase meters are normally subjected to the same tests made on single-phase meters, because polyphase meters can be conveniently tested as a single-phase meter. Such a test on a polyphase meter can be made, using a single-phase standard meter, by paralleling the potential circuits of the test meter and connecting the current circuits in series or testing each stator separately. However, the polyphase meters are subjected to an additional test to balance out any irregularities in the levels of the driving torque of the individual stators. Details of this test are described in meter test procedures, which are usually available from manufacturers of test equipment.

Testing Demand Meters—The testing of integrated-demand meters consists of measuring the demand interval and the rate of chart travel for a recording meter. The watthour meter is tested in the usual manner of testing that type of meter. The permissible deviations in demand and demand interval are usually the same, which is ordinarily much greater than the percentage error in the watthour meter.

The testing of lagged-demand meters consists of calibrating the meter for accuracy of demand measurements. The demand interval of a lagged-demand meter has been considered to be the time required for a meter to indicate ninety per cent of the full value of a constant load suddenly applied. The demand interval of a thermally lagged-demand meter is determined by the thermal characteristics of the meters which are not adjustable. A thermally lagged-demand meter is usually tested by comparing its response with the response of a previously calibrated meter.

VII. SPECIAL METERING

18. Metering Off-Peak Water Heater Loads.[13]

The rate schedules of some utilities include special rates for off-peak water heater (o.p.w.h.) loads, which are lower than the usual rate for the particular classes of load being served. The off-peak rate may be applicable on one or both elements of a two-element heater. In two-element heaters, the respective heater thermostats usually are interlocked so that only one element can be "on" at a time. Both or only the primary (lower or smaller) element may be restricted. Metering off-peak water heater loads applies only to metering the restricted element. Four general methods are employed for metering the o.p.w.h. load. These are as follows.

1) Separate meter and time switch control for the o.p.w.h.
2) Combination single register meter and time switch which meters both the house and o.p.w.h. load and controls the o.p.w.h. only.
3) Combination two-rate register meter and time switch which meters the house load at o.p.w.h. load during off-peak at off-peak rates, controls the o.p.w.h., and meters the house load during on-peak at on-peak rate.
4) Combination two-rate register meter without water heater contacts, in which the water heater is unrestricted, the house and w.h. are metered on the same meter at the same rate, and on-peak and off-peak load consumptions are indicated on separate registers.

The schematic diagrams of connections for the various methods of metering off-peak water loads are shown in Fig. 42.

19. Loss Metering and Compensators[31]

In some metering applications, it is desirable either to determine the energy loss in a transformer or to compensate for the loss. Loads served at primary voltage are applications for the loss compensator. Due to the difference in the costs of the instrument transformers rated at primary service voltage and instrument transformers rated at utilization voltage, it is more economical to do the metering at utilization voltage. However, the connection point (metering point) for services served at primary voltage is on the primary side of the distribution transformer or substation. Such services can be metered at secondary voltage if the transformer losses are metered, or transformer loss compensation is applied to the low-voltage metering.

Compensation of the total transformer losses consists of developing additional driving torques in the low-side metering proportional to the transformer core and copper losses. The core loss is very nearly proportional to the square of the voltage; the copper is proportional to the square of the current. The object of transformer loss compensators is to apply to the normal low-side watthour meter quantities which result in additional driving torques proportional to E^2 and I^2, without altering the driving torque which is proportional to the low side kilowatt load. Analysis of the principles and applications of transformer loss compensators is given in reference 31.

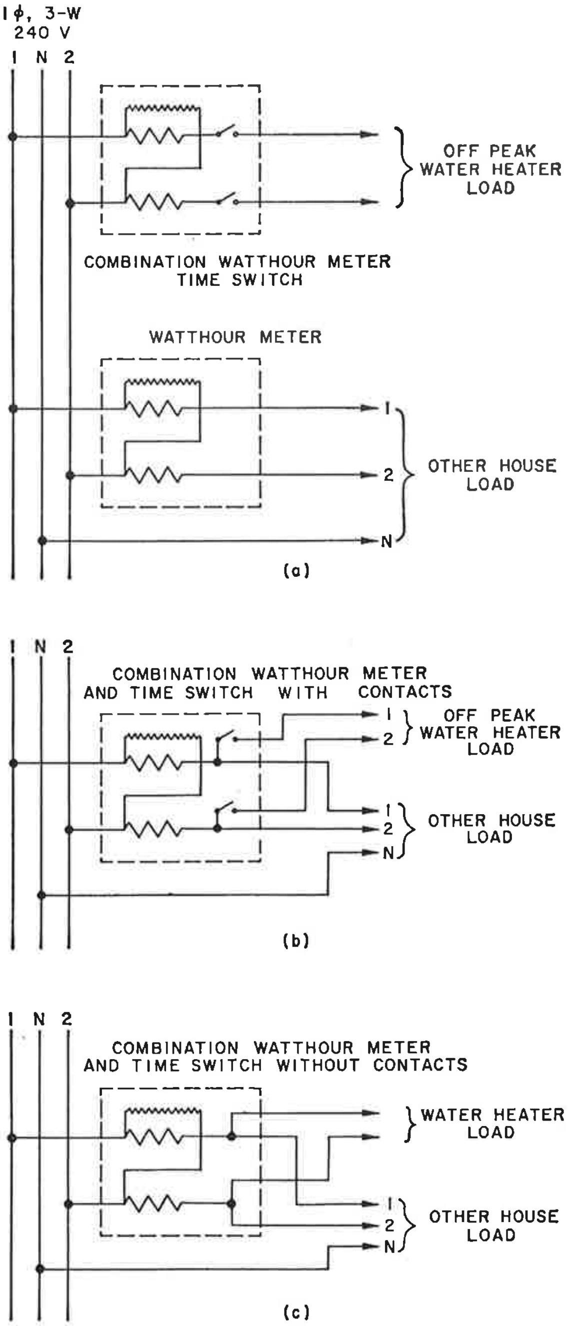


Fig. 42—Diagram of various arrangements for metering off-peak water heaters.

20. Totalizing and Remote Metering.[32, 33, 34]

Where it is necessary to determine either the total of metered quantities (kwh, rvarh, or demand quantities) on different circuits, or to indicate the metered value at a point remote from the metering point, totalization or remote metering is required. Totalizing and remote metering are two separate and distinct applications, although a particular application may be either or a combination of both applications. However, totalizing and remote metering are treated independently here.

Although totalization may be applicable to other measurements, this treatment is restricted to demand and energy or other integrated quantities mentioned above. Accepted terms are used to classify totalization in certain respects, while remote metering is a general term. Totalization is classed, according to the proximity of the circuits to be totalized, either as local totalization or remote totalization. Totalization is also classed according to the method of totalizing, as mechanical, electrical, or impulse totalizing. No distinction is made between remote metering and telemetering, although telemetering is usually associated with a particular method of accomplishing the more general requirement of remote metering. Telemetering is usually associated with carrier current transmission channels rather than with wire channels, although the association might be erroneous and misleading. Remote metering is applicable to remote presentation of measurements in general and is not restricted to remote totalization.

Totalization—Local and remote totalization are not clearly defined with regard to areas of application; however, local totalization implies that the metering points and the totalizing equipment are in the same immediate area, such that wire circuits are applicable for data transmission. On the other hand, remote totalization implies the application of telemetering or remote metering and totalization of measurements taken at individual but remote points. Therefore, remote totalization implies that individual metering and totalizing points are separated by several miles. Totalization as used here is restricted to local totalization; however, it may also be applicable to remote totalization in which the remote measurements are totalized at the receiver terminals of carrier current channels.

Methods of totalizing are clearly defined as mechanical, electrical, and impulse totalization, according to the principal method involved.

Mechanical Totalization—Mechanical totalization is the totalizing of mechanical quantities (usually torques or forces) into which electrical measurements have been translated. An example of mechanical totalization is the watthour meter for totalizing energy consumption on a 3-phase, 3-wire circuit and a single-phase circuit. The meter has the necessary stators for metering each circuit independently. The disks which are driven by the respective stators are coupled to a common shaft. Therefore, the torques developed by the stators associated with the respective circuits are totalized in the common shaft, which is geared to a common register to indicate the total consumption. The totalizing meter may be subjected to a much wider range of load than that to which an individual meter would be subjected. This may result in errors at extremely light and heavy loads. Economics normally limits to two the number of circuits to be mechanically totalized; however, in special applications, several circuits have been mechanically totalized. An advantage of mechanical totalization is that the circuits to be totalized can be independent with respect to the phase relationship of the voltages of the circuits to be totalized.

Electrical Totalization—Several circuits can be electrically totalized by paralleling the secondaries of the current transformers on corresponding phases of the circuits to be totalized. Electrical totalization is also subject to errors at extremely light and heavy loads, due to the wide range of loading to which the meter might be subjected. Also, electrical totalization is subject to additional errors because of variations in current transformer burdens, which may be due to one or more primary circuits being open or to wide variation in the loads on the individual circuits. These errors can be reduced to a minimum if the burden common to the transformers is kept to a minimum by paralleling the transformer secondary circuits at the meter terminals rather than at the transformer terminals. Errors can result from the additional burden imposed by excessively long transformer secondary leads. If this is the limiting factor of the number of circuits to be electrically totalized, it makes little difference if the current transformer external burdens are paralleled at the transformers or at the meter. One restriction of electrical totalization which does not exist with mechanical totalization is the requirement of correspondence of the phase voltages on the circuits to be totalized. The potentials required for metering can be supplied from one set of potential transformers; however, the potential source must be highly reliable and be available at any time a circuit to be totalized is energized.

A second restriction on electrical totalization is the requirement that the c.t. ratios in all circuits to be totalized must be equal. If the primary c.t. ratios are dissimilar, auxiliary totalizing current transformers must be interposed between the primary transformers and the meter to make the overall c.t. ratios of the circuits equal.

Circuits can also be electrically totalized by using meters with multiple current windings, so that a current winding is provided for each circuit to be totalized. The number of circuits to be totalized by multiple current windings or by paralleling current transformer secondaries is usually limited to two or three. Circuit diagrams showing the basic methods of electrical totalization are shown in Fig. 43.

Impulse Totalizing—Impulse totalizing consists essentially of translating the intelligence of measurements taken at the individual metering points into electrical impulses for transmission to totalizing relays or to a totalizing meter to obtain the aggregate of the measurements. By attachment of a contact device which momentarily makes and breaks its contacts for a specific number of revolutions of the disk, a watthour measurement is translated into electrical impulses, each cycle of which is proportional to the "kwh" at the metering point. The contact device momentarily makes and interrupts the circuit between the meter and the totalizing meter or relaying point to alternately energize and de-energize a solenoid. The solenoid advances a register or device for each impulse cycle to register the total number of impulses or kwh measurements received from the metering points. The transmission circuit (the circuit containing the contact devices, solenoids, and the

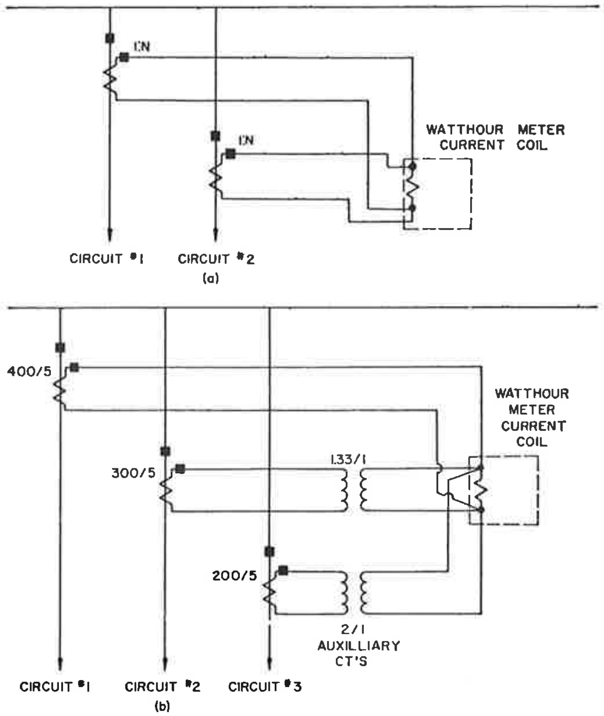


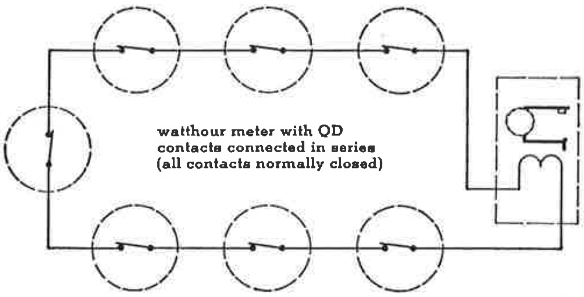
Fig. 43—Circuit diagrams of basic methods of electrical totalization.

connecting conductors) may be low voltage and either a.c. or d.c. The transmission circuit must be highly reliable, so that voltage is available to the data transmission channel at any time a circuit to be totalized is energized. The number of impulses registered in a given interval is proportional to the aggregate demand of all circuits totalized. The aggregate demand can be either indicated or recorded.

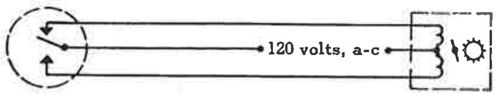
Data Transmission Circuit—Either of two basic types of circuits is used for transmission of the impulses to the totalizing relay or meter circuit. These are the two-wire circuit or the three-wire circuit. Either a.c. or d.c. voltages can be applied to both basic circuits. However, a.c. is preferred, because it results in less wear on the contact devices and has the additional advantage of being available for synchronizing the chart or timing mechanism for demand measurements at the metering and totalizing points. Circuit diagrams of the basic types of data transmission channels and variations in 3-wire transmission channels are shown in Fig. 44. The choice of the data transmission channel and contact devices is influenced by the requirements of the totalization receivers. The manufacturer of the totalization equipment should be consulted for his recommendations and details of requirements.

Impulse-Operated Metering Apparatus—Westinghouse impulse meters are available to correspond with the various watthour meters and block interval demand meters. However, only one type of totalizer is required for each general type of watthour-demand meter, regardless of the types of circuits being totalized. Westinghouse impulse-operated metering apparatus is of the low-rate type, i.e., less than 50 impulses per minute. Contact devices mounted on watthour meters are connected directly to the impulse receivers without the use of auxiliary equipment. Various combinations of contact devices, totalizing relays, and receivers can be made to meet the requirements of particular applications. In impulse totalizing, it is not necessary that the transmitting meters be of the same type as the receivers. However, the transmitting meters must be equipped with suitable contact devices for application with the transmitting channel and receiving equipment. Either the transmitter or the receiver, or neither, may be a recording or indicating demand-watthour meter. Also, the receiver (totalizer) may be only an indicating demand meter.

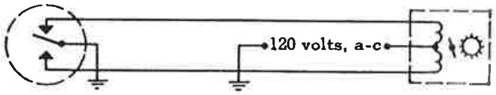
The type WRA impulse recorder is of the double operating coil type and totalizes the impulses from two



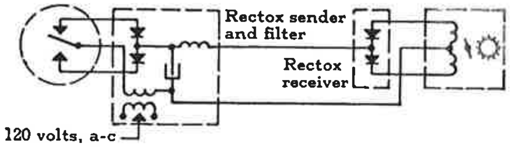
3-wire channel



grounded 2-wire channel



2-wire channel with Rectox rectifier units



grounded simplex telephone circuit

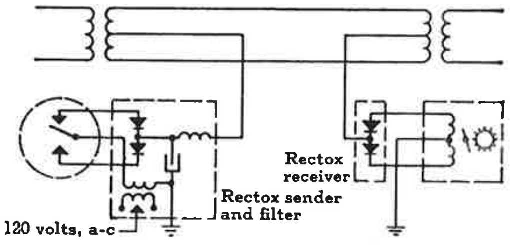


Fig. 44—Basic impulse totalization data transmission circuits.

separate contact devices. If more than two circuits are to be totalized, a WT totalizing relay must be used. The type WT impulse totalizing relay adopts the modern concepts of semi-conductor devices and logic elements to combine and retransmit impulses from a number of sources to a single circuit or receiver. It is available in units to totalize from three to seven input circuits, and may be used to totalize two input circuits. Such input impulses may originate from any 3-wire contact device or single-pole-double-throw impulse device relay. Input-to-output ratios of 1 to 1, 2 to 1, and 4 to 1 are provided. The WRA receives kwh impulses, totalizes kwh, and records totalized kw demand. A duplex WRA meter, consisting of two WRA meters in one case, is available for receiving both kwh and rkvah impulses, totalizing each commodity, registering the total of each, and recording the totalized demand of each.

Auxiliary relays are available for application with the type WT impulse totalizing relay. The type WS impulse storage relay is used when impulses cannot be continuously transmitted because of temporary use of transmission lines for other purposes. This device makes use of a stepping motor as its impulse-actuated driving element, and stores up to approximately 500 impulses. The type WD impulse difference relay is used when a difference between impulses from two sources is to be accomplished and the difference is re-transmitted. The type WD relay makes use of two stepping motors as its operating elements.

The type WRI impulse operated kva receiver is essentially the RI recording watthour demand meters, with the watthour and varhour elements each replaced with a two-circuit (three-wire) totalizing relay. Each relay consists of two pairs of operating coils, with a differential mechanism which totalizes the output. One two-circuit relay totalizes the kwh impulses; the other relay totalizes the rkvah impulses. The outputs of the totalizing relays drive a modified RI register- and ball-mechanism, which is described under Recording Kva Demand Meters. The WRI meter registers only the kwh and kvah, whereas the RI also registers the rkvah.

The WRA and WRI impulse totalizing meters require three-wire transmission channels, or the 2-wire modified channel in which a rectox filter unit is applied. Where direct connection is made between the senders and receivers with a 120-volt a.c. supply, it is recommended that the resistance of the loop not exceed 1000 ohms. The totalizing relay coils require approximately .080 ampere at 60 cycles for correct operation. This corresponds to a maximum loop distance of approximately 5.6 miles of #22 twisted pair copper conductors, and approximately 11.25 miles of #19 twisted pair copper conductors.

Westinghouse impulse operated indicating demand meters are available in the various types of mountings and various types of registers which might be required. The meter is essentially a watthour demand meter in which the meter stators and magnets are replaced by a single coil notching relay which moves a notch for each impulse cycle. The various types of Westinghouse impulse operated demand meters are shown in Table 5.

21. Load Survey Recorders

The load survey recorder is a special meter which was developed principally for the purpose of obtaining load data for use in making rate studies. Therefore, it should be of particular interest to electric utility rate engineers. The object of the development was to produce a recording demand meter which would record the data in such a manner that it could be readily processed on high speed data processing machines.

At present, two types of load survey recorders are available in which the data are recorded differently on each meter. The recorders used on these meters are (1) magnetic tape recorder, and (2) punched tape recorder[35, 36]. Load survey recorders differ in the manner in which the data is obtained by the meter, i.e., the measurement of the demand is made within the load survey meter, or it is made on an auxiliary watthour meter and translated into impulses by a contact device for application to the recorder. The load survey recorders either measure and record, or only record the integrated or block-interval kilowatt-demand. The function of the meter varies with different manufacturers. Survey recorders have two characteristics in common, which are (1) the quantity recorded is integrated kilowatt-demand and (2) a translator is required for translating the data to punched cards or punched tape for use on data processing machines.

DSL

DSL-5

DSL: Socket type to replace customer's meter, complete with DS meter and contact device.

DSL-5: Socket type to replace customer's meter with type DS-5 meter and contact device.

DSLD

DSLD-5

DSLD: Same as DSL except with additional socket for retaining customer's meter for revenue billing.

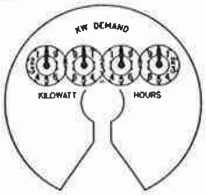
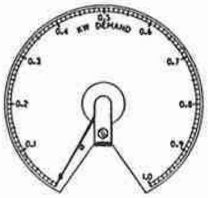
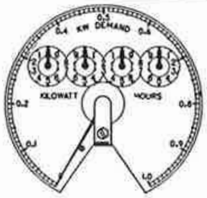
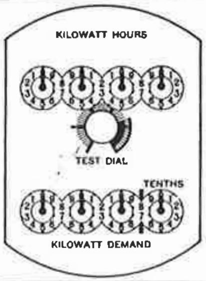
DSLD-5: Same as DSL-5 except with additional socket for retaining customer's meter for revenue billing.

DAL

Recorder unit in a separate box enclosure with flexible cable for use with other than socket type meters. Also used where impulse source is not a watthour meter.

Fig. 45—Various arrangements available in the Westinghouse Load Survey Recorder.

Table 5—Available Westinghouse Impulse Operated Indicating Demand Meters

Application:	Meter Type			
	Kilowatt hours	Indicating Kw Demand	Kilowatt Hours Indicating Kw Demand	Kilowatt Hours Cumulative Kw Demand
dial plate:				
type of case				
bottom-connected meter case	WA	WA-1	WA-2	WA-3
glass projection switchboard	WB	WB-1	WB-2	WB-3
Flexitest switchboard	WB-F	WB-1F	WB-2F	WB-3F
instrument switchboard	WM	WM-1	WM-2	WM-3

The Westinghouse Load Survey Recorder applies magnetic tape as the recording means. The tape is driven by a synchronous motor, so that in case of interruption of service to a load being recorded, the tape movement stops and the interruption is recorded. Upon restoration of service, the tape resumes its movement. A clock which is driven by the tape-driving motor indicates the total duration of interruptions of service. Tapes are available in either 8-day (150 ft.) or 32-day (600 ft.) reels.

The kilowatt load data is fed to the Load Survey Recorder in the form of impulses from a contact device in the associated watthour meter. The number of impulses recorded in specific given intervals is proportional to the energy consumption and average kilowatt load (demand) in that interval. The source of impulses is dependent upon the particular application of the recorder.

The Westinghouse Load Survey is available for application to a variety of conditions, depending upon the permanent metering which is installed at the point where the load is to be recorded. The recorder is available as a complete unit, type DSL, with watthour meter with contact device and the tape recorder, for socket mounting to replace the customer's meter. In another arrangement, type DSLD, the watthour meter and recorder units are mounted in a trough which contains an additional socket for installation of the existing watthour meter, such as the customer's meter. The recorder is available in type DAL, which includes recording unit and integrating meter with flexible cable connection for use with other than socket-type meters or where the impulse source is not a watthour meter. The socket-mounted load survey recorders are available for application to single-phase loads (using type DS watthour meter) type DSL or three-phase loads (using DS-5 watthour meter) type DSL-5, 2-stator network meter. Arrangements of the Westinghouse Load Survey Recorder are shown in Fig. 45. The internal circuit diagrams are shown in Fig. 46.

The magnet tape record is processed to translate the data to either punched cards or punched tape. A 600 ft. tape can be translated to punched cards in thirty-two minutes, or to a punched tape in 16 minutes. The translation to punched cards is done in the type WLT-1 translator, used in conjunction with an IBM-526 printing summary punch machine. Translation to punched tape is done in the type WLT-2 translator. Two plans are available for translating the tapes into punched cards. The translator can be purchased, or a rental service is provided for translating the tapes.

The punched card output contains information required for processing the data. The card is designed so that the measured demand is punched in certain columns and other pertinent information is punched in assigned columns. A punched card is shown in Fig. 47 which also shows the addresses of data on the card. The card contains data for the intervals, so that six cards are required for recording 15-minute demands for a 24-hour day, or 3 cards are required for recording 30-minute intervals. The identification of the load measured and the time of measurement are among other pertinent data punched on the card.

VIII. INSTRUMENT TRANSFORMERS

This discussion of instrument transformers is general, with the emphasis on the application of transformers to metering and metering outfits.

22. Definitions

This definitions have been extracted from "American Standard Requirements, Terminology, and Test Code for Instrument Transformers," C57.13-1954[37]. Where used in this presentation, the standard definition is intended.

Functional Definitions—

(1) Instrument Transformer. An instrument transformer is a transformer which is intended to reproduce in its secondary circuit, in a definite and known proportion suitable for utilization in measurement, control, or protective devices, the current (or voltage) of its primary circuit, with its phase relations substantially preserved.

(2) Potential (Voltage) Transformer. A potential (voltage) transformer is an instrument transformer which is intended to have its primary winding connected in shunt with a power supply circuit, the voltage of which is to be measured or controlled.

(3) Current Transformer. A current transformer is an instrument transformer intended to have its primary winding connected in series with a power supply circuit carrying the current to be measured or controlled.

Rating—

(1) Burden of an Instrument Transformer. The burden of an instrument transformer is that property of the circuit connected to its secondary winding which determines the active and reactive power at its secondary terminals. The burden is expressed either as total ohms impedance together with the effective resistance and reactance components of impedance or as the total volt-amperes and power factor of the secondary devices and leads, to a specified value of frequency and current or voltage. The impedance expression is more applicable to current transformers, the volt-ampere power factor to potential transformers.

(2) Accuracy Burden Rating. The accuracy burden rating of an instrument transformer defines a burden which can be carried at a specified accuracy for an unlimited period without causing the established limitations to be exceeded.

(3) Thermal Burden Rating of a Potential Transformer. The thermal burden rating of a potential transformer is the volt-amperes which the potential transformer will carry continuously at rated voltage and frequency without causing the specified temperature limitations to be exceeded.

(4) Quarter Thermal Burden Ambient Temperature for a Potential Transformer. The quarter thermal burden ambient temperature is the maximum ambient temperature at which the transformer can be safely operated when the transformer is energized at rated voltage and frequency and is carrying 25 per cent of its thermal burden rating without exceeding the specified temperature limitations.

(5) Rated Primary Voltage of a Potential Transformer. The rated primary voltage of a potential (voltage) transformer is the voltage selected for the basis of performance specifications.

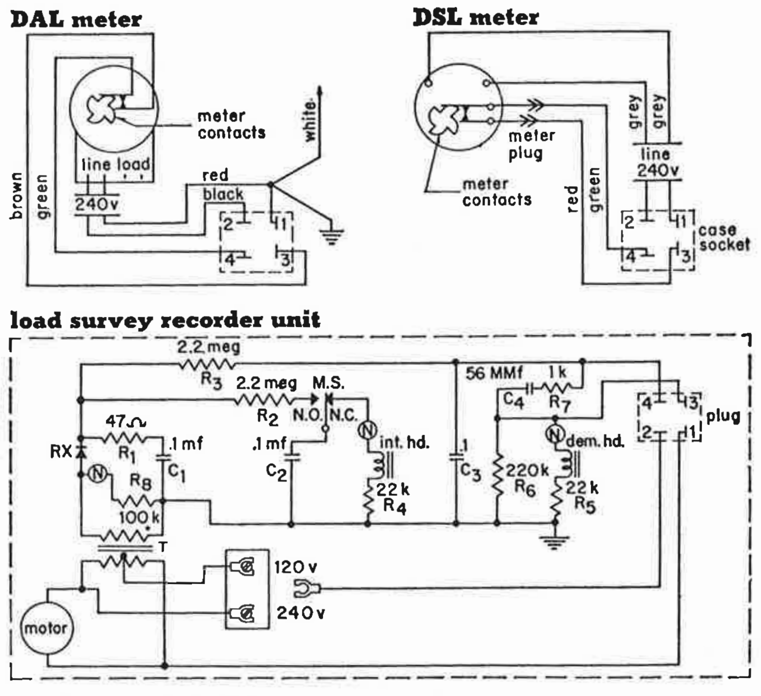
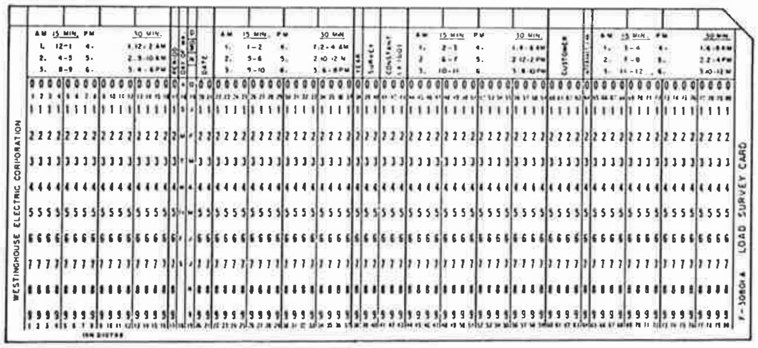


Fig. 46—Internal circuit diagram of a Westinghouse Load Survey Recorder.



Card Markings

Column Number	Marking
1-16, 22-37, 44-59, 65-80	sixteen 15-minute interval totals (4 columns per interval to permit use of same card for totalizing)
17	periods of day (1 through 6 for 6 cards per day)
18	day of week
19	month
20, 21	date
38	year
39, 40	survey number
41, 42, 43	demand constant
60, 61, 62, 63	customer identification
64	intervals per hour

Fig. 47—Punched card obtained for translation of Load Survey Recorder tape showing addresses of data on card.

(6) Rated Primary Voltage of a Current Transformer. The rated primary voltage of a current transformer designates the insulation class of the primary winding.

(7) Rated Primary Current of a Current Transformer. The rated primary current of a current transformer is the current selected for the basis of performance specifications.

(8) Continuous-Thermal-Current-Rating Factor. The continuous-thermal-current rating factor is the factor by which the rated primary current is multiplied to obtain the maximum allowable primary current based on the limiting temperature rise on a continuous basis.

(9) Phase Angle Correction Factor. The phase-angle correction factor is that factor by which the reading of a wattmeter or registration of a watthour meter, operated from the secondary of a current, or a potential transformer, or both, must be multiplied to correct for the effect of phase displacement of secondary current, or voltage, or both, with respect to primary values due to instrument transformer phase angles.

(10) Instrument-Transformer Correction Factor (Transformer Correction Factor). The instrument-transformer correction factor is the factor by which the reading of a wattmeter or the registration of a watthour meter must be multiplied to correct for the effects of the error in ratio and the phase angle of the instrument transformer. This factor is the product of the ratio and phase-angle correction factors for the existing conditions of operation.

23. Functions of Instrument Transformers

In a particular application, an instrument transformer performs either or both of two principal functions. It may be necessary to transform the electrical quantities (voltage and current) to be measured, relayed, or controlled, individually or as functions of both individual quantities, into quantities which are suitable for application to standard meters and relays, or control devices. Neither the satisfactory operating range nor the insulation class of the instruments, meters, relays, etc. should be exceeded. The transformation may be necessary because of the magnitude of the system quantities to be measured, or the voltage-to-ground of the point on the system may be such as to require insulating the instruments, meters, etc. from the system. The system quantities are referred to as *primary* quantities.

The transformation must be such that definite and known proportionalities and phase relationships exist between primary and secondary quantities. Measurements made on secondary quantities must be representations of primary measurements with known and acceptable accuracies. The accuracy requirements depend upon the purpose of the *measurements*. Metering used for billing purposes requires greater accuracy than measurements for protective relaying.

24. Classification of Instrument Transformers.

Instrument transformers are classified according to: 1) the particular function; 2) method of installation; 3) type of major insulation; 4) method of cooling; and 5) mechanical construction as shown in Table 6.[37] Each instrument transformer may be classified as being of one type listed under each major classification, with the exception of mechanical construction, which is applicable to current transformers only. The specific types in each classification are defined in the American Association Standard C-57.13-1954, from which the definitions in (22) have been extracted.

25. Potential Transformers.[38]

Analysis—The function of a potential transformer is to produce a voltage which is applicable to standard instruments, meters, or relays, and which is a representation of the primary voltage in a known and acceptable proportionality and phase relationship. In general, the secondary voltage of a constant potential transformer is proportional to turns ratio, and in phase with or in phase opposition to the primary voltage (depending upon the reference terminal designation). Such would be the case of an ideal transformer, which has no leakage impedance, losses, or exciting current. However, in the actual constant potential transformer, the energy necessary to magnetize the magnetic circuit of the transformer must be supplied from the primary lines through the leakage impedance of the primary winding. Also, the presence of load current in the transformer windings causes a voltage drop in the leakage impedance of the primary and secondary windings. Load current and exciting current produce an overall voltage drop in the transformer, which results in a ratio error and a phase angle other than 180° between primary and secondary terminal voltages.

In the usual analysis of an instrument potential transformer, the saturation effects may be neglected and the assumption of linear, bilateral impedances is valid. Although conditions may exist in which the effects of nonlinearity are not negligible, such are abnormal conditions and are not discussed here. Usually the instrument potential transformer can be analyzed with reasonable accuracy by representing the transformer by the equivalent circuit shown in Fig. 48(a). The vector diagram resulting from sinusoidal applied voltage is shown in Fig. 48(b).

It becomes apparent from an analysis of the vector diagram that the secondary burden (magnitude and power factor) has a pronounced effect on the accuracy with which the secondary voltage represents the applied voltage. For an ideal transformer (without losses or impedance), the secondary voltage would be in-phase (or 180° out of phase) with the applied voltage; and the ratio of primary to secondary voltage would be equal to the turns ratio. However, the actual transformer has impedance and corresponding losses and internal voltage drops. The voltage drops due to exciting current I_e and load current I_2 cause the secondary voltage to be less than (for the usually lagging power factor burdens) and slightly out of phase with the primary voltage. Equations have been developed for calculation of the ratio and phase angle. However, I_e is usually so very much smaller than I_1, and is very nearly constant, that it can usually be neglected without seriously affecting the accuracy. If I_e is neglected, the expressions for the true ratio and phase angle are both sufficiently linear functions of load current at a given voltage and burden power factor.

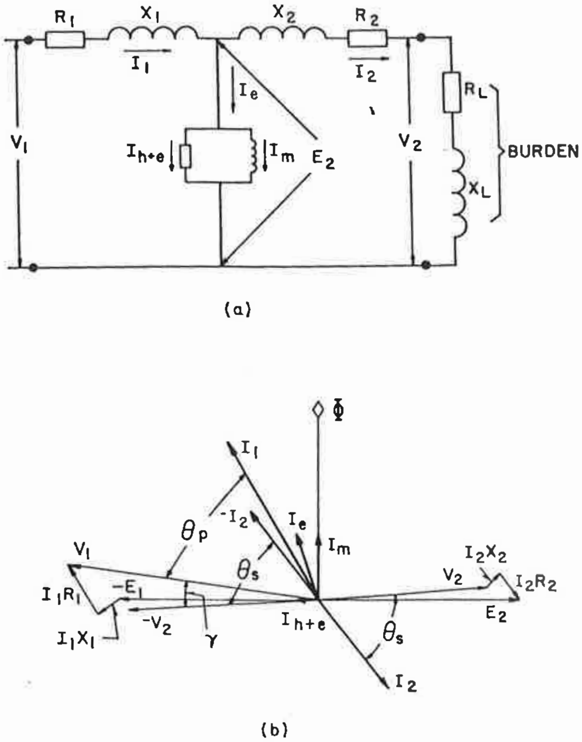


Fig. 48—(a) An equivalent circuit of an instrument potential transformer, (b) Vector diagram of (a).

Errors in Potential Transformers[39, 40]—The ratio correction factor (*RCF*) of a potential transformer is that factor by which the marked ratio (ratio as indicated on the nameplate) must be multiplied to obtain the true ratio, V_1/V_2, and is given by Equation 38.

$$RCF = \frac{V_1/V_2}{\text{Marked Ratio}} \tag{38}$$

The phase angle (γ) of a potential transformer is the angle between the secondary voltage from the identified

Table 6—Classification of Instrument Transformers

Application		Classes of Instrument Transformers		
Major Function	Method of Installation	Major Insulation	Method of Cooling	Mechanical Construction*
(1) Potential	(1) Indoor	(1) Dry-Type	(1) Dry-Type Self-Cooled	(1) Wound (Wound-Primary) Type
(2) Current	(2) Outdoor	(2) Compound-Filled	(2) Oil-Immersed Self-Cooled	(2) Bar Type
	(3) Protected Outdoor	(3) Liquid Immersed		(3) Window Type
				(4) Bushing Type
				(5) Split-Core Type
				(6) Three-Wire Type

(1) Metering and Relaying
(2) Relaying
*Applies to Current Transformers Only.

to the unidentified terminal and the corresponding primary voltage. The angle is considered positive when the secondary voltage leads the primary voltage, or when $-V_2$ leads V_1.

The phase-angle correction factor ($PACF$) of a potential transformer is that factor by which the apparent power factor must be multiplied to obtain the true (system) power factor. For positive transformer phase angles, $-V_2$ leads V_1; therefore for a lagging power factor load, the true power factor angle, θ_p, is less than the indicated power factor angle, θ_s. Assuming no ratio error exists, the phase angle correction factor for a potential transformer is given by Equation 39.

$$(PACF)=K_\gamma=\frac{\text{Cos}\,\theta_p}{\text{Cos}\,\theta_s} \qquad \text{(a)}$$

$$K_\gamma=\frac{\text{Cos}\,(\theta_s-\gamma)}{\text{Cos}\,\theta_s} \qquad \text{(b)} \quad (39)$$

$$K_\gamma=\frac{\text{Cos}\,\theta_p}{\text{Cos}\,(\theta_p+\gamma)} \qquad \text{(c)}$$

where γ = transformer phase angle
$\text{Cos}\,\theta_p$ = true or primary system power factor
$\text{Cos}\,\theta_s$ = apparent system power factor as indicated on secondary side of the transformer

The ($PACF$) can be expressed in terms of the apparent system power factor angle θ_s (as indicated on the secondary side of the transformer), as is given by Equation 39(b). It can also be expressed in terms of the true system power factor angle θ_p, as is given by Equation 39(c). Since the apparent system power factor is known, some individuals choose to express the ($PACF$) in terms of θ_s. However, in regard to the standard accuracy classifications for metering service which are given in the standards on instrument transformers, the accuracy standards are based on the system power factor.

Since γ is usually very small of the order of minutes, K_γ can be given in terms of θ_s or θ_p with sufficient accuracy by Equations 40(a) or 40(b), respectively.

$$K_\gamma\approx 1+\gamma\,\frac{\tan\theta_p}{3438} \qquad \text{(a)}$$

$$K_\gamma\approx 1+\gamma\,\frac{\tan\theta_p}{3438} \qquad \text{(b)} \quad (40)$$

where γ is expressed in minutes.

The transformer correction factor (TCF) is the factor by which the reading on a wattmeter or registration of a watthour meter must be multiplied to correct for the effects of the error in ratio and phase angle of the potential transformer. It is numerically equal to the product of (RCF) and K_γ. The ratio of the true system power to the indicated system power (as indicated by a wattmeter, including the marked turns ratio) is given approximately by Equations 41(d) and 41(e), respectively.

$$TCF=\frac{P_t}{P_m}=\frac{V_1\,I_m\,\text{Cos}\,(\theta_s-\gamma)}{(\text{Marked Ratio})\;V_2\,I_m\,\text{Cos}\,\theta_s} \qquad \text{(a)}$$

$$TCF=\frac{V_1\,I_m\,\text{Cos}\,\theta_p}{(\text{Marked Ratio})\times V_2\,I_m\,\text{Cos}\,(\theta_p+\gamma)} \qquad \text{(b)} \quad (41)$$

$$\text{Marked Ratio}=\frac{V_1}{V_2\times(RCF)} \qquad \text{(c)}$$

$$\therefore \quad TCF=(RCF)\times K_\gamma$$

$$TCF\approx RCF\left(1+\frac{\gamma\tan\theta_s}{3438}\right) \qquad \text{(d)} \quad (41)$$

$$TCF\approx RCF\left(1+\frac{\gamma\tan\theta_p}{3438}\right) \qquad \text{(e)}$$

In measurements of voltage only, the ratio error is the only error of importance. However, in the measurement of a quantity which is a function of the product of voltage and current (watt meters and watthour meters), the ratio error and phase angle are both involved. An RCF greater than unity indicates that the true turns ratio is greater than the marked ratio, and results in a low meter reading, based on the marked ratio. Positive phase angle results in low and high meter readings and PACF greater and less than unity for lagging and leading power factor loads, respectively.

Errors in a potential transformer depend upon the transformer burden, transformer impedance, degree of saturation of the core, and the magnetic properties of the core. Standards of accuracy classification at standard burdens have been established for rating a transformer with regard to accuracy when operated at rated voltage and frequency.

Ratings of Potential Transformers[37]—The rating of a potential transformer includes: 1) rated primary voltage and ratio; 2) insulation class; 3) impulse level in terms of full-wave-test voltage; 4) standard accuracy classes at specified standard burdens, voltage, and frequency; and 5) thermal burden rating.

Standard values of (1), (2), and (3) are shown in Table 7. The rated primary voltage is the voltage used as the basis of performance specifications, which include the insulation requirements as well as its functional performance. Typical primary connections for potential transformers in Groups 1, 2, and 3 of Table 7 are shown in Fig. 49.

Standard accuracy classifications for metering service are shown in Table 8. The accuracy classification corresponds with the transformer correction factor. The standard burdens for potential transformers for accuracy rating purposes are shown in Table 9. Standard burdens are based on a secondary voltage of 120 volts for two winding transformers, and 69.3 volts for the tertiary winding of transformers having such a winding.

The standard accuracy classes for potential transformers for metering service are shown in Table 8. The standards take into account the effect of phase angle by allowing a larger phase angle if the ratio error is such that the error introduced in a product meter reading by the phase angle compensates for the ratio error. The effects of coordination of phase angle and ratio errors can be seen in the parallelograms shown in Fig. 50. The parallelograms indicate the limits of both phase angle and ratio error for the standard accuracy classes. The relationship of TCF, RCF, θ_p, and γ is given by Equation 41(e).

$$TCF\approx RCF\left(1+\frac{\gamma\tan\theta_p}{3438}\right) \qquad \text{(41e)}$$

The limits of *TCF* for various accuracy classes are given in Table 8 for ranges of indicated system power factors of from .6 to 1.0. If the limit of θ_p is considered, i.e., tan θ_p is considered as ± 1.333, the limits of γ are adequately expressed by Equation 42. The limits of *RCF* and phase angle apply within ± 10 per cent of rated voltage at rated frequency and from zero burden to rated burden on a 120-volt secondary base or 69.3-volt tertiary base.

$$\gamma = 2600\ (TCF - RCF) \qquad (42)$$

where

γ = limit of phase angle, minutes.

The parallelograms of Fig. 50 are based on Equation 42, rather than the more accurate expression which is given in Equation 41(b). The exact limits of *RCF* and phase angle are obtained by applying the limits of system power factor to Equation 41(b). Therefore, for a system power factor of 60 per cent, Equation 41(b) becomes

$$\text{Cos}\ (57.13^\circ + \gamma) = .6\ \frac{RCF}{TCF}$$

Service Conditions Affecting Potential Transformer Errors

Burden[38]—The ratio is approximately linear with burden at constant burden power factor and voltage. Characteristics at various burden power factors meet at zero burden. This factor makes it possible to determine the characteristics of any burden power factor, if the characteristics are known for one power factor. This is discussed under Potential Transformer Application Data.

At a particular burden power factor, the angle of which is equal to the through impedance angle of the transformer, the phase angle is equal to the phase angle at zero burden for the usual range of burdens. However, for the same burden power factor, the rate of change of *RCF* with burden is maximum. At extremely low and high burden power factors, the effects of ratio and phase angle errors tend to compensate for one another in the measurement of power.

Frequency—Increasing frequency at a fixed voltage has little effect in the potential transformer characteristics, since it increases the voltage drop due to leakage flux and decreases the flux density and the required exciting current. Unless the frequency is more than doubled, the effect on performance is usually small.

Decreasing the frequency results in an increase in flux density and a corresponding increase in exciting current. A potential transformer should not be operated at less than about 95 per cent of rated frequency.

Temperature—The resistance of the windings increases proportionately to the absolutely temperature. Therefore, the resistance drop and the corresponding error increase with temperature. Typical curves are usually based on a temperature of 50°C, which represents an average operating winding temperature. Measurements made at an ambient temperature of 20°C result in a resistance drop, which is low by 12 per cent.

Voltage—The accuracy of a potential transformer at other than rated voltage is influenced by the degree by which the exciting current deviates from the normal value. The accuracy characteristics are unchanged at reduced voltage. At abnormally high voltage, the exciting current is excessive and may result in serious error. Normal voltage variations do not result in serious errors.

26. Current Transformers.

Analysis—The function of a current transformer is to produce a current which is applicable to standard instruments, meters, or relays, and which is a representation of the primary current in known and acceptable proportionality and phase relationship. The magnitude of the primary current may be within the range of the standard instruments; however, it may be necessary to use a current transformer to insulate the primary circuit from the instrument circuit, due to the voltage of the primary circuit. Conversely, although the voltage of the supply circuit may be suitable for application to an instrument, the magnitude of the primary current may exceed the ratings of standard instruments. It is then necessary to produce a current for application to the instrument which is smaller than the current in the supply circuit by a known and acceptable proportionality and phase relationship.

Table 8—Standard Accuracy Classes for Potential Transformers for Metering Service*

Accuracy Class	Limits of Transformer Correction Factor	Limits of Power Factor (Lagging) of Metered Power Load
1.2	1.012–0.988	0.6–1.0
0.6	1.006–0.994	0.6–1.0
0.3	1.003–0.997	0.6–1.0

*ASA Standard C57.13—1954.

An equivalent circuit and the corresponding general vector diagram of a current transformer are shown in

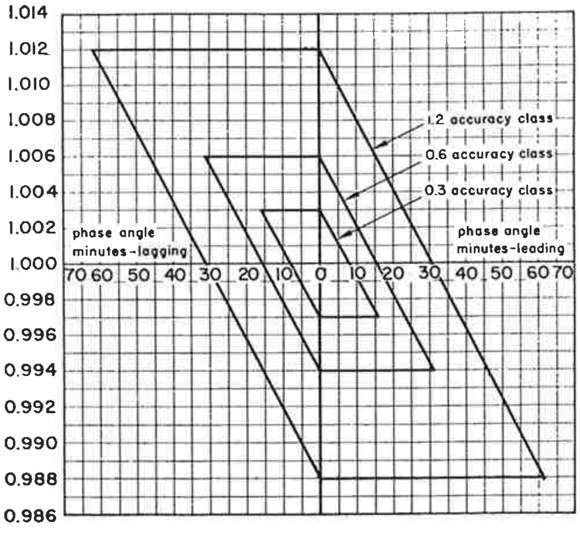


Fig. 50—Limits of ratio correction factors and phase-angle for standard accuracy classes for potential transformers for metering service.

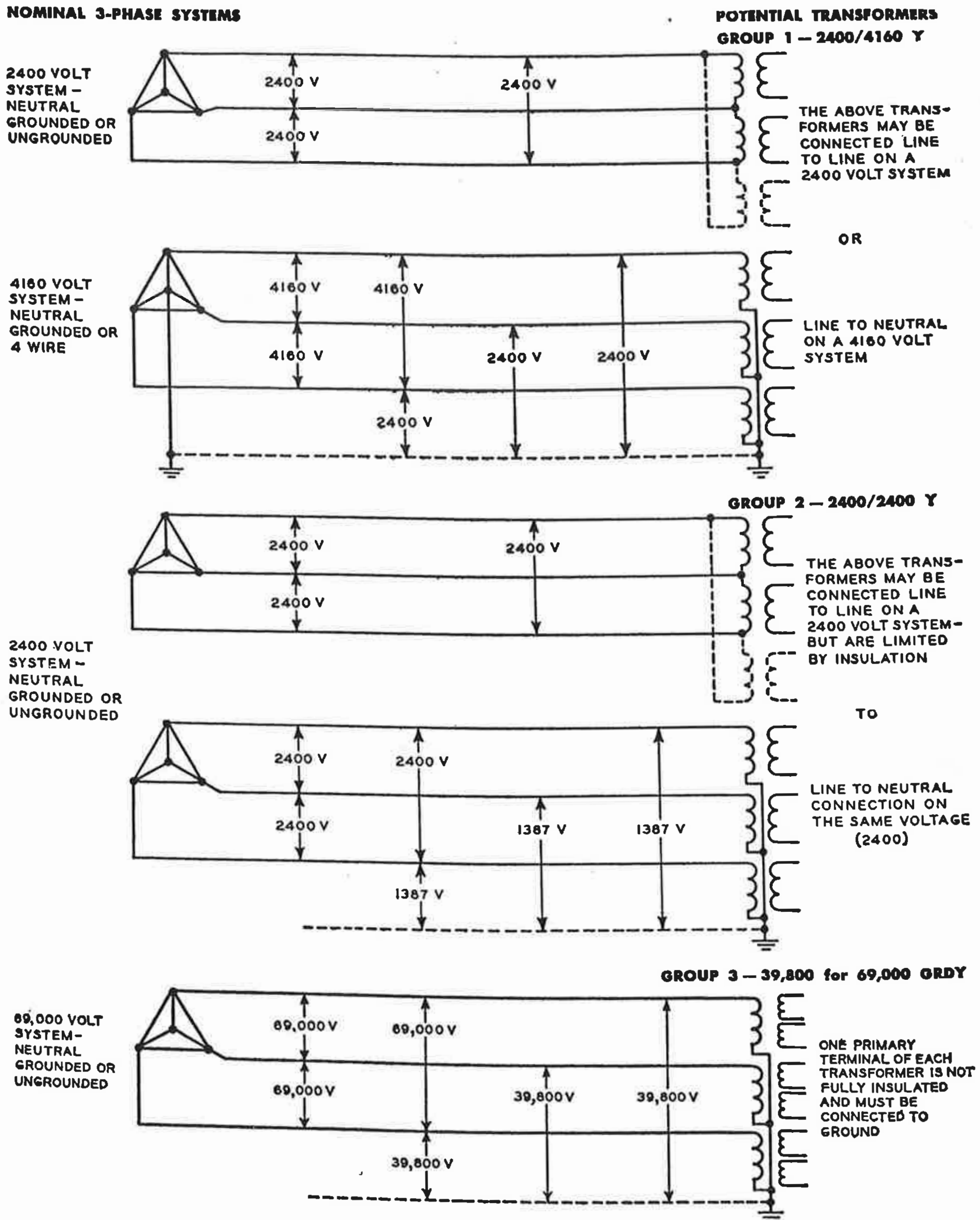
Table 7—Standard Insulation Classes Marked Ratios, Primary Voltage Ratings and Dielectric Tests for Potential Transformers*

Nameplate Marking			Usual Circuit Voltage: Volts,	Permissible Transformer Connection	Standard Dielectric Tests			
Standard Insulation Class: Kv	Standard Marked Ratio	Standard Primary Voltage Rating: Volts			Standard Low Frequency Test: Kv Rms	Standard Impulse Tests		
						Chopped Wave		Full Wave: Kv
						Crest Voltage: Kv	Min. Time to Flash-over: μ sec	
GROUP 1: 1.2 TO 15 KV, FULL INSULATION, *Y* VOLTAGE LIMIT EQUALS $\sqrt{3}$ TIMES Δ VOLTAGE LIMIT								
1.2	1:1	120/208Y	120	Δ or Y	10	36	1.0	30
			208	Y only				
	2:1	240/416Y	240	Δ or Y	10	36	1.0	30
			416	Y only				
	4:1	480/832Y	480	Δ or Y	10	36	1.0	30
			832	Y only				
	5:1	600/1040Y	600	Δ or Y	10	36	1.0	30
			1040	Y only				
5.0	20:1	2400/4160Y	2400	Δ or Y	19	69	1.5	60
			4160	Y only				
8.7	35:1	4200/7280Y	4200	Δ or Y	26	88	1.6	75
			7280	Y only				
	40:1	4800/8320Y	4800	Δ or Y	26	88	1.6	75
			8320	Y only				
15L	60:1	7200/12470Y	7200	Δ or Y	34	110	1.8	95
			12470	Y only				
	70:1	8400/14560Y	8400	Δ or Y	34	110	1.8	95
			14560	Y only				
15H	60:1	7200/12470Y	7200	Δ or Y	34	130	2.0	110
			12470	Y only				
	70:1	8400/14560Y	8400	Δ or Y	34	130	2.0	110
			14560	Y only				
GROUP 2: 2.5 TO 345 KV, FULL INSULATION, *Y* VOLTAGE LIMIT EQUALS Δ VOLTAGE LIMIT								
2.5	20:1	2400/2400Y	2400	Δ or Y	15	54	1.25	45
5.0	40:1	4800/4800Y	4800	Δ or Y	19	69	1.5	60
8.7	60:1	7200/7200Y	7200	Δ or Y	26	88	1.6	75
15L	100:1	12000/12000Y	12000	Δ or Y	34	110	1.8	95
	120:1	14400/14400Y	14400	Δ or Y	34	110	1.8	95
15H	100:1	12000/12000Y	12000	Δ or Y	34	130	2.0	110
	120:1	14400/14400Y	14400	Δ or Y	34	130	2.0	110
25	200:1	24000/24000Y	24000	Δ or Y	50	175	3.0	150
34.5	300:1	34500/34500Y	34500	Δ or Y	70	230	3.0	200
46	400:1	46000/46000Y	46000	Δ or Y	95	290	3.0	250
69	600:1	69000/69000Y	69000	Δ or Y	140	400	3.0	350
92ᵡ	800:1	92000/92000Y	92000	Δ or Y	185	520	3.0	450
115	1000:1	115000/115000Y	115000	Δ or Y	230	630	3.0	550
138	1200:1	138000/138000Y	138000	Δ or Y	275	750	3.0	650
161	1400:1	161000/161000Y	161000	Δ or Y	325	865	3.0	750
196ᵡ	1700:1	196000/196000Y	196000	Δ or Y	395	1035	3.0	900
230	2000:1	230000/230000Y	230000	Δ or Y	460	1210	3.0	1050
287ᵡ	2500:1	287000/287000Y	287000	Δ or Y	575	1500	3.0	1300
345	3000:1	345000/345000Y	345000	Δ or Y	690	1785	3.0	1550
GROUP 3: 25 TO 345 KV, REDUCED INSULATION AT NEUTRAL END, GRD *Y* APPLICATION ONLY†								
25	120-200:1	14400 for 25000 grd Y	24000	grd Y only	50	175	3.0	150
34.5	175-300:1	20125 for 34500 grd Y	34500	grd Y only	70	230	3.0	200
46	240-400:1	27600 for 46000 grd Y	46000	grd Y only	95	290	3.0	250
69	350-600:1	40250 for 69000 grd Y	69000	grd Y only	140	400	3.0	350
92ᵡ	480-800:1	55200 for 92000 grd Y	92000	grd Y only	185	520	3.0	450
115	600-1000:1	69000 for 115000 grd Y	115000	grd Y only	230	630	3.0	550
138	700-1200:1	80500 for 138000 grd Y	138000	grd Y only	275	750	3.0	650
161	800-1400:1	92000 for 161000 grd Y	161000	grd Y only	325	865	3.0	750
196ᵡ	1000-1700:1	115000 for 196000 grd Y	196000	grd Y only	395	1035	3.0	900
230	1200-2000:1	138000 for 230000 grd Y	230000	grd Y only	460	1210	3.0	1050
287ᵡ	1500-2500:1	172500 for 287000 grd Y	287000	grd Y only	575	1500	3.0	1300
345	1800-3000:1	207000 for 345000 grd Y	345000	grd Y only	690	1785	3.0	1550

ᵡThese system voltages are not in the *EEI-NEMA Preferred Voltage Ratings for A-C Systems and Equipment* report (EEI R-6, NEMA 117).

*ASA Standard C57.13—1954.

†For insulation class of neutral see per 13-11.541 ASA Standard C57.13—1954.



NOTE TO GROUP 3: The double ratio for the transformers in Group 3 is obtained by a secondary winding and a tertiary winding, to provide the same nominal voltage in the secondary from line to neutral as from line to line.

Fig. 49—Typical potential transformer primary connections for transformers in Groups 1, 2, and 3 of Table 7.

Fig. 51. Although the vector diagram in Fig. 48 for a constant potential transformer may be applicable to an analysis of a current transformer, Fig. 51 is preferable for this purpose, due to the fundamental differences in the transformers. In a potential transformer, the applied voltage, flux density, and exciting current are approximately constant, and the transformer current is determined by the leakage impedance of the transformer. In a current transformer, the primary current is determined by the load being metered and is not influenced by the transformer or its burden; the flux density and exciting current are variable and are determined by the secondary circuit impedance and primary current. The vector diagram is restricted to fundamental frequency components and does include any harmonics. This factor should be recognized in analyzing the operation of the current transformer in the regions of non-linearity.

Table 9—Standard Burdens for Potential Transformers*

Designation of Burden	Secondary Volt-Amperes	Burden Power Factor
W	12.5	0.10
X	25	0.70
Y	75	0.85
Z	200	0.85
ZZ	400	0.85

*ASA Standard C57.13—1954.

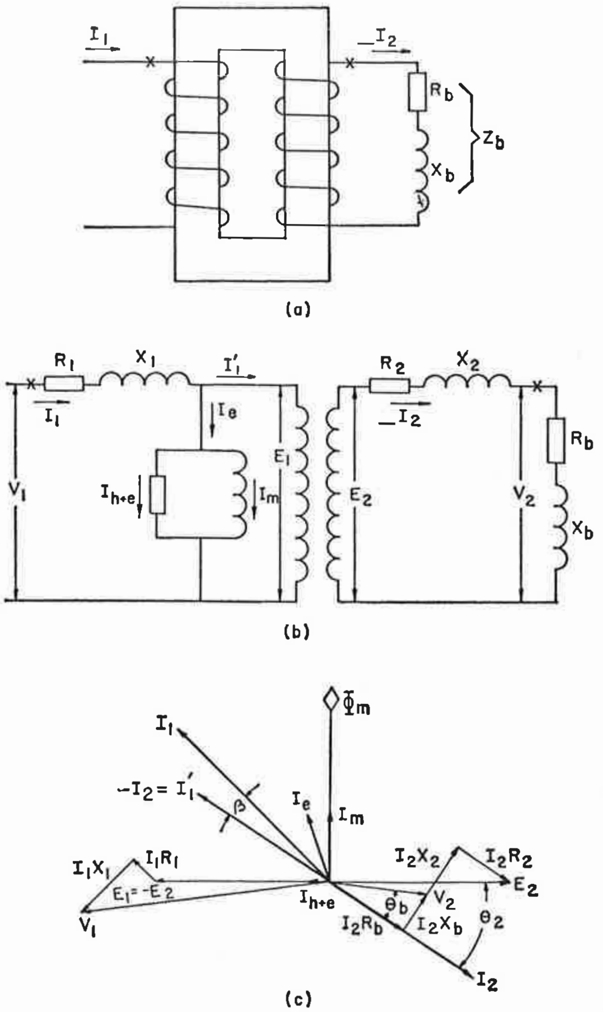


Fig. 51—(a) Circuit of an Instrument Current Transformer, (b) An Equivalent circuit of an instrument current transformer, (c) Vector diagram of (a) and (b).

Due to the phase relationships which exist between other quantities and the induced voltage, E_2, it is convenient to take E_2 as the reference vector. The mutual flux is in leading quadrature and proportional to E_2. The exciting current, I_e, is made up of the power component, I_{h+e}, in leading quadrature with ϕ, and the magnetizing component, I_m, in phase with ϕ. The demagnetizing effect of the secondary current, I_2, must be balanced out by $\frac{N_2I_2}{N_1}=I_1'$, the transformer load component of primary current, I_1. The primary current is determined by the primary load being metered and is independent of the transformer in its burden. However, the primary current is the sum of I_e and I_1'. The flux is variable and is determined by the induced voltage necessary to circulate I_2 through the total secondary impedance, Z_b+Z_2. Since ϕ is variable and the manners in which I_{h+e} and I_m vary with ϕ are different, the required E_2 and ϕ have direct bearings on the magnitude and phase angle of I_e. The magnitude and phase angle of I_2 and I_e have direct influences on the relative magnitudes and phase angle of I_1 and I_1'. This is the only characteristic which is of direct importance. The angle, β, by which I_1' leads I_1 is the phase angle of the transformer for that particular burden and saturation. The ratio, I_1/I_2, is the ratio of the transformer for a particular burden and saturation. If it were not for the exciting current, the total primary ampere-turns would exactly balance out the secondary ampere-turns. No phase displacement between primary and secondary currents would exist and the ratio of I_1/I_2 would be equal to exactly the turns ratio.

For a qualitative analysis of a current transformer, it is necessary to consider the variations in magnitude of I_{h+e} and I_m with ϕ, and the relation of both components to I_2 in magnitude and phase. In order to minimize I_e, the current transformer is designed to be operated at a low flux density of the order of one kilogouss. In this region, the permeability is much lower than the maximum effective permeability. The ratio of I_m to ϕ, E_2, or I_2 for a given burden decreases for increases in ϕ, E_2, or I_2. In the same region, I_{h+e} is approximately proportional to ϕ, E_2, or I_2 for a fixed burden. For a fixed burden, I_{h+e} is proportional to I_2, and I_m increases at a lesser rate than I_2. Therefore, as I_2 increases, I_e increases at a lesser rate and leads ϕ by a greater angle.

The magnitude and power factor of the transformer burden have pronounced effects on the ratio and phase angle of a current transformer. For high power factor burdens, the principal influence on the ratio error is I_{h+e}, but the principal influence on phase angle is I_m.

An increase in line current has less effect on the ratio error than it has on the phase angle. However, the phase angle decreases for increases in line current. For low power factor burdens, the principal influence on the per cent ratio error is I_m, but the principal influence on phase angle is I_{h+e}. Since I_m does not increase as rapidly as I_1 or I_2, the decrease in per cent ratio error with line current is slightly greater for low power factor burdens than it is for high power factor burdens. Also, the change in phase angle with I_1 or I_2 is slightly greater for high power factor burdens. For a given magnitude of Z_b and I_1 or I_2, the ratio error increases for decreases in burden power factor, reaches a maximum when I_e and I_1 are in phase, and decreases for further reductions in burden power factor. The phase angle decreases as the burden power factor decreases, becomes zero when I_e and I_1 are in-phase, and becomes negative for further decreases in burden power factor. The per cent ratio error and phase angle are greater at high burdens and low line currents, since I_e then represents a large portion of the line current.

For a typical condition, the burden power factor may be of the order of 35 to 65 per cent. In the absence of compensation, the ratio would be greater than $\frac{N_2}{N_1}$ throughout the range of load currents, and decreasing at a decreasing rate. Since the turns ratio $\frac{N_2}{N_1}$ is at the designer's selection, the designer usually compensates the transformer by choosing $\frac{N_2}{N_1}$ less than the desired ratio, such that at about 60 per cent of rated line current, the ratio error is zero.

Table 10—Standard Primary-Current Rating and Standard Ratios for Current Transformers*

(a) Single-Ratio Current Transformers

Standard-Primary Current Rating	Standard Ratio	Standard Primary-Current Rating	Standard Ratio	Standard Primary-Current Rating	Standard Ratio
10	2:1	100	20:1	800	160:1
15	3:1	150	30:1	1200	240:1
25	5:1	200	40:1	1500	300:1
40	8:1	300	60:1	2000	400:1
50	10:1	400	80:1	3000	600:1
75	15:1	600	120:1	4000	800:1

(b) Double-Ratio Current Transformers

Standard Primary-Current Rating	Standard Ratio	Standard Primary-Current Rating	Standard Ratio
25/50	5/10:1	200/400	40/80:1
50/100	10/20:1	400/800	80/160:1
100/200	20/40:1	600/1200	120/240:1

(c) Multiratio Transformers (Bushing Type)

Standard Primary-Current Rating Maximum	Standard Ratios
600	120/80/60/40/20:1
1200	240/160/120/80/40:1
2000	400/300/240/160:1
3000	600/400/300:1
4000	800/600/400:1

*ASA Standard C57.13—1954, Instrument Transformers.

Errors In Instrument Current Transformers—As has been discussed in the preceding section, the current transformers are subject to ratio errors and a phase angle between primary and secondary values.

The ratio correction factor (RCF) of a current transformer is that factor by which the marked ratio (ratio indicated on the nameplate) must be multiplied to obtain the true ratio I_1/I_2. The RCF of a current transformer is given by Equation 43.

$$RCF = \frac{I_1/I_2}{\text{Marked Ratio}} \tag{43}$$

The phase angle (β) of a current transformer is the angle between the current leaving the identified secondary terminal and the current entering the identified primary terminal. The phase angle (β) is considered positive if the secondary current leaving the marked terminal leads the primary current entering the marked terminal.

The phase angle correction factor ($PACF$) of a current transformer, like the $PACF$ of a potential transformer, is that factor by which the indicated system power factor on the secondary side of a current transformer must be multiplied to obtain the true system power factor of the load being measured. The $PACF$ of a current transformer is given by

$$\left.\begin{aligned} PACF = K_\beta &= \frac{\cos\theta_p}{\cos\theta_s} && \text{(a)} \\ K_\beta &= \frac{\cos(\theta_s+\beta)}{\cos\theta_s} && \text{(b)} \\ K_\beta &= \frac{\cos\theta_p}{\cos(\theta_p-\beta)} && \text{(c)} \end{aligned}\right\} \quad (44)$$

where

θ_p = true system power factor angle

θ_s = apparent system lagging power factor angle

β = current transformer phase angle, minutes

By following a development similar to that used in the analysis of potential transformers, an approximate expression for the $PACF$ is reached. The approximate expression for $PACF$ is given by Equation 45

$$\left.\begin{aligned} PACF = K_\beta &\approx \left(1-\frac{\beta\tan\theta_s}{3438}\right) && \text{(a)} \\ K_\beta &\approx \left(1-\frac{\beta\tan\theta_p}{3438}\right) && \text{(b)} \end{aligned}\right\} \quad (45)$$

Like the transformer correction factor for a potential transformer, the transformer correction factor for a current transformer is the product of ($PACF$) and (RCF) and is given by Equation 46

$$\left.\begin{aligned} TCF &= (RCF)\ (PACF) = (RCF)\ K_\beta && \text{(a)} \\ TCF &\approx (RCF)\left[1-\frac{\beta\tan\theta_p}{3438}\right] && \text{(b)} \end{aligned}\right\} \quad (46)$$

Table 11—Standard Burdens for Standard 5-Ampere Secondary-Current Transformers*

Designation of Burden	Standard Burden Characteristics		Standard Secondary-Burden Impedance Ohms and Power Factor and Standard Secondary Volt-Ampere Burdens					
			For 60-Cycle and 5-Ampere Secondary Current			For 25-Cycle and 5-Ampere Secondary Current		
	Resistance Ohms	Inductance Millihenrys	Impedance Ohms	Volt Amperes	Power Factor	Impedance Ohms	Volt-Amperes	Power Factor
B-0.1	0.09	0.116	0.1	2.5	0.9	0.0918	2.3	0.98
B-0.2	0.18	0.232	0.2	5.0	0.9	0.1836	4.6	0.98
B-0.5	0.45	0.580	0.5	12.5	0.9	0.4590	11.5	0.98
B-1	0.5	2.3	1.0	25	0.5	0.617	15.4	0.81
B-2	1.0	4.6	2.0	50	0.5	1.234	30.8	0.81
B-4	2.0	9.2	4.0	100	0.5	2.468	61.6	0.81
B-8	4.0	18.4	8.0	200	0.5	4.936	123.2	0.81

*ASA Standard C57.13—1954, Instrument Transformers.

In general, the accuracy of a current transformer depends upon the transformer burden, transformer secondary winding impedance, degree of saturation of the core, and the magnetic properties of the core. Standards of accuracy classification of standard burdens have been established for rating a current transformer with regard to accuracy when operated at rated current and frequency. Due to the differences in accuracy requirements for metering and relaying, current transformer accuracy standards have been established for metering and relaying applications.

Ratings of Current Transformers—The definition of an instrument current transformer in terms of its rating includes: 1) primary and secondary currents; 2) ambients; 3) continuous thermal-current rating factor; 4) insulation class; 5) impulse level in terms of full-wave test voltage; 6) frequency; 7) standard accuracy-class at specified standard burden, current, and frequency; and 8) short-time thermal and short-time mechanical current rating.

Standard primary-current rating, and standard ratios for current transformers are shown in Tables 10(a), (b), and (c). The primary current rating of current transformers should be the lowest standard primary current rating which is equal to or greater than the full load current of the circuit or apparatus to which it is applied.

Standard burdens for 5-ampere secondary, 60 and 25 cycles standard current transformers are expressed in resistance, inductance, impedance, volt-amperes, and power factor. Expressing the burden in terms of impedance rather than in volt-amperes is preferable. The volt-ampere burden is that burden imposed by an impedance Z at rated secondary current or is I^2Z. Standard burdens are shown in Table 11. Standard burdens for metering service are B-0.1, B-0.2 and B-0.5, which are impedances of 90 per cent power factor at 60 cycles of 0.1, 0.2, and 0.5 ohms, respectively. Standard burdens for relaying service are B-1, B-2, B-4, and B-8 which are impedances at 50 per cent power factor at 60 cycles of 1, 2, 4, and 8 ohms, respectively. Standard burdens at all frequencies have the same value of resistance and inductance as shown in Table 11.

Both ratio errors and phase angles may be of importance for metering service. However, such a high degree of accuracy is not required or practicable for relaying

Table 12—Standard Accuracy Classes and Corresponding Limits of Transformer Correction Factors for Current Transformers for Metering Service*

Accuracy Class	Limits of Transformer Correction Factor				Limits of Power Factor (Lagging) of Metered Power Load
	100-Percent Rated Current		10-Percent Rated Current		
	Minimum	Maximum	Minimum	Maximum	
1.2	0.988	1.012	0.976	1.024	0.6–1.0
0.6	0.994	1.006	0.988	1.012	0.6–1.0
0.3	0.997	1.003	0.994	1.006	0.6–1.0
0.5	0.995†	1.005†	0.995	1.005	0.6–1.0

†These values also apply to 150-percent rated current.
*ASA Standard C57.13—1954, Instrument Transformers.

service; therefore, the ratio error, usually being the error of particular interest, is the prime consideration in accuracy classifications for relaying service.

Standard accuracy classes for current transformers and corresponding limits of transformer correction factor (*TCF*) for metering service are shown in Table 12. The true system power factor θ_p is assumed to range from .6 lagging to unity. The standards take into account the effect of phase angle by allowing a larger phase angle when the ratio in error is such that a larger phase angle error may be tolerated to yield the same transformer correction factor. The relationship between the limits of ratio correction factor and phase angles for limiting values of transformer correction factors given in Table 12 are shown in Fig. 52. The *TCF* is given by Equation 46.

$$TCF = (RCF)\ (PACF) = (RCF)\ K_\beta \quad \text{(a)}$$

$$TCF \approx RCF\ \left(1 - \frac{\beta \tan \theta_p}{3438}\right) \quad \text{(b)} \quad (46)$$

where

β = phase angle in minutes

The accuracy standards apply for all currents from 10 per cent to 100 per cent rated. Therefore, the *RCF* and β shall be within the outer and inner parallelograms at 100 and 10 per cent rated current, respectively. Since *RCF* is approximately unity, for any known *RCF*, the positive and negative limiting values of β in minutes can be adequately expressed by Equation 47.

$$\beta = 2600\ (RCF - TCF) \quad (47)$$

The parallelograms are based on this expression rather than the more accurate expression of Equation 44(c.) The limits of *RCF* and β are obtained by applying the limits of system power factor to Equation 44(c.) Therefore, application of a system power factor of 60 per cent in Equation 44(c) results in Equation 48.

$$\text{Cos}\ (53.13° - \beta) = .6\ \frac{RCF}{TCF} \quad (48)$$

27. Final Instrument Transformer Correction Factor

In metering applications involving both potential and current transformers, the apparent power or energy as indicated or registered on a wattmeter or watthour meter must be multiplied by the final transformer correction factor to give the true power or energy. The

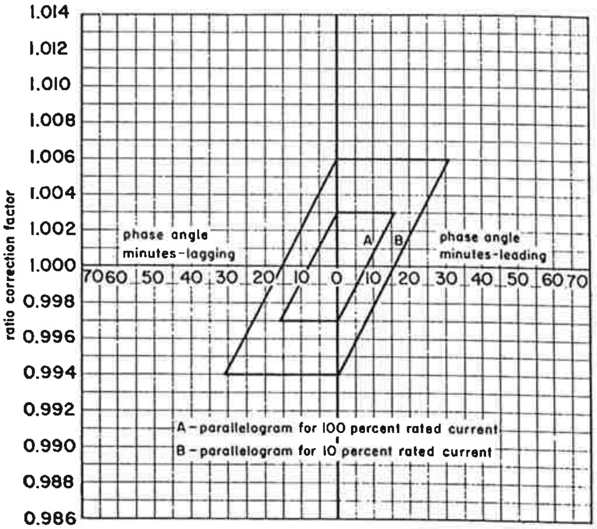


figure 3: Accuracy class 0.3

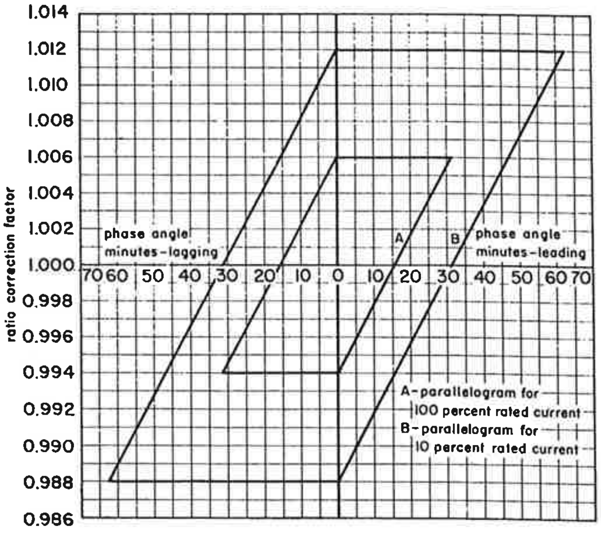


figure 4: Accuracy class 0.6

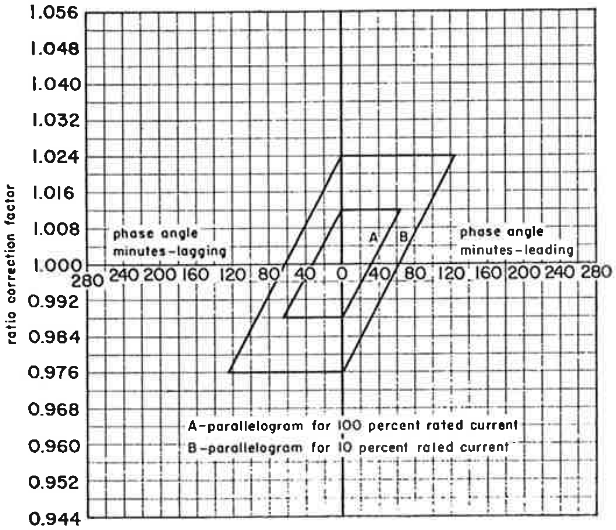


figure 5: Accuracy class 1.2

Fig. 52—Limits of ratio correction factor and phase-angle for standard accuracy classes for current transformers for metering service.

final transformer correction factor is the product of the potential and current transformer ratio correction factors and the combined phase angle correction factor, K_c. Correction must be made for the combined effects of the phase angle of the wattmeter potential circuit and the potential and current transformers, α, γ, and β respectively. In watthour meter applications, no meter potential circuit phase angle is involved and α is zero. The instrument transformer ratio correction factors have been discussed and require no further remarks. However, the combined phase-angle correction factor requires special consideration.

The combined phase angle correction factor is the factor by which the apparent (indicated by the meter) power factor must be multiplied to obtain the true power factor. The true or primary lagging power factor angle is greater than the apparent lagging power factor angle by $(-\alpha+\beta-\gamma)$. As with the (*PACF*) for the individual transformers, the combined (*PACF*) is given by Equation 49.

In the Master Test Code for Electrical Measurements in Power Circuits and the American Standard Code for Electricity Meters, the *PACF* is expressed in terms of θ_s, the apparent power factor of the load as measured on the secondary sides of the transformers involved.

$$PACF = K_c = \frac{\cos\theta}{\cos\theta_2} \qquad \text{(a)}$$

$$= \frac{\cos(\theta_2-\alpha+\beta-\gamma)}{\cos\theta_2} \qquad \text{(b)} \quad (49)$$

$$\approx 1 - \frac{(-\alpha+\beta-\gamma)\tan\theta_s}{3438} \qquad \text{(c)}$$

where

α, β, γ = phase angle of meter potential circuit, current transformer, and potential transformers, respectively in minutes

θ = true system power factor

θ_s = apparent (indicated) system power factor angle

The notations θ and θ_2 of Equation 49 correspond with θ_p, the true system power factor angle, and θ_s, the apparent or indicated system power factor angle, respectively, which have been adopted elsewhere in this chapter. The expressions given in Equations 49(a) and 49(b) are as given in the Master Test Code and the American Standard Code; however, in the American Standard Code, α, the phase angle of the meter potential circuit is not included, since that code applies to watthour meters only.

The instrument transformer final correction factor is given by

Table 13—Standard Insulation Classes and Standard Dielectric Tests for Current Transformers**

Standard Insulation Class (Name-Plate Rating)	Maximum Line-to-Line Voltage	Standard Dielectric Tests			
		Standard Low-Frequency Tests	Standard Impulse Tests		
			Chopped Wave		Full Wave
			Crest Voltage	Minimum Time to Flashover	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
Kv	Kv	Kv Rms	Kv Crest	μ Second	Kv Crest
0.6	0.6	4	12	1.0	10
1.2	1.2	10	36	1.0	30
2.5	2.5	15	54	1.25	45
5.0	5.0	19	69	1.5	60
8.7	8.66	26	88	1.6	75
15 L	15	34	110	1.8	95
15 H	15	34	130	2.0	110
25	25	50	175	3.0	150
34.5	34.5	70	230	3.0	200
46	46	95	290	3.0	250
69	69	140	400	3.0	350
92*	92	185	520	3.0	450
115	115	230	630	3.0	550
138	138	275	750	3.0	650
161	161	325	865	3.0	750
196*	196	395	1035	3.0	900
230	230	460	1210	3.0	1050
287*	287	575	1500	3.0	1300
345*	345	690	1785	3.0	1550

*These system voltages are not in the *EEI-NEMA Preferred Voltage Ratings for A-C Systems and Equipment* report (EEI R-6, NEMA 117).
**ASA Standard C57.13—1954, Instrument Transformers.

$$(TCF)_f = (RCF)_P\,(RCF)_I\,K_c \qquad (50)$$

where

$(RCF)_P$, $(RCF)_I$ = ratio correction factors of potential and current transformers, respectively.

K_c = phase angle correction factor

$$K_c \approx 1 - \frac{(-\alpha+\beta-\gamma)\tan\theta_s}{3438}$$

Since each of the correction factors are usually very near unity, the $(TCF)_f$ is given with sufficient accuracy by

$$(TCF)_f \approx (RCF)_P + (RCF)_I + (K_c) - 2 \qquad (51)$$

28. Insulation Requirements for Instrument Transformers

Modern lines of instrument transformers are rated at definite impulse voltage levels and are given low frequency dielectric tests in line with ASA Standard C-57. However, the insulation class must be coordinated with system connections to avoid dielectric stresses that may result in reduced life expectancy, radio interference, and corona. The manner in which standard insulation class is coordinated with typical system voltages and power transformer connections should be of prime importance in the selection of instrument transformers.

Standard Insulation Classes, Standard Marked Ratios, Standard Primary-Voltage Ratings and Standard Dielectric Tests for Potential Transformers are shown in Table 7. Typical Primary Connections for Potential Transformers which correspond with the groups of Table 7 are shown in Fig. 49. Standard Insulation Classes and Standard Dielectric Tests for Current Transformers are shown in Table 13.

Transformers shown in Table 7 are segregated into three groups of potential transformers designed for specific connections. Transformers in group 1 are designed for operation line-to-line, line-to-neutral, or line-to-ground. Those in group 2 are designed for operation for line-to-line only. Those in group 3 are three-winding transformers, and are designed for connection between line and ground only.

Comparison of standard insulation class and circuit voltages in Table 7 and maximum line-to-line voltage in Table 13 shows that the insulation class in kv to always be greater than the circuit voltage. The circuit voltage in Table 7 is the maximum line-to-line, three-phase voltage. These tables indicate that the maximum continuous operating voltage-to-ground should not exceed the $\frac{\text{insulation class voltage}}{\sqrt{3}}$. Clarification of this rule is discussed in detail with examples in reference 42.

Application of current transformers and potential transformers to some typical system voltages and connections is shown in Table 14. It is by no means complete, but it covers most major applications from 600 volts to 24,000 volts. The table is not extended beyond 24,000 volts, since the examples seem to be typical of the entire range However, lines 6, 22, and 27 are worthy of further mention, because such are special applications for potential transformers. Potential transformers in these applications are principally for ground fault detection. In case of ground fault, the voltage across the transformer on the faulted phase collapses, and the other two transformers swing into open delta from line-to-line, and have the applied voltages increase by $\sqrt{3}$. The potential transformers on lines 6 and 22 are normally applied at reduced voltage, while the transformer in line 27 is a standard design operating at low enough induction to operate continuously at $\sqrt{3}$ times normal voltage.

If a transformer is operated at excessive voltage-to-ground, failure of the transformer may result in either of two ways: 1) by destruction of the insulation due to corona or dielectric heating; and 2) by lightning. Although the lightning arresters may adequately protect other insulation on a part of the system, they may offer inadequate protection for a transformer in a standard insulation class less than that applied on other related apparatus.

Application of current transformers in the neutral of grounded wye-connected transformers justify special consideration, because reduced insulation may be applicable in the neutral transformer. Minimum Insulation Class for current transformers in the neutral grounding connection is shown in Table 15. Full insulation is required on applications in which the standard insulation class of the line is less than 15 kv.

29. General Application Data for Instrument Transformers

Much of the data required for application of instrument transformers has been discussed in connection with the transformer ratings and insulation requirements. Most of the rating data is also general application data. However, the accuracy standards are for rating purposes only and may not be suitable for practical metering application. Also, other topics such as operating limitations, determination of burdens, and polarity identification are of prime importance in applications of instrument transformers.

Accuracies of Instrument Transformers in Metering Applications—The standards burdens and accuracy rating standards of instrument transformers are for rating purposes only. In metering applications, the established tolerances in metering apply equally well to metering involving instrument transformers and self-contained metering. The tolerances include the instrument transformer errors. In calibration of transformer rated meter applications, the watthour meter is calibrated for application with the particular instrument transformer with which it is used. The meter is calibrated at the tests normally given self-contained meters. The final instrument transformer correction factors for the test conditions are determined first. Using the transformer correction factors as a reference, the watthour meter is calibrated so that the overall accuracy of the meter and instrument transformers is within the required tolerance.

Accuracy certificates for a particular instrument transformer at the standard burdens are available from the manufacturer. Typical characteristics are shown in Fig. 53. The variation in accuracy characteristics with burden and burden power factor can be evaluated from

Table 14—Application of Potential and Current Transformers to Some Typical Operating Circuit Voltages

Line No.	System Line-to-Line Voltage	Circuit Connections: see Figure:	ASA Insulation Class and FWI Levels Required by Circuit		Application of Standard Instrument Transformer to Circuit as Indicated		
						Potential Transformers	
			Kv Class (1)	Impulse Levels Full Wave: Kv	Current Transformers: Kv Class	Rating	Type of Application for Metering or Relaying
1	600	(a)	1.2	30	1.2	600/1040 Y	in delta (2)
2	600	(c)	1.2	30	1.2	600/1040 Y	line to grd.
3	1040	(b)	1.2	30	1.2	600/1040 Y	line to neutral
4	1040	(b)	1.2	30	1.2	1040/1040 Y	in delta (3)
5	2400	(a)	2.5	45	2.5	2400/2400 Y	in delta (4)
6	2400	(a)	2.5	45	2.5	2400/2400 Y	in wye to grd. (5)
7	2400	(c)	5.0	60	5.0	2400/4160 Y	line to grd (6)
8	4160	(a)	5.0	60	5.0	4800/4800 Y or	in delta (4)
9						4200/7280 Y (7)	in delta
10	4800	(a)	5.0	60	5.0	4800/4800 Y or	in delta (4)
11						4800/8320 Y (7)	in delta
12	4160	(b)	5.0	60	5.0	2400/4160 Y	line to neutral
13	4160	(b)	5.0	60	5.0	same as lines 8 and 9	
14	4800	(b)	5.0	60	5.0	same as lines 10 and 11	
15	4800	(c)	8.7	75	8.7	4800/8320 Y	line to grd. (6)
16	7200	(a)	8.7	75	8.7	7200/7200 Y or	in delta (4)
17						7200/12470Y (7)	in delta
18	7200	(b)	8.7	75	8.7	4200/7280 Y	in wye
19	7200	(b)	8.7	75	8.7	7200/7200 Y	in delta (4)
20	7200	(c)	15	95 or 110	15	7200/12470 Y	line to grd. (6)
21	12000	(a)	15	95 or 110	15	12000/12000 Y	in delta (4)
22	12000	(a)	15	95 or 110	15	12000/12000 Y	in wye to grd. (5)
23	12000	(b)	15	95 or 110	15	12000/12000 Y	in delta (4)
24	12000	(b)	15	95 or 100	15	7200/12470 Y	in wye
25	12000	(c)	25	150	25	12000/20800 Y (8)	line to grd. (6)
26	24000	(a)	25	150	25	24000/24000 Y	in delta (4)
27	24000	(a)	25	150	25	14400 for 25000 grd. Y	in wye, line to grd. for relaying grd. fault on an ungrounded system (9)
28	24000	(b)	25	150	25	24000/240000 Y	in delta

(1) The standard insulation class in kv is not the maximum continuous operating voltage to ground; this value is $\frac{\text{standard insulation class kv}}{\sqrt{3}}$ = maximum continuous operating voltage to ground. Operation in excess of this value is limited by dielectric over-stress of the insulation which may result in corona, radio influence and deterioration of insulation. Usually it is permissible, considering the above factors, to operate a system under emergency conditions for periods of time without failure but with some sacrifice in life expectancy.

example: A 24,000-volt, 3-phase, 3-wire ungrounded system on which one phase may become grounded.

(2) In this application, since the transformer is designed for application in wye, this circuit could be operated with any corner of the delta permanently grounded without any sacrifice in life expectancy of these transformers, though other apparatus on the system might be affected by such operation.

(3) Special transformer.

(4) In this application, the transformers are not good for operation in wye; therefore, note (2) does not apply, but note (1) does.

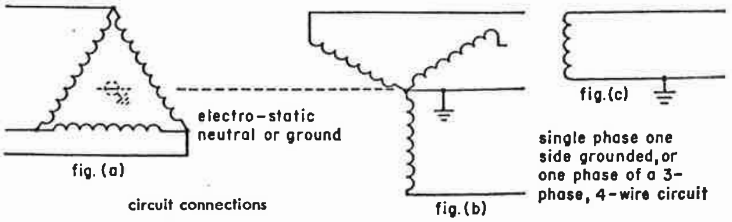
(5) These applications and similar applications to other circuits are for ground fault detection. Normal operation is at reduced induction (voltage); however, a phase fault to ground places $\sqrt{3}$ times greater voltage and dielectric stress on the two voltage transformers on the unfaulted phases. Since the transformers under fault condition to the ground are operating at normal voltage, the application is satisfactory; however, the insulation to ground is over-stressed for continuous operation. See note (9) (b).

(6) This is a common single-phase application to rural single-phase lines or railway lines where one side of the circuit is grounded. If one side of the circuit were not grounded, the next lower class of insulation could be used.

(7) This unit is over-insulated but is a stock rating that would be applied normally.

(8) This is a special design with 25-kv class insulation.

(9) Note that in this application: (a) transformers of standard design may be used; they are designed to operate on an emergency basis with $\sqrt{3}$ times normal voltage across the terminals; (b) the insulation class is not increased, which indicates this is not a continuous operating condition. Note the applications in lines 6 and 22 are similar applications using standard transformers with reduced voltage across the winding.



the accuracy certificates. The variation in the RCF and phase angle with burden and burden power factor may be so small as to be constant. Also, the errors might be negligible. Also, the particular burden may be sufficiently close to a standard burden that the accuracy under the particular burden may be estimated with sufficient accuracy. However, determining the accuracies of a particular burden may be necessary. Since the ratio correction factor (RCF) and phase angle, γ, of potential transformers for a specific burden are linear functions of burden, the characteristics at a particular burden can be determined from the characteristics at a standard burden. However, such is not the case with current transformers. The characteristics of a current transformer at a particular burden and current require certain tests on the transformer. The potential transformer is considered first. Having determined the particular burden imposed on the potential transformer, the (RCF) and phase angle can be determined from Equation 50.

$$R_x = R_b \cos(\theta_b - \theta_x) + \frac{P_b}{3438} \sin(\theta_b - \theta_x) \qquad \text{(a)}$$

$$(50)$$

$$P_x = P_b \cos(\theta_b - \theta_x) - 3438\ R_b \sin(\theta_b - \theta_x) \qquad \text{(b)}$$

where

R_x = the change in ratio error from zero to 100 per cent secondary burden at the new burden power factor, per unit.

P_x = the change in phase angle from zero to 100 per cent secondary burden at the new burden power factor, minutes.

θ_x = lagging power factor angle of new burden. (The sign of θ_x is "+" for lagging power factor burdens.)

R_b = the change in ratio error from zero to 100 per cent secondary burden at the power factor for which the characteristics are given on typical curves, per unit.

P_b = the change in phase angle from zero to 100 per cent secondary burden at the power factor for which the characteristics are given on typical curves, minutes.

θ_b = lagging power factor angle for burdens represented in typical characteristics curves. (The sign of θ_b is "+" for lagging power factor burdens.)

The errors present in a transformer at no load are due to the exciting current drawn. Therefore, all RCF vs. per cent secondary burden curves for all power factors pass through the same point at zero burden. Also, all phase angle vs. per cent secondary burden curves for all power factors pass through the same point at zero burden.

Since the ratio correction factor and phase angle characteristics of a current transformer are not linear, it is not practical to determine these characteristics at a particular burden from the known characteristics at a standard burden. Determining the characteristics for a current transformer requires tests on the transformer at the particular burden.[43, 44] Various methods are applicable to calibrating current transformers; however, most methods require special equipment. A simple method for determining the ratio error and phase angle of a current transformer is discussed in reference 43. This method requires determining the open-circuit voltage as a function of the components of exciting current, the transformer secondary leakage reactance and resistance, and the exact turns ratio. The characteristics derived by this method agree reasonably well for metering purposes with characteristics determined from more expensive tests.

Table 15—Minimum Insulation Class for Current Transformers in the Neutral Grounding Connection*

Winding Insulation Class at Line End	Minimum Insulation Class Grounded Solidly or Through Current Transformer
Col. 1	Col. 2
Kv	Kv
1.2	Same as line end
2.5	
5.0	
8.66	
15	8.66
25	8.66
34.5	8.66
46	15
69	15
92	15
115	15
138	15
161	15
196	15
230	15
287	15
345	15

*ASA Standard C57.13—1954, Instrument Transformers.

Correction Factors—Phase-angle, (*PACF*), ratio (*RCF*), and transformer (*TCF*) are discussed at length under "Errors . . ." for both potential and current transformers. The discussions are summarized here for reference purposes, in the applications of instrument transformers.

Ratio Correction Factor (*RCF*)

$$\text{for } PT\text{'s } (RCF)_p = \frac{V_1/V_2}{\text{Marked Ratio}} \tag{38}$$

$$\text{for } CT\text{'s } (RCF)_I = \frac{I_1/I_2}{\text{Marked Ratio}} \tag{43}$$

Phase-Angle Correction Factor, (*PACF*)

$$\text{for } PT\text{'s } (PACF)_p = K_\gamma \approx \left(1 + \frac{\gamma \tan \theta_s}{3438}\right) \tag{40a}$$

$$K_\gamma \approx \left(1 + \frac{\gamma \tan \theta_p}{3438}\right) \tag{40b}$$

$$\text{for } CT\text{'s } (PACF)_I = K_\beta \approx \left(1 - \frac{\beta \tan \theta_s}{3438}\right) \tag{45a}$$

$$K_\beta \approx \left(1 - \frac{\beta \tan \theta_p}{3438}\right) \tag{45b}$$

for both *PT*'s, *CT*'s and instrument combined

$$PACF = K_c \approx 1 - \frac{(-\alpha + \beta - \gamma)}{3438} \tan \theta_s \tag{49}$$

where α = phase angle of instrument potential circuit

Transformer Correction Factors (*TCF*)

$$\text{for } PT\text{'s } \quad (TCF)_p = (RCF)_p K_\gamma$$

$$\approx (RCF)_p \left(1 + \frac{\gamma \tan \theta_s}{3438}\right) \tag{41d}$$

$$\approx (RCF)_p \left(1 + \frac{\gamma \tan \theta_p}{3438}\right) \tag{41e}$$

$$\text{for } CT\text{'s } \quad (TCF)_I = (RCF)_I K_\beta$$

$$\approx (RCF)_I \left(1 - \frac{\beta \tan \theta_s}{3438}\right) \tag{45a}$$

$$\approx (RCF)_I \left(1 - \frac{\beta \tan \theta_p}{3438}\right) \tag{45b}$$

Final $(TCF)_f$, combined *PT*'s and *CT*'s

$$(TCF)_f = (RCF)_p (RCF)_I K_c \tag{50}$$

or

$$(TCF)_f \approx (RCF)_p + (RCF)_I + K_c - 2 \tag{51}$$

where γ, β = phase-angle, minutes of *PT* and *CT*, respectively

θ_s = apparent (indicated) lagging load power-factor angle.

Instrument transformer phase-angle correction factors are given in Table 16 for various phase-angles $(-\alpha+\beta-\gamma)$ and apparent load power-factors, where α is the phase angle of the instrument potential circuit. For only *PT*'s or *CT*'s, consider only the phase angle of the transformer involved; consider the phase angle of the transformer or instrument not involved as zero. For watthour meters, α is zero. Transformer correction factors for *PT*'s and *CT*'s are shown in Tables 17(a) and 17(b), respectively.[40] Table 17(b) is also applicable to the final $(TCF)_t$ if the *RCF* is equal to either $[(RCF)_P \times (RCF)_I]$ or $[(RCF)_P+(RCF)_I-1]$ and β which is shown is considered as $(\beta-\gamma)$.

Determining PT Burden The burden on a potential transformer is the total load on the transformer. If the effects of the secondary leads are neglected, the burden on potential transformer is composed of instruments or relays in parallel. Additional burdens are added in parallel. The resulting total burden is most easily calculated by determining the total watts burden and total reactive volt-amperes burden separately, and then determining the resultant burden in volt-amperes by Equation 52.

$$\text{total burden (volt-amperes)} = \sqrt{(\text{total watts})^2+(\text{total reactive volt-amperes})^2} \quad \text{(a)}$$

$$\text{power factor of burden} = \frac{\text{total watts}}{\text{total burden (volt-amperes)}} \quad \text{(b)} \qquad (52)$$

By referring to typical ratio and phase angle curves supplied by the manufacturer for the transformer in question, the performance at the above burden may be determined.

However, if the instruments are located a considerable distance from the transformer, the secondary leads may have sufficient impedance to introduce an additional voltage drop and phase shift in the voltage. If the impedance of the secondary leads are in series with the circuit which is composed of instruments in parallel and the resistance of the secondary leads is greater than .0005 times the resistance of the watt element of the total instrument burden $\left(R=\frac{E^2}{\text{watts}}\right)$, the additional per cent ratio and phase angle applicable to a typical curve should be calculated from application of Equation 53.

$$\text{Increase in per cent ratio} = \frac{I_s(R_L\cos\theta+X_L\sin\theta)}{E_s}\times 100 \quad \text{(a)}$$

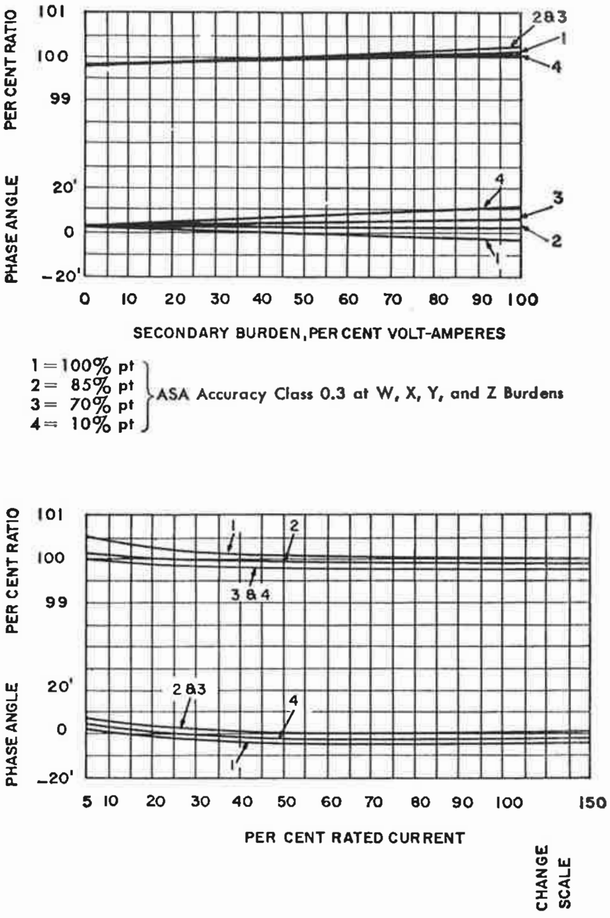
$$(53)$$

$$\text{Increase in phase angle} = \frac{I_s\,(R_L\sin\theta-X_L\cos\theta)}{E_s}\times 3438 \text{ minutes} \quad \text{(b)}$$

Where

θ = total burden power factor angle
R_L = resistance of secondary leads, ohms
X_L = reactance of secondary lead, ohms
I_S = potential transformer secondary current
E_S = potential transformer secondary voltage

The increase in per cent ratio and phase angle as determined from Equation 53 is added algebraically to the respective potential transformer calibration curves to get the actual per cent ratio of primary to burden voltage and the actual phase difference between primary and burden voltages.



1 = 2.0r, .50 pt, 50 VA at 5 amperes
2 = 0.5r, .90 pt, 12.5 VA at 5 amperes
3 = 0.2r, .90 pt, 5.0 VA at 5 amperes
4 = 0.1r, .90 pt, 2.5 VA at 5 amperes

Fig. 53—Typical accuracy characteristics from accuracy certificates of instrument transformers (a) Potential transformer, (b) Current transformer.

The single-phase burdens imposed on potential transformers by typical instruments and meters are shown in Table 18. The devices included in Table 18 are supplied by Westinghouse, but the values are representative for each particular type of device. Where a high degree of accuracy is required, the actual burden imposed by the particular device must be considered.

Polyphase connections are so varied that it is difficult to give specific instructions for calculation of polyphase burdens. Generally, the procedure will be to calculate the phase position and magnitude of the current in each transformer and determine what equivalent single-phase burden would require the same current. The performance is then determined for the equivalent single-phase burden which would require the same current.

Table 16(a)—Instrument Transformer

CORRECTION FACTORS $\left(\frac{\cos\theta}{\cos\theta_2}\right)$ FOR PHASE ANGLES

For Lagging Current When $(-\alpha+\beta-\gamma)$ Is Positive
For Leading Current When $(-\alpha+\beta-\gamma)$ Is Negative

Phase-angle $(-\alpha+\beta-\gamma)$	Apparent Power Factor (Cos θ_2) †													
	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95	0.99	1.00
5′	0.9855	0.9904	0.9929	0.9944	0.9954	0.9967	0.9975	0.9981	0.9985	0.9989	0.9993	0.9995	0.9998	1.0000
10′	0.9711	0.9808	0.9857	0.9887	0.9907	0.9933	0.9950	0.9961	0.9970	0.9978	0.9986	0.9990	0.9996	1.0000
15′	0.9566	0.9712	0.9786	0.9831	0.9861	0.9900	0.9924	0.9942	0.9955	0.9967	0.9979	0.9986	0.9994	1.0000
20′	0.9421	0.9616	0.9715	0.9775	0.9815	0.9867	0.9899	0.9922	0.9940	0.9956	0.9972	0.9981	0.9992	1.0000
25′	0.9276	0.9520	0.9643	0.9718	0.9768	0.9833	0.9874	0.9903	0.9926	0.9945	0.9965	0.9976	0.9989	1.0000
30′	0.9131	0.9424	0.9572	0.9662	0.9722	0.9800	0.9848	0.9883	0.9911	0.9934	0.9957	0.9971	0.9987	1.0000
40′	0.8842	0.9232	0.9429	0.9549	0.9629	0.9733	0.9798	0.9844	0.9881	0.9912	0.9943	0.9961	0.9983	0.9999
50′	0.8552	0.9040	0.9286	0.9436	0.9536	0.9666	0.9747	0.9805	0.9851	0.9890	0.9929	0.9951	0.9978	0.9999
1° 0′	0.8262	0.8848	0.9143	0.9323	0.9444	0.9599	0.9696	0.9766	0.9820	0.9868	0.9914	0.9941	0.9974	0.9998
10′	0.7972	0.8656	0.9000	0.9209	0.9350	0.9531	0.9645	0.9726	0.9790	0.9845	0.9899	0.9931	0.9969	0.9998
20′	0.7682	0.8464	0.8857	0.9096	0.9257	0.9464	0.9594	0.9687	0.9760	0.9823	0.9885	0.9921	0.9964	0.9997
30′	0.7392	0.8271	0.8714	0.8983	0.9164	0.9397	0.9543	0.9648	0.9730	0.9800	0.9870	0.9911	0.9959	0.9997
40′	0.7102	0.8079	0.8571	0.8869	0.9071	0.9329	0.9492	0.9608	0.9699	0.9778	0.9855	0.9900	0.9954	0.9996
50′	0.6812	0.7886	0.8428	0.8756	0.8978	0.9262	0.9441	0.9568	0.9668	0.9755	0.9840	0.9890	0.9949	0.9995
2° 0′	0.6521	0.7694	0.8284	0.8642	0.8884	0.9194	0.9389	0.9529	0.9638	0.9732	0.9825	0.9879	0.9944	0.9994
10′	0.6231	0.7501	0.8141	0.8529	0.8791	0.9127	0.9338	0.9489	0.9607	0.9709	0.9810	0.9869	0.9939	0.9993
20′	0.5941	0.7308	0.7997	0.8415	0.8697	0.9059	0.9287	0.9449	0.9576	0.9686	0.9795	0.9858	0.9934	0.9992
30′	0.5650	0.7115	0.7854	0.8301	0.8603	0.8991	0.9235	0.9409	0.9545	0.9663	0.9779	0.9847	0.9928	0.9990
40′	0.5360	0.6923	0.7710	0.8187	0.8510	0.8923	0.9183	0.9369	0.9515	0.9640	0.9764	0.9836	0.9923	0.9989
50′	0.5069	0.6730	0.7566	0.8073	0.8416	0.8855	0.9132	0.9329	0.9483	0.9617	0.9748	0.9825	0.9917	0.9988
3° 0′	0.4779	0.6537	0.7422	0.7959	0.8322	0.8787	0.9080	0.9288	0.9452	0.9594	0.9733	0.9814	0.9912	0.9986
10′	0.4488	0.6344	0.7279	0.7845	0.8228	0.8719	0.9028	0.9248	0.9421	0.9570	0.9717	0.9803	0.9906	0.9985
20′	0.4198	0.6151	0.7135	0.7731	0.8134	0.8651	0.8976	0.9208	0.9390	0.9547	0.9701	0.9792	0.9900	0.9983
30′	0.3907	0.5957	0.6991	0.7617	0.8040	0.8583	0.8924	0.9167	0.9359	0.9523	0.9686	0.9781	0.9894	0.9981
40′	0.3616	0.5764	0.6847	0.7503	0.7946	0.8514	0.8872	0.9127	0.9327	0.9500	0.9670	0.9769	0.9888	0.9980
50′	0.3326	0.5571	0.6702	0.7388	0.7852	0.8446	0.8820	0.9086	0.9296	0.9476	0.9654	0.9758	0.9882	0.9978
4° 0′	0.3035	0.5378	0.6558	0.7274	0.7758	0.8377	0.8767	0.9046	0.9264	0.9452	0.9638	0.9746	0.9876	0.9976
10′	0.2744	0.5185	0.6414	0.7160	0.7663	0.8309	0.8715	0.9005	0.9232	0.9429	0.9622	0.9735	0.9870	0.9974
20′	0.2453	0.4991	0.6270	0.7045	0.7569	0.8240	0.8663	0.8964	0.9201	0.9405	0.9605	0.9723	0.9864	0.9971
30′	0.2163	0.4798	0.6125	0.6930	0.7474	0.8171	0.8610	0.8923	0.9169	0.9381	0.9589	0.9711	0.9857	0.9969
40′	0.1872	0.4604	0.5981	0.6816	0.7380	0.8103	0.8558	0.8882	0.9137	0.9357	0.9573	0.9699	0.9851	0.9967
50′	0.1581	0.4411	0.5837	0.6701	0.7285	0.8034	0.8505	0.8841	0.9105	0.9333	0.9556	0.9687	0.9844	0.9964
5° 0′	0.1290	0.4217	0.5692	0.6586	0.7191	0.7965	0.8452	0.8800	0.9073	0.9308	0.9540	0.9675	0.9838	0.9962
10′	0.0999	0.4024	0.5548	0.6472	0.7096	0.7896	0.8400	0.8759	0.9041	0.9284	0.9523	0.9663	0.9831	0.9959
20′	0.0708	0.3830	0.5403	0.6357	0.7001	0.7827	0.8347	0.8717	0.9008	0.9260	0.9507	0.9651	0.9824	0.9957

Interpolation for correction factors corresponding to values $(-\alpha+\beta-\gamma)$ lying between those given in the table, may be made without error. Interpolation for correction factors corresponding to values of cos θ_2 lying between those given in the table, may be made without exceeding an error of 0.0010 in the sections of the tables lying between the heavy black lines; outside of these sections, and in all cases where the adjacent values of cos θ_2 are separated by the heavy black lines the maximum error in interpolation will exceed 0.0010.

ACCORDING TO ASA STANDARDS:

α IS POSITIVE WHEN THE CURRENT IN THE WATTMETER POTENTIAL CIRCUIT LEADS THE VOLTAGE.

β IS POSITIVE WHEN THE SECONDARY CURRENT LEADS THE PRIMARY CURRENT.

γ IS POSITIVE WHEN THE SECONDARY VOLTAGE LEADS THE PRIMARY VOLTAGE.

† IN THE CASE OF POLYPHASE MEASUREMENTS, THE METER OR ELEMENT IN EACH PHASE MUST BE CORRECTED SEPARATELY, CONSIDERING θ AS THE ANGLE BETWEEN THE VOLTAGE AND CURRENT ON THE METER OR ELEMENT BEING CORRECTED (NOT THE ANGLE REPRESENTED BY THE POLYPHASE POWER FACTOR).

Table 16(b) Instrument Transformer

Correction Factors $\left(\frac{\cos\theta}{\cos\theta_2}\right)$ For Phase Angles

For Lagging Current When $(-\alpha+\beta-\gamma)$ Is Negative
For Leading Current When $(-\alpha+\beta-\gamma)$ Is Positive

Phase-angle $(-\alpha+\beta-\gamma)$	Apparent Power Factor ($\cos\theta_2$) †													
	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95	0.99	1.00
5′	1.0145	1.0096	1.0071	1.0056	1.0046	1.0033	1.0025	1.0019	1.0015	1.0011	1.0007	1.0005	1.0002	1.0000
10′	1.0289	1.0192	1.0142	1.0113	1.0092	1.0067	1.0050	1.0039	1.0030	1.0022	1.0014	1.0010	1.0004	1.0000
15′	1.0434	1.0288	1.0214	1.0169	1.0139	1.0100	1.0075	1.0058	1.0044	1.0033	1.0021	1.0014	1.0006	1.0000
20′	1.0579	1.0383	1.0285	1.0225	1.0185	1.0133	1.0101	1.0077	1.0059	1.0043	1.0028	1.0019	1.0008	1.0000
25′	1.0723	1.0479	1.0356	1.0281	1.0231	1.0166	1.0126	1.0097	1.0074	1.0054	1.0035	1.0024	1.0010	1.0000
30′	1.0868	1.0575	1.0427	1.0338	1.0277	1.0200	1.0151	1.0116	1.0089	1.0065	1.0042	1.0028	1.0012	1.0000
40′	1.1157	1.0766	1.0569	1.0450	1.0369	1.0266	1.0201	1.0154	1.0118	1.0087	1.0056	1.0038	1.0016	0.9999
50′	1.1446	1.0958	1.0711	1.0562	1.0461	1.0332	1.0251	1.0193	1.0147	1.0108	1.0069	1.0047	1.0020	0.9999
1° 0′	1.1735	1.1149	1.0853	1.0674	1.0553	1.0398	1.0301	1.0231	1.0177	1.0129	1.0083	1.0056	1.0023	0.9998
10′	1.2024	1.1340	1.0995	1.0787	1.0645	1.0464	1.0351	1.0269	1.0206	1.0151	1.0097	1.0065	1.0027	0.9998
20′	1.2313	1.1531	1.1137	1.0898	1.0737	1.0530	1.0400	1.0308	1.0235	1.0172	1.0110	1.0074	1.0030	0.9997
30′	1.2601	1.1722	1.1279	1.1010	1.0829	1.0596	1.0450	1.0346	1.0264	1.0193	1.0123	1.0083	1.0034	0.9997
40′	1.2890	1.1913	1.1421	1.1122	1.0921	1.0662	1.0500	1.0384	1.0292	1.0214	1.0137	1.0091	1.0037	0.9996
50′	1.3178	1.2104	1.1562	1.1234	1.1012	1.0728	1.0549	1.0421	1.0321	1.0235	1.0150	1.0100	1.0040	0.9995
2° 0′	1.3466	1.2294	1.1704	1.1346	1.1104	1.0794	1.0598	1.0459	1.0350	1.0256	1.0163	1.0109	1.0044	0.9994
10′	1.3755	1.2485	1.1845	1.1457	1.1195	1.0859	1.0648	1.0497	1.0379	1.0276	1.0176	1.0117	1.0047	0.9993
20′	1.4043	1.2675	1.1986	1.1569	1.1286	1.0925	1.0697	1.0535	1.0407	1.0297	1.0189	1.0126	1.0050	0.9992
30′	1.4331	1.2866	1.2127	1.1680	1.1377	1.0990	1.0746	1.0572	1.0435	1.0318	1.0202	1.0134	1.0053	0.9990
40′	1.4618	1.3056	1.2268	1.1791	1.1469	1.1055	1.0795	1.0610	1.0464	1.0338	1.0215	1.0142	1.0055	0.9989
50′	1.4906	1.3246	1.2409	1.1902	1.1560	1.1120	1.0844	1.0647	1.0490	1.0359	1.0227	1.0150	1.0058	0.9988
3° 0′	1.5194	1.3436	1.2550	1.2013	1.1650	1.1185	1.0893	1.0684	1.0520	1.0379	1.0240	1.0158	1.0061	0.9986
10′	1.5481	1.3626	1.2691	1.2124	1.1741	1.1250	1.0942	1.0721	1.0548	1.0399	1.0252	1.0166	1.0063	0.9985
20′	1.5768	1.3816	1.2832	1.2235	1.1832	1.1315	1.0990	1.0758	1.0576	1.0419	1.0265	1.0174	1.0066	0.9983
30′	1.6056	1.4005	1.2972	1.2346	1.1923	1.1380	1.1039	1.0795	1.0604	1.0439	1.0277	1.0182	1.0068	0.9981
40′	1.6343	1.4195	1.3113	1.2456	1.2013	1.1445	1.1087	1.0832	1.0632	1.0459	1.0289	1.0190	1.0071	0.9980
50′	1.6630	1.4384	1.3253	1.2567	1.2103	1.1509	1.1136	1.0869	1.0660	1.0479	1.0301	1.0197	1.0073	0.9978
4° 0′	1.6916	1.4573	1.3393	1.2677	1.2194	1.1574	1.1184	1.0906	1.0687	1.0499	1.0313	1.0205	1.0075	0.9976
10′	1.7203	1.4763	1.3533	1.2788	1.2284	1.1638	1.1232	1.0942	1.0715	1.0519	1.0325	1.0212	1.0077	0.9974
20′	1.7489	1.4952	1.3673	1.2898	1.2374	1.1703	1.1280	1.0979	1.0742	1.0538	1.0337	1.0220	1.0079	0.9971
30′	1.7776	1.5141	1.3813	1.3008	1.2464	1.1767	1.1328	1.1015	1.0770	1.0558	1.0349	1.0227	1.0081	0.9969
40′	1.8062	1.5329	1.3953	1.3118	1.2554	1.1831	1.1376	1.1052	1.0797	1.0577	1.0361	1.0234	1.0083	0.9967
50′	1.8348	1.5518	1.4092	1.3228	1.2644	1.1895	1.1424	1.1088	1.0824	1.0596	1.0373	1.0241	1.0085	0.9964
5° 0′	1.8634	1.5707	1.4232	1.3337	1.2733	1.1959	1.1472	1.1124	1.0851	1.0616	1.0384	1.0248	1.0086	0.9962
10′	1.8920	1.5895	1.4371	1.3447	1.2823	1.2023	1.1519	1.1160	1.0878	1.0635	1.0396	1.0255	1.0088	0.9959
20′	1.9205	1.6083	1.4510	1.3557	1.2912	1.2086	1.1567	1.1196	1.0905	1.0654	1.0407	1.0262	1.0089	0.9957

Interpolation for correction factors corresponding to values $(-\alpha+\beta-\gamma)$ lying between those given in the table, may be made without error. Interpolation for correction factors corresponding to values of $\cos\theta_2$ lying between those given in the table, may be made without exceeding an error of 0.0010 in the sections of the tables lying between the heavy black lines; outside of these sections, and in all cases where the adjacent values of $\cos\theta_2$ are separated by the heavy black lines the maximum error in interpolation will exceed 0.0010.

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† IN THE CASE OF POLYPHASE MEASUREMENTS, THE METER OR ELEMENT IN EACH PHASE MUST BE CORRECTED SEPARATELY, CONSIDERING θ AS THE ANGLE BETWEEN THE VOLTAGE AND CURRENT ON THE METER OR ELEMENT BEING CORRECTED (NOT THE ANGLE REPRESENTED BY THE POLYPHASE POWER FACTOR).

Table 17(a)—Instrument Potential Transformer—Transformer Correction Factors

Ratio Correction Factor (RCF)	Phase Angle γ	Transformer Correction Factor (TCF)				
		Power Factor of Metered Load—Lagging				
		0.6	0.7	0.8	0.9	1.0
0.995	−15′	0.9892	0.9905	0.9917	0.9929	0.9950
	−10′	0.9911	0.9920	0.9928	0.9936	0.9950
	− 5′	0.9931	0.9935	0.9939	0.9943	0.9950
	− 2′	0.9942	0.9944	0.9946	0.9947	0.9950
	0′	0.9950	0.9950	0.9950	0.9950	0.9950
	+ 2′	0.9958	0.9956	0.9954	0.9953	0.9950
	+ 5′	0.9969	0.9965	0.9961	0.9957	0.9950
	+10′	0.9989	0.9980	0.9972	0.9964	0.9950
	+15′	1.0008	0.9994	0.9983	0.9971	0.9950
	+20′	1.0027	1.0009	0.9993	0.9978	0.9950
	+30′	1.0065	1.0039	1.0015	0.9992	0.9950
0.996	−15′	0.9902	0.9915	0.9927	0.9939	0.9960
	−10′	0.9921	0.9930	0.9938	0.9946	0.9960
	− 5′	0.9941	0.9945	0.9949	0.9953	0.9960
	− 2′	0.9952	0.9954	0.9956	0.9957	0.9960
	0′	0.9960	0.9960	0.9960	0.9960	0.9960
	+ 2′	0.9968	0.9966	0.9964	0.9963	0.9960
	+ 5′	0.9979	0.9975	0.9971	0.9967	0.9960
	+10′	0.9999	0.9990	0.9982	0.9974	0.9960
	+15′	1.0018	1.0004	0.9993	0.9981	0.9960
	+20′	1.0037	1.0019	1.0003	0.9988	0.9960
	+30′	1.0076	1.0049	1.0025	1.0002	0.9960
0.997	−15′	0.9912	0.9925	0.9937	0.9949	0.9970
	−10′	0.9931	0.9940	0.9948	0.9956	0.9970
	− 5′	0.9951	0.9955	0.9959	0.9963	0.9970
	− 2′	0.9962	0.9964	0.9966	0.9967	0.9970
	0′	0.9970	0.9970	0.9970	0.9970	0.9970
	+ 2′	0.9978	0.9976	0.9974	0.9973	0.9970
	+ 5′	0.9989	0.9985	0.9981	0.9977	0.9970
	+10′	1.0009	1.0000	0.9992	0.9984	0.9970
	+15′	1.0028	1.0014	1.0003	0.9991	0.9970
	+20′	1.0047	1.0029	1.0013	0.9998	0.9970
	+30′	1.0086	1.0059	1.0035	1.0012	0.9970
0.998	−15′	0.9922	0.9935	0.9947	0.9959	0.9980
	−10′	0.9941	0.9950	0.9958	0.9966	0.9980
	− 5′	0.9961	0.9965	0.9969	0.9973	0.9980
	− 2′	0.9972	0.9974	0.9976	0.9977	0.9980
	0′	0.9980	0.9980	0.9980	0.9980	0.9980
	+ 2′	0.9988	0.9986	0.9984	0.9983	0.9980
	+ 5′	0.9999	0.9995	0.9991	0.9987	0.9980
	+10′	1.0019	1.0010	1.0002	0.9994	0.9980
	+15′	1.0038	1.0024	1.0013	1.0001	0.9980
	+20′	1.0057	1.0039	1.0023	1.0008	0.9980
	+30′	1.0096	1.0069	1.0045	1.0022	0.9980
0.999	−15′	0.9932	0.9945	0.9957	0.9969	0.9990
	−10′	0.9951	0.9960	0.9968	0.9976	0.9990
	− 5′	0.9971	0.9975	0.9979	0.9983	0.9990
	− 2′	0.9982	0.9984	0.9986	0.9987	0.9990
	0′	0.9990	0.9990	0.9990	0.9990	0.9990
	+ 2′	0.9998	0.9996	0.9994	0.9993	0.9990
	+ 5′	1.0009	1.0005	1.0001	0.9997	0.9990
	+10′	1.0029	1.0020	1.0012	1.0004	0.9990
	+15′	1.0048	1.0034	1.0023	1.0011	0.9990
	+20′	1.0067	1.0049	1.0033	1.0018	0.9990
	+30′	1.0106	1.0079	1.0055	1.0032	0.9990
1.000	−15′	0.9942	0.9955	0.9967	0.9979	1.0000
	−10′	0.9961	0.9970	0.9978	0.9986	1.0000
	− 5′	0.9981	0.9985	0.9989	0.9993	1.0000
	− 2′	0.9992	0.9994	0.9996	0.9997	1.0000
	0′	1.0000	1.0000	1.0000	1.0000	1.0000
	+ 2′	1.0008	1.0006	1.0004	1.0003	1.0000
1.000 continued	+ 5′	1.0019	1.0015	1.0011	1.0007	1.0000
	+10′	1.0039	1.0030	1.0022	1.0014	1.0000
	+15′	1.0058	1.0044	1.0033	1.0021	1.0000
	+20′	1.0077	1.0059	1.0043	1.0028	1.0000
	+30′	1.0116	1.0089	1.0065	1.0042	1.0000
1.001	−15′	0.9952	0.9965	0.9977	0.9989	1.0010
	−10′	0.9971	0.9980	0.9988	0.9996	1.0010
	− 5′	9.9991	0.9995	0.9999	1.0003	1.0010
	− 2′	1.0002	1.0004	1.0006	1.0007	1.0010
	0′	1.0010	1.0010	1.0010	1.0010	1.0010
	+ 2′	1.0018	1.0016	1.0014	1.0013	1.0010
	+ 5′	1.0029	1.0025	1.0021	1.0017	1.0010
	+10′	1.0049	1.0040	1.0032	1.0024	1.0010
	+15′	1.0068	1.0054	1.0043	1.0031	1.0010
	+20′	1.0087	1.0069	1.0053	1.0038	1.0010
	+30′	1.0126	1.0099	1.0075	1.0052	1.0010
1.002	−15′	0.9962	0.9975	0.9987	0.9999	1.0020
	−10′	0.9981	0.9990	0.9998	1.0006	1.0020
	− 5′	1.0001	1.0005	1.0009	1.0013	1.0020
	− 2′	1.0012	1.0014	1.0016	1.0017	1.0020
	0′	1.0020	1.0020	1.0020	1.0020	1.0020
	+ 2′	1.0028	1.0026	1.0024	1.0023	1.0020
	+ 5′	1.0039	1.0035	1.0031	1.0027	1.0020
	+10′	1.0059	1.0050	1.0042	1.0034	1.0020
	+15′	1.0078	1.0064	1.0053	1.0041	1.0020
	+20′	1.0097	1.0079	1.0063	1.0048	1.0020
	+30′	1.0136	1.0109	1.0085	1.0062	1.0020
1.003	−15′	0.9972	0.9985	0.9997	1.0099	1.0030
	−10′	0.9991	1.0000	1.0008	1.0016	1.0030
	− 5′	1.0011	1.0015	1.0019	1.0023	1.0030
	− 2′	1.0022	1.0024	1.0026	1.0027	1.0030
	0′	1.0030	1.0030	1.0030	1.0030	1.0030
	+ 2′	1.0038	1.0036	1.0034	1.0033	1.0030
	+ 5′	1.0049	1.0045	1.0041	1.0037	1.0030
	+10′	1.0069	1.0060	1.0052	1.0044	1.0030
	+15′	1.0088	1.0074	1.0063	1.0051	1.0030
	+20′	1.0107	1.0089	1.0083	1.0058	1.0030
	+30′	1.0146	1.0119	1.0095	1.0072	1.0030
1.004	−15′	0.9982	0.9995	1.0007	1.0019	1.0040
	−10′	1.0001	1.0010	1.0018	1.0026	1.0040
	− 5′	1.0021	1.0025	1.0029	1.0033	1.0040
	− 2′	1.0032	1.0034	1.0036	1.0037	1.0040
	0′	1.0040	1.0040	1.0040	1.0040	1.0040
	+ 2′	1.0048	1.0046	1.0044	1.0043	1.0040
	+ 5′	1.0059	1.0055	1.0051	1.0047	1.0040
	+10′	1.0079	1.0070	1.0062	1.0054	1.0040
	+15′	1.0098	1.0084	1.0073	1.0061	1.0040
	+20′	1.0117	1.0099	1.0083	1.0068	1.0040
	+30′	1.0156	1.0129	1.0105	1.0082	1.0040
1.005	−15′	0.9992	1.0005	1.0017	1.0029	1.0050
	−10′	1.0011	1.0020	1.0028	1.0036	1.0050
	− 5′	1.0031	1.0035	1.0039	1.0043	1.0050
	− 2′	1.0042	1.0044	1.0046	1.0047	1.0050
	0′	1.0050	1.0050	1.0050	1.0050	1.0050
	+ 2′	1.0058	1.0056	1.0054	1.0053	1.0050
	+ 5′	1.0069	1.0065	1.0061	1.0057	1.0050
	+10′	1.0089	1.0080	1.0072	1.0064	1.0050
	+15′	1.0108	1.0094	1.0083	1.0071	1.0050
	+20′	1.0127	1.0109	1.0093	1.0078	1.0050
	+30′	1.0167	1.0139	1.0115	1.0092	1.0050

Note: Interpolation between points may be made for intermediate values of ratio correction factor, phase angle or line power factor.

Table 17(b)—Instrument Current Transformer—Transformer Correction Factors

Ratio correction Factor (RCF)	Phase Angle β	Transformer Correction Factor (TCF)				
		Power Factor of Metered Load—Lagging				
		0.6	0.7	0.8	0.9	1.0
0.995	−15′	1.0008	0.9994	0.9983	0.9971	0.9950
	−10′	0.9989	0.9980	0.9972	0.9964	0.9950
	− 5′	0.9969	0.9965	0.9961	0.9957	0.9950
	− 2′	0.9958	0.9956	0.9954	0.9953	0.9950
	0′	0.9950	0.9950	0.9950	0.9950	0.9950
	+ 2′	0.9942	0.9944	0.9946	0.9947	0.9950
	+ 5′	0.9931	0.9935	0.9939	0.9943	0.9950
	+10′	0.9911	0.9920	0.9928	0.9936	0.9950
	+15′	0.9892	0.9905	0.9917	0.9929	0.9950
	+20′	0.9872	0.9890	0.9906	0.9922	0.9950
	+30′	0.9834	0.9861	0.9884	0.9907	0.9950
0.996	−15′	1.0018	1.0004	0.9993	0.9981	0.9960
	−10′	0.9999	0.9990	0.9982	0.9974	0.9960
	− 5′	0.9979	0.9975	0.9971	0.9967	0.9960
	− 2′	0.9968	0.9966	0.9964	0.9963	0.9960
	0′	0.9960	0.9960	0.9960	0.9960	0.9960
	+ 2′	0.9952	0.9954	0.9956	0.9957	0.9960
	+ 5′	0.9941	0.9945	0.9949	0.9953	0.9960
	+10′	0.9921	0.9930	0.9938	0.9946	0.9960
	+15′	0.9902	0.9915	0.9927	0.9939	0.9960
	+20′	0.9882	0.9900	0.9916	0.9932	0.9960
	+30′	0.9843	0.9871	0.9894	0.9917	0.9960
0.997	−15′	1.0028	1.0014	1.0003	0.9991	0.9970
	−10′	1.0009	1.0000	0.9992	0.9984	0.9970
	− 5′	0.9989	0.9985	0.9981	0.9977	0.9970
	− 2′	0.9978	0.9976	0.9974	0.9973	0.9970
	0′	0.9970	0.9970	0.9970	0.9970	0.9970
	+ 2′	0.9962	0.9964	0.9966	0.9967	0.9970
	+ 5′	0.9951	0.9955	0.9959	0.9963	0.9970
	+10′	0.9931	0.9940	0.9948	0.9956	0.9970
	+15′	0.9912	0.9925	0.9937	0.9949	0.9970
	+20′	0.9892	0.9910	0.9926	0.9942	0.9970
	+30′	0.9853	0.9881	0.9904	0.9927	0.9970
0.998	−15′	1.0038	1.0024	1.0013	1.0001	0.9980
	−10′	1.0019	1.0010	1.0002	0.9994	0.9980
	− 5′	0.9999	0.9995	0.9991	0.9987	0.9980
	− 2′	0.9988	0.9986	0.9984	0.9983	0.9980
	0′	0.9980	0.9980	0.9980	0.9980	0.9980
	+ 2′	0.9972	0.9974	0.9976	0.9977	0.9980
	+ 5′	0.9961	0.9965	0.9969	0.9973	0.9980
	+10′	0.9941	0.9950	0.9958	0.9966	0.9980
	+15′	0.9922	0.9935	0.9947	0.9959	0.9980
	+20′	0.9902	0.9920	0.9936	0.9952	0.9980
	+30′	0.9863	0.9891	0.9914	0.9937	0.9980
0.999	−15′	1.0048	1.0034	1.0023	1.0011	0.9990
	−10′	1.0029	1.0020	1.0012	1.0004	0.9990
	− 5′	1.0009	1.0005	1.0001	0.9997	0.9990
	− 2′	0.9998	0.9996	0.9994	0.9993	0.9990
	0′	0.9990	0.9990	0.9990	0.9990	0.9990
	+ 2′	0.9982	0.9984	0.9986	0.9987	0.9990
	+ 5′	0.9971	0.9975	0.9979	0.9983	0.9990
	+10′	0.9951	0.9960	0.9968	0.9976	0.9990
	+15′	0.9932	0.9945	0.9957	0.9969	0.9990
	+20′	0.9912	0.9930	0.9946	0.9962	0.9990
	+30′	0.9873	0.9901	0.9924	0.9947	0.9990
1.000	−15′	1.0058	1.0044	1.0033	1.0021	1.0000
	−10′	1.0039	1.0030	1.0022	1.0014	1.0000
	− 5′	1.0019	1.0015	1.0011	1.0007	1.0000
	− 2′	1.0008	1.0006	1.0004	1.0003	1.0000
	0′	1.0000	1.0000	1.0000	1.0000	1.0000
	+ 2′	0.9992	0.9994	0.9996	0.9997	1.0000
1.000 continued	+ 5′	0.9981	0.9985	0.9989	0.9993	1.0000
	+10′	0.9961	0.9970	0.9978	0.9986	1.0000
	+15′	0.9942	0.9955	0.9967	0.9979	1.0000
	+20′	0.9922	0.9940	0.9956	0.9972	1.0000
	+30′	0.9883	0.9911	0.9934	0.9957	1.0000
1.001	−15′	1.0068	1.0054	1.0043	1.0031	1.0010
	−10′	1.0049	1.0040	1.0032	1.0024	1.0010
	− 5′	1.0029	1.0025	1.0021	1.0017	1.0010
	− 2′	1.0018	1.0016	1.0014	1.0013	1.0010
	0′	1.0010	1.0010	1.0010	1.0010	1.0010
	+ 2′	1.0002	1.0004	1.0006	1.0007	1.0010
	+ 5′	0.9991	0.9995	0.9999	1.0003	1.0010
	+10′	0.9971	0.9980	0.9988	0.9996	1.0010
	+15′	0.9952	0.9965	0.9977	0.9989	1.0010
	+20′	0.9932	0.9950	0.9966	0.9982	1.0010
	+30′	0.9893	0.9921	0.9944	0.9967	1.0010
1.002	−15′	1.0078	1.0064	1.0053	1.0041	1.0020
	−10′	1.0059	1.0050	1.0042	1.0034	1.0020
	− 5′	1.0039	1.0035	1.0031	1.0027	1.0020
	− 2′	1.0028	1.0026	1.0024	1.0023	1.0020
	0′	1.0020	1.0020	1.0020	1.0020	1.0020
	+ 2′	1.0012	1.0014	1.0016	1.0017	1.0020
	+ 5′	1.0001	1.0005	1.0009	1.0013	1.0020
	+10′	0.9981	0.9990	0.9998	1.0006	1.0020
	+15′	0.9962	0.9975	0.9987	0.9999	1.0020
	+20′	0.9942	0.9960	0.9976	0.9992	1.0020
	+30′	0.9903	0.9931	0.9954	0.9977	1.0020
1.003	−15′	1.0088	1.0074	1.0063	1.0051	1.0030
	−10′	1.0069	1.0060	1.0052	1.0044	1.0030
	− 5′	1.0049	1.0045	1.0041	1.0037	1.0030
	− 2′	1.0038	1.0036	1.0034	1.0033	1.0030
	0′	1.0030	1.0030	1.0030	1.0030	1.0030
	+ 2′	1.0022	1.0024	1.0026	1.0027	1.0030
	+ 5′	1.0011	1.0015	1.0019	1.0023	1.0030
	+10′	0.9991	1.0000	1.0008	1.0016	1.0030
	+15′	0.9972	0.9985	0.9997	1.0009	1.0030
	+20′	0.9952	0.9970	0.9986	1.0002	1.0030
	+30′	0.9913	0.9941	0.9964	0.9987	1.0030
1.004	−15′	1.0098	1.0084	1.0073	1.0061	1.0040
	−10′	1.0079	1.0070	1.0062	1.0054	1.0040
	− 5′	1.0059	1.0055	1.0051	1.0047	1.0040
	− 2′	1.0048	1.0046	1.0044	1.0043	1.0040
	0′	1.0040	1.0040	1.0040	1.0040	1.0040
	+ 2′	1.0032	1.0034	1.0036	1.0037	1.0040
	+ 5′	1.0021	1.0025	1.0029	1.0033	1.0040
	+10′	1.0001	1.0010	1.0018	1.0026	1.0040
	+15′	0.9982	0.9995	1.0007	1.0019	1.0040
	+20′	0.9962	0.9980	0.9996	1.0012	1.0040
	+30′	0.9923	0.9951	0.9974	0.9997	1.0040
1.005	−15′	1.0108	1.0094	1.0083	1.0071	1.0050
	−10′	1.0089	1.0080	1.0072	1.0064	1.0050
	− 5′	1.0069	1.0065	1.0061	1.0057	1.0050
	− 2′	1.0058	1.0056	1.0054	1.0053	1.0050
	0′	1.0050	1.0050	1.0050	1.0050	1.0050
	+ 2′	1.0042	1.0044	1.0046	1.0047	1.0050
	+ 5′	1.0031	1.0035	1.0039	1.0043	1.0050
	+10′	1.0011	1.0020	1.0028	1.0036	1.0050
	+15′	0.9992	1.0005	1.0017	1.0029	1.0050
	+20′	0.9972	0.9990	1.0006	1.0022	1.0050
	+30′	0.9932	0.9961	0.9984	1.0007	1.0050

Note: Interpolation between points may be made for intermediate values of ratio correction factor, phase angle or line power factor.

Determining CT Burden—When two or more instruments are connected in series, the exact value of the resultant burden in the CT can be calculated from the resistance and reactance of each instrument. The total resistance is the sum of the resistances of the individual instruments. The total reactance is the sum of the reactances of the individual instruments. Usually the burdens imposed by the leads to the instruments are sufficiently large to be appreciable and should be added to the burdens imposed by the instruments. The burdens may be given in volt-amperes rather than in ohms; then the components are given in watts and reactive volt-amperes (vars). Then the total watts and total vars are the sum of the individual values. This is expressed in Equation 54.

$$\text{Total burden (ohms)} = \sqrt{(\Sigma R)^2 + (\Sigma X_L)^2} \qquad \text{(a)}$$

$$\text{Total burden (volt-amperes)} = \sqrt{(\Sigma \text{watts})^2 + (\Sigma \text{vars})^2} \qquad \text{(b)}$$

$$(54)$$

$$\text{Burden power factor} = \frac{\text{total resistance}}{\text{total ohms}} \qquad \text{(c)}$$

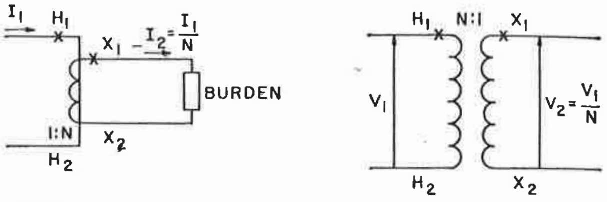
$$\text{Burden power factor} = \frac{\text{total watts}}{\text{total volt-amperes}} \qquad \text{(d)}$$

Typical burdens imposed on current transformers by various instruments are given in Table 19.

Polarity of an Instrument Transformer—When instrument transformers are used with instruments and relays which operate only according to magnitude of voltage or current, the phase relationship is of no consequence. Reversal of connections to the meter gives the same indication on the relay or instrument.

The relative phase positions of two or more quantities applied to devices which depend on the interaction of the quantities for correct operation are of prime importance. Product meters and relays such as wattmeters, watthour meters, power relays, and directional relays are devices in which the phase relationship of the quantities involved, or the phase relationship of each with respect to a common reference, must be known. For correct operation of such devices, it is necessary to know the relative directions of currents in the primary and secondary windings. The polarity markings on the instrument transformer are the identifications used to indicate the relative instantaneous polarities of the primary and secondary currents and voltages.

On potential transformers, during most of each half-cycle in which the identified primary terminal is positive with respect to the unidentified primary terminal; the identified secondary terminal is also positive with respect to the unidentified secondary terminal. The polarity marks are so placed on current transformers that during most of each half-cycle, when the direction of the instantaneous current is into the identified primary terminal, the direction of the instantaneous secondary current is out of the corresponding identified secondary terminal. This convention is in accord with that by which standard terminal markings H_1, X_1, are correlated.[37] This is illustrated in Fig. 54. Various methods of determining the polarity of instrument transformers are described in the Standards.



CURRENT TRANSFORMER POTENTIAL TRANSFORMER

Fig. 54—Circuit diagrams showing significance of polarity identification and notation of current and potential transformers

30. Operating Limitations of Instrument Transformers

The effects of some variations in normal operating conditions on instrument transformers have been discussed in the section regarding the particular type of transformer. The operation of transformers under some rather abnormal conditions are of prime importance and are discussed here.

Neutral Inversion[45,46,47]—Potential transformers connected wye-wye with the high voltage neutral grounded on an otherwise ungrounded system are universally subject to oscillations of the neutral from the third harmonic voltage developed, and are universally subject to inversion of the neutral, under favorable conditions of line capacitance and inductance. Such reference is usually given to the condition when the neutral is displaced to points outside of the delta.

Special designs can be made which will practically preclude inversion except under most unusual conditions, but the best prevention of inversion is a ballasting load on each secondary winding. A resistance load in watts equal to the exciting volt-amperes of the transformer of normal line-to-ground voltage will practically prevent inversion.

Overvoltages—The exciting current and ratio error and phase angle of a potential transformer increase rapidly as the applied voltage exceeds 110 per cent of normal. In general, if the applied voltage exceeds 110 per cent, the errors become excessive. Instrument transformers, according to ASA Standards, shall be capable of operating continuously at 10 per cent above rated voltage.

Momentary overvoltages up to twice normal voltage can usually be absorbed by potential transformers. This usually is important only in the event of a ground-fault which results in application of line-to-line voltage to a wye-connected transformer. Unless specifically designed for this contingency, potential transformers will not withstand continuous operation at $\sqrt{3}$ times normal voltage. This has been discussed previously. Under no conditions should the thermal voltampere-output rating of the transformer be exceeded.

Operation of Current Transformer With Secondary Open-Circuited—If the secondary circuit of a current transformer is opened while current flows in the primary circuit, the demagnetizing effect of the secondary winding mmf, which is usually large, is removed. Normally, the

Table 18—Burdens Imposed by Instruments and Meters on Potential Transformers

Values given are for a single element.

Kind and Type of Instrument	25 Cycles				60 Cycles				Remarks
	Volt-Amperes	Watts	Vars	% Power Factor	Volt-Amperes	Watts	Vars	% Power Factor	
Voltmeters									
0–150 volts CA, MA, NA, VA	0.9	0.9	0.0	100.	0.9	0.9	0.0	0.0	
0–150 volts HA, KA, JY-2, LY-2, SY-2, DY-2	3.51	3.51	0.023	99. +	3.51	3.51	0.055	99. +	ext. res. on KA, JY-2, DY-2
0–150 volts DY, LY, SY, JY, WY	9.5	9.5	0.0	100.	9.5	9.5	0.1	100.	ext. res. used
0–150 volts SM, TM, GM	11.5	10.9	3.82	94.7	10.3	9.9	1.02	96.	ext. res. used
0–150 volts PY-4	.9	.9	0.0	100.	.9	.9	0.0	100.	
0–150 volts PY-5	2.84	2.84	0.0	100.	2.84	2.84	0.0	100.	
0–300 volts PY-4	.25	.25	0.0	100.	.25	.25	0.0	100.	
0–300 volts PY-5	.75	.75	0.0	100.	.75	.75	0.0	100.	
0–150 volts PC	5.45	5.45	0.0	100.	5.45	5.45	0.0	100.	
90–130 volts 90–140 volts type U recorder	33.8	33.6	4.7	99.	32.5	31.4	8.5	97.	ext. res. used
90–140 volts type A recorder	23.4	22.7	3.9	99.	23.4	21.5	9.4	92.	ext. res. used
90–140 volts type R recorder	13.8	13.8	0.05	100.	13.8	13.8	0.1	100.	ext. res. used
0–150 volts type R recorder	11.4	11.4	0.4	100.	11.4	11.4	0.08	100.	ext. res. used
Wattmeters									
single phase HY, KY	3.27	3.27	0.0	100.	3.27	3.27	0.0	100.	ext. res. on KY
polyphase HY, KY	2.88	2.88	0.0	100.	2.88	2.88	0.0	100.	ext. res. used on KY
single phase DY, LY, SY, WY	11.6	11.6	0.0	100.	11.6	11.6	0.0	100.	ext. res. used
polyphase DY, LY, SY, WY	8.3	8.3	0.0	100.	8.3	8.3	0.0	100.	ext. res. used
0–75 volts 0–150 volts PY-4	1.58	1.58	0.0	100.	1.58	1.58	0.0	100.	
0–150 volts 0–300 volts PY-4	1.21	1.21	0.0	100.	1.21	1.21	0.0	100.	
0–75 volts 0–150 volts PY-5	5.6	5.6	0.0	100.	5.6	5.6	0.0	100.	
0–150 volts 0–300 volts PY-5	2.12	2.12	0.0	100.	2.12	2.12	0.0	100.	
0–150 volts PC	5.45	5.45	0.0	100.	5.45	5.45	0.0	100.	
types SM, TM, GM	8.65	7.32	4.58	85.	10.1	9.16	4.26	91.	ext. res. used
types M, R recorders	10.7	10.7	0.0	100.	10.7	10.7	0.0	100.	ext. res. used
Watthour Meters									
single phase, OC, CA, CS, DA, DS	.....	.....	.....	.....	8.7	1.4	8.6	16.	
polyphase C-2, C-3; R-2, R-3; RI-2, RI-3	.....	.....	.....	.....	12.7	2.3	12.4	18.	
polyphase CS-2, CA-2, CB-2	.....	.....	.....	.....	8.5	1.7	8.3	20.	
polyphase DSP-2, DAP-2, etc.	.....	.....	.....	.....	6.1	1.4	5.94	23.	
demand attachment—additional on any meter	.....	.....	.....	.....	2.3	1.5	1.7	65.	
polyphase demand meters C-2, C-3, etc.	.....	.....	.....	.....	14.6	3.8	14.1	26.	
reactive VA type RI	.....	.....	.....	.....	11.0	1.6	10.8	15.	
Power Factor Meters									
single phase DY, LY, SY, HY, KY	17.8	13.9	11.1	78.	17.8	13.9	11.1	78.	ext. reactor used
polyphase 50-100-50, DY, LY, SY, WY	12.2	12.2	0.0	100.	12.2	12.2	0.0	100.	ext. res. used
polyphase 50-100-50, HY, KY	3.7	3.7	0.0	100.	3.7	3.7	0.0	100.	
polyphase 10-100-80, DY, LY, SY, WY	10.	9.8	3.7	93.7	10.5	9.8	3.7	93.7	ext. res. used
polyphase 10-100-80, HY, KY	3.2	3.2	0.0	100.	3.2	3.2	0.0	100.	
types SI, TI	12.0	10.9	4.95	91.	12.0	10.9	4.95	91.	ext. res. used
reactive factor SI, TI	12.0	10.9	4.95	91.	12.0	10.9	4.95	91.	ext. res. used
PC portable	8.7	6.5	5.8	75.	8.7	6.5	5.8	75.	
polyphase recorder, type R	10.7	10.7	0.0	100.	10.7	10.7	0.0	100.	
Frequency Meters									
resonant type HY, KY, LY, DY, SY, WY	3.5	3.5	.13	100.	3.5	3.5	0.24	100.	ext. reactor used
resistor-reactor type SY, LY, DY, WY	16.3	13.9	8.5	85.	16.3	13.9	8.5	85.	ext. reactor used
types SD, TD, PD	21.8	16.3	14.4	75.	21.8	16.3	14.4	75.	ext. reactor used
types M, R, reactor	27.1	23.2	14.1	85.	28.4	24.0	15.2	85.	ext. reactor used
type RF recorder	30.0	12.0	27.5	40.	30.0	12.0	27.5	40.	
Synchroscopes									
SI, TI bottom circuit running machine	10.9	10.0	4.25	92.0	10.9	10.0	4.25	92.0	ext. reactor used
SI, TI top circuit incoming machine	12.2	12.2	.25	100.	12.2	12.2	.....	100.	
HA bottom circuit incoming machine	3.2	2.1	2.4	65.	3.2	2.1	2.4	65.	
HA top circuit running machine	2.9	1.8	2.2	63.	2.9	1.8	2.2	63.	ext. reactor used

Table 19—Burdens Imposed by Instruments and Meters on Current Transformers

Values given are for a single element. For watthour meters, values shown are for 5-ampere meters at 5 amperes except (†) which are 2½ ampere meters at 5 amperes. Data are per winding per stator.

kind and type of instrument	25 Cycles					60 Cycles				
	Impedance: Ohms	Resistance: Ohms	Reactance: Ohms	Volt-Amperes	% Power Factor	Impedance: Ohms	Resistance: Ohms	Reactance: Ohms	Volt-Amperes	% Power Factor
Ammeters										
5 amp. CA, MA, NA, PY-4 portable	.0108	.0108	.00092	0.27	99.8	.0112	.0108	.00212	0.28	99.1
5 amp. HA, KA, SY-2, LY-2, DY-2, JY-2, PY-5 portable	.0180	.0172	.00568	0.45	95.0	.0216	.0172	.01344	0.54	79.0
5 amp. SY, LY, DY, JY, WY	.1280	.1280	.01840	3.20	99.0	.1320	.1240	.04400	3.30	94.8
5 amp. SM, TM, JM	.2520	.2400	.07600	6.30	95.0	.1128	.1112	.03520	2.82	98.5
5 amp. PM portable	.1800	.1600	.08000	4.50	89.0	.1800	.1600	.08000	4.50	89.0
5 amp. A recorder	.3760	.1880	.32400	9.40	49.7	.3800	.0880	.37200	9.50	23.2
5 amp. R recorder	.1512	.1464	.03760	3.78	96.3	.1548	.1320	.08120	3.87	85.3
5 amp. U recorder	.2860	.2180	.18800	7.15	76.2	.5760	.2840	.50400	14.40	49.3
Wattmeters										
5 amp. HY, KY, DY, LY, SY, WY	.0760	.0760	.00490	1.90	99.5	.0760	.0760	.01160	1.90	99.0
4 amp. HY, KY, DY, LY, SY, WY	.1200	.1200	.00800	3.00	99.0	.1200	.1200	.00176	3.00	99.0
7½ amp. HY, KY, SY, LY, DY, WY	.0308	.0308	.00200	0.77	99.0	.0312	.0308	.00480	0.78	99.0
5 amp. SM, TM, GM	.0420	.0400	.01200	1.05	95.8	.0480	.0400	.02760	1.20	82.5
5 amp. PY-4 portable	.0112	.0108	.00100	0.28	99.0	.0124	.0108	.00560	0.31	97.5
5 amp. PY-5 portable	.0324	.0320	.00240	0.81	99.0	.0328	.0320	.00600	0.82	98.0
5 amp. PC portable	.1004	.0920	.04000	2.51	92.0	.1292	.0920	.09600	3.23	69.0
5 amp. R recorder	.1728	.1648	.05040	4.32	95.5	.2148	.1648	.12480	5.37	77.6
Watthour Meters										
single phase OC, CA, CS	.....	.....	......	....	....	.0128	.0072	.0106	0.32	56
single phase, DA, DS†	.....	.....	......	....	....	.0460	.020	.0415	1.15	43
polyphase {C-2, C-3, etc. R-2, R-3, etc. RI-2, RI-3, etc.}	.....	.....	......	....	....	.0236	.0104	.0212	0.59	44
same with demand attachment or demand meter reactive VA type RI	.....	.....	......	....	....	.05	.0352	.0355	1.25	70
polyphase {CS-2, CS-3, etc. CA-2, CA-3, etc. CB-2, CB-3, etc.}	.....	.....	......	....	....	.0116	.0064	.0097	0.29	55
RK-2, RK-3, etc.	.....	.....	......	....	....	.0236	.0104	.0212	0.59	44
polyphase DSP-2, DAP-2, etc.	.....	.....	......	....	....	.050	.019	.0468	1.25	38
Power Factor Meters										
5 amp. HY, KY, DY, LY, SY, WY—100° scale	.0160	.0160	.04800	1.90	99.5	.0160	.0760	.11660	1.90	99.0
5 amp. HA—360° scale	.1076	.1056	.01880	2.69	98.0	.1152	.1056	.04520	2.88	92.0
5 amp. SI, TI—360° scale	.0656	.0600	.02600	1.64	92.0	.0868	.0600	.06240	2.17	69.0
5 amp. PC portable	.1004	.0920	.04000	2.51	92.0	.1332	.0920	.09600	3.33	69.0
5 amp. R recorder	.1728	.1648	.05040	4.32	95.5	.2148	.1648	.12480	5.37	77.6
type TA industrial analyzer	.5040	.5000	.05600	12.60	99.0	.5280	.5240	.06800	13.20	99.0

exciting current, when the transformer is carrying rated current and maximum rated burden, is of the order of 0.5 per cent primary current. If the secondary circuit is opened when the primary is carrying rated current, the primary current becomes the exciting current and is a value of about 200 times normal. This results in a very high core flux density and correspondingly high induced voltage in the transformer winding. The abnormally high flux density will cause excessive core loss, which if sustained for a sufficiently long period of time, may result in destructive heating in the core. It may also leave a high residual flux in the core, which can subsequently result in a change in the ratio error and phase angle of the transformer. The voltage induced in the secondary winding under open-circuit conditions may be sufficiently high to constitute a hazard to the operator and the transformer insulation.

If the secondary circuit is accidentally opened, possible high residual flux can be removed by either of two methods: 1) short circuit the secondary through a 30 ohm resistor and gradually increase the primary alternating current to full rated value after which it is gradually reduced to zero; 2) with the primary open, gradually increase the alternating current through the secondary to rated value after which it is gradually reduced to zero.

Although current transformers are not intended to be operated with the secondary open-circulated, they are capable of operating in this manner for short times under emergency conditions, provided the open circuit (secondary induced voltage) does not exceed 3500-volts crest. Since the induced voltage is a function of the primary current and wave shape, overvoltage protection should be considered on its own merits in the particular application. Also, since the flux is proportional to the integral with respect to time of the induced voltage, the wave form of the induced voltage has a pronounced effect on the degree of saturation in the core. The voltage of 3500-volts crest across a closed secondary circuit may be exceeded if the rate of change of the primary current is sufficiently rapid, such as would be the case in the initial charge or discharge current of a large capacitor installation flowing through the primary winding.

Inverted Operation of Current Transformers—Although application of a current transformer as a "step-up" transformer to obtain larger currents either for metering or testing may appear reasonable, such an application can lead to serious error. Such an application may be that of using instruments of unusually high range in the measurement of very small currents. In such a case, the high-range instrument is connected in series (across) with the high-current winding and the current being measured is passed through the low-current winding: Since the impedances are reflected from the high-current (low-voltage) side to the low-current (high-voltage) side approximately as the square of the turns ratio, a very small impedance on the high-current side may represent a high impedance on the base of the low-current winding, if the turns ratio is appreciable. Such an impedance referred to the low-current winding may exceed the rated maximum burden of the transformer. Such a condition results in abnormally high transformer winding induced voltages, saturation of the core, large exciting current, and an intolerable ratio error. The high-current side impedance must be extremely low to avoid this condition.

Somewhat similar results may occur when attempting to invert a current transformer to obtain large alternating currents for test or other purpose. A load impedance referred to the high-current winding must be kept extremely low if currents of the order of the high-current rating are to be obtained. Any metering applied on the high-current winding contributes to the impedance. If saturation results, serious error can result from metering on the low-current side. Therefore, it is very difficult to obtain a high degree of accuracy when inverting a current transformer. The induced voltage referred to the low-current winding necessary for saturation may be of the order of 30 to 300 volts, the exact value depending upon the type of transformer involved.

31. Metering Outfits

The necessary instrument transformers for outdoor primary metering installations in standard insulation classes from 2.5 kv through 161 kv are available as packaged units in metering outfits. The packaged units are available for single-phase, two-wire, three-phase, three-wire and three-phase, four-wire applications.

The single-phase outfits consist of one current transformer and one potential transformer connected to one or two high-voltage bushings and a neutral grounding bushing or grounding terminal.

The metering outfits for use on three-phase, three-wire circuits consist of two current transformers and two potential transformers connected to three high-voltage bushings. Outfits for use on three-phase, four-wire circuits consist of three current transformers and either two or three potential transformers connected to three high-voltage bushings and a neutral grounding bushing or grounding terminal.

REFERENCES

1. Development of Watthour Meters, Thomas D. Barnes, *Westinghouse Engineer*, Vol. 10, November 1950, pp. 226–32.
2. Progress in the Art of Metering Electric Energy, Pts. I, II, III, and IV, *Electrical Engineering*, Vol. 61, 1941, pp. 421–7, pp. 469–78 pp. 540–6, and pp. 581–9.
3. Lightning Protection of Domestic Watthour Meters, A. M. Opsahl, *Westinghouse Engineer*, Vol. II, May 1942, p. 38.
4. *Electrical Measurements* (book), Frank A. Laws, McGraw-Hill Book Company, 1938.
5. *Measurement of Alternate Current Energy* (book), Donald T. Canfield, McGraw-Hill Book Company, 1940.
6. *Handbook for Electrical Metermen*, 1923 Edition, (book), National Electric Light Association, 1923.
7. Design Considerations for the Life-Time Meter, Warren Schmidt and Ray Forrest, *Westinghouse Engineer*, Vol. 15, September 1955, pp. 166–9.
8. American Standard Code for Electricity Meters, ASA C12-1941, Edison Electric Institute, 1941.
9. Watt-Hour Meter Bearings, I. F. Kinnard and J. H. Goss, *AIEE Transactions*, Vol. 56, 1937, pp. 129–37.
10. Effects of Harmonics on Watthour Meter Accuracy, M. A. Faucett and C. A. Keener, *Electrical World*, October 27, 1945, pp. 82–4.
11. Watt-Hour Meter Performance with Power Rectifiers, C. T. Weller, H. E. Trekell, and F. O. Stebbins, *AIEE Transactions*, Vol. 59, 1940, pp. 449–56.
12. AEIC-EEI-NEMA Standards for Watthour Meters, EEI Pub. No. MSF-10, NEMA Pub. No. EI-20, February 1958.
13. *Electrical Metermen's Handbook*, Sixth Edition, (book), Edison Electric Institute, 1950.
14. *Westinghouse Watthour and Demand Meter Handbook*, Fifth Edition, Westinghouse Electric Corp., Meter Division.
15. Polyphase-Meter Applications, Paul MacGahan, *The Electric Journal*, Vol. 33, October 1936, pp. 453–8.
16. *Applied Mathematics for Engineers and Physicists*, Second Edition, (book), Louis Albert Pipes, McGraw-Hill Book Company, 1958.
17. Measurements of the Energy of Polyphase Currents, A. Blondell, Proc. Internat. Elec. Cong., Chicago, 1893, p. 12.
18. The Fundamental Accuracy of Single-Phase, Three-Wire Metering, E. C. Wentz and A. J. Petzinger, *AIEE Transactions*, Vol. 71, Pt. I, September 1952, pp. 295–302.
19. Reactive Metering, V. B. Shah, Electrical Review, Vol. 140, June 13, 1947; pp. 979–83.
20. Autotransformer Connections for Varhour Metering, E. J. Boland, *General Electric Review*, Vol. 43, July 1940, pp. 298–301.
21. Metering Reactive Loads, A. L. Carvill, *Electric Light and Power*, Vol. 36, August 1, 1958, pp. 55–60, 71–2.
22. American Standard Definitions of Electrical Terms, Group 30, ASA C42.30, 1957.

23. The Character of Thermal Storage Demand Meters, P. M. Lincoln, *AIEE Transactions*, February 1918, pp. 189–210.
24. An Improved Electrothermic Instrument, P. M. Lincoln, *AIEE Transactions*, Vol. 54, 1935, pp. 474–81.
25. New Thermal Volt-Ampere Demand Meter, M. E. Douglass and W. H. Morong, *AIEE Transactions*, Vol. 68, Pt. I, 1949, pp. 79–83.
26. A Polyphase Thermal Ampere-Demand Meter, A. J. Petzinger, *AIEE Transactions*, Vol. 66, 1947, pp. 167–74.
27. A Polyphase Thermal Kilovolt-Ampere Demand Meter, A. J. Petzinger, *AIEE Transactions*, Vol. 70, Pt. II, 1951, pp. 1774–7.
28. Recent Developments in Kilovolt-Ampere Metering, B. H. Smith and A. R. Ritter, *AIEE Transactions*, Vol. 43, 1924, pp. 297–301.
29. Improvement in Modern Meter-Testing Technique, Edward E. Lynch and Mark A. Princi, *AIEE Transactions*, Vol. 61, 1942, pp. 218–33.
30. Stroboscopic Method of Testing Watthour Meters, H. P. Sparkes, *AIEE Transactions*, Vol. 46, 1927, pp. 405–8.
31. Metering with Transformer Loss Compensators, G. B. Schleicher, *AIEE Transactions*, Vol. 66, 1947, pp. 851–61.
32. Demand Totalization Using Simplified Impulse Telemetering System, A. R. Rutter and P. MacGahan, *Electrical Journal*, Vol. 32, 1935, pp. 151–2.
33. A Report on Telemetering, Supervisory Control and Associated Communication Circuits, Joint Subcommittee of the AIEE, *Electrical Engineering*, Vol. 51, September 1932, pp. 613–20.
34. Load Totalization Pts. I, II, III, IV, E. J. Boland, *General Electric Review*, Vol. 41, 1938, pp. 194–9, 238–43, 282–7, and 326–9.
35. Load Survey Data Recorded on Tape, T. D. Barnes, *Electrical World*, Vol. 146, No. 9, August 20, 1956, pp. 125 and 128.
36. Demand Meter Produces Punched-Tape Record Fast, *Electrical World*, Vol. 146, No. 20, November 12, 1956, pp. 137–40.
37. Standard Requirements, Terminology and Test Code for Instrument Transformers, ASA C57.13, 1954, American Standards Association.
38. *Instrument Transformers* (book), B. Hague, Sir Isaac Pifman and Son, 1936.
39. Accuracy of the Formulas for the Ratio, Regulation and Angle of Transformers, P. G. Agnew and F. B. Silsbee, Scientific Papers of the Bureau of Standards, No. 211, Reprinted from Bulletin of Bureau of Standards, Vol. 10.
40. Master Test Code for Electrical Measurements in Power Circuits, AIEE Standard 552, November 1955.
41. A Study of the Current Transformer with Particular Reference to Iron Loss, P. G. Agnew, No. 164, Bulletin of the Bureau of Standards, Vol. 7, 1911.
42. Insulation Level is Criterion for Instrument Transformer Application, J. H. Chiles, Jr., *Electric Light and Power*, Vol. 25, March 1947, pp. 68–9, 72.
43. A Simple Method for Determination of Ratio Error and Phase Angle Error in Current Transformers, E. C. Wentz, *AIEE Transactions*, Vol. 60, 1941, pp. 949–54.
44. A Proposed Method of Determination of Current Transformer Errors, G. Camilli and R. L. Tenbrock, *AIEE Transactions*, Vol. 59, 1940, pp. 547–50.
45. Physical Nature of Neutral Instability, A. Boyajian and O. P. McCarty, *AIEE Transactions*, Vol. 50, 1931, pp. 317–27.
46. Experiences with Grounded-Neutral, Y-Connected Potential Transformers on Ungrounded Systems, C. T. Weller, *AIEE Transactions*, Vol. 50, 1931, pp. 299–316.
47. Ferroresonance of Grounded Potential Transformers on Ungrounded Power Systems, R. F. Karlicek and E. R. Taylor, Jr., *AIEE Transactions*, Paper No. 59–97.

CHAPTER 12

STREET LIGHTING

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The basic purpose of street lighting is to promote safety and convenience on the streets at night through adequate visibility, and to promote civic progress. Statistics show that good street-lighting installations bring about material reductions in traffic accidents, act as a deterrent to crime, and promote more business in commercial areas.

I. GENERAL

1. History[1]

Oil lamps were the first artificial sources of light used for systematic illumination of streets in the United States. No records exist as to when and where the first of these installations was made. The use of gas lamps followed the oil lamps. As early as 1816, the Gas Light Company of Baltimore was founded to manufacture gas for street-lighting purposes. The first electric street-lighting systems came into existence in the late 1870's, with the open carbon-arc lamp and the carbonized-bamboo filament lamp appearing at about the same time. The open carbon-arc lamp, which required daily trimming, was followed in 1893 by the enclosed carbon-arc lamp that required only weekly trimming. The initial efficiency of the enclosed carbon-arc lamp was about four to seven lumens per watt. The flaming-arc lamps and the magnetite, or luminous-arc lamps, were a big improvement over their arc lamp predecessors. Efficiencies up to 19 lumens per watt and a lamp life of 100 hours were possible with the enclosed flaming-arc lamp, and 20 lumens per watt and a 350-hour life were possible with the magnetite lamp.

The carbonized-bamboo filament lamp of 1879 had an efficiency of 2 lumens per watt. The carbonized-cellulose filament of 1891 produced 3 lumens per watt. In 1905, the first of the metallic-filament lamps appeared. Improvements in this lamp have led to the modern, gas-filled lamps having efficiencies up to 21 lumens per watt and a service life up to 3000 hours.

Mercury lamps were first used for street lighting in 1936. The first mercury lamps had an efficiency of about 13 lumens per watt. Modern mercury lamps provide between 50 and 60 lumens per watt and have a rated service life of 6000 to 10,000 hours.

Sodium lamps, first used in 1934, have efficiencies as high as 56 lumens per watt and a service life of approximately 4000 hours.

Fluorescent lamps, which have just recently entered the street-lighting picture, produce approximately 52 lumens per watt and have a rated service life of 7500 hours.

It has been estimated that there are approximately five million street lights in service in the United States today. Of this total number, it is estimated that approximately 90 per cent of these units are filament lamps. The great majority of the remaining 10 per cent are mercury-vapor units. It has been estimated that by 1966, when the total number of street lights in the country should reach ten million, that approximately half of the lumens provided for street lighting will be from either mercury or fluorescent lamps.

2. Illumination Levels

Definitions[2]—The standard unit of luminous intensity in a given direction is the International Candle. An ordinary wax candle has a luminous intensity, in a horizontal direction, of approximately one candle. The International Candle is the basic quantity in all measurements of light. The luminous intensity of a light source expressed in candles is its candlepower. Candlepower is always a property of a source of light and gives information regarding luminous flux at its origin.

The unit of luminous flux is the lumen. A lumen is defined as the light flux falling on a surface one square foot in area, with every point on the surface of the area one foot away from a uniform point source of one candle. The lumen differs from the candle in that it is a measure of light flux irrespective of direction.

Illumination refers to the density of luminous flux on a surface. The unit of illumination is the foot-candle. A foot-candle is defined as the illumination at a point on a surface that is one foot from, and perpendicular to, a uniform point source of one candle. From the definition of a lumen, it is obvious that one lumen uniformly distributed over one square foot of surface produces an illumination of one foot-candle.

Brightness is the luminous intensity in a given direction per unit of projected area. A surface, or an object, has brightness by reason of light emitted, reflected, or transmitted. Brightness is ordinarily independent of distance of observation. Brightness is expressed in two ways: in candles per unit area, or in lumens per unit area. By definition, a surface emitting or reflecting light in a given direction, at the rate of one candle per square inch of projected area, has a brightness in that direction of one candle per square inch. A surface which has a brightness equal to the uniform brightness of a perfectly diffusing surface emitting or reflecting one lumen per square foot has a brightness of one footlambert. The footlambert is also the average brightness of any surface emitting or reflecting one lumen per square foot.

The following terms are commonly used in street and highway lighting and merit definition here to avoid confusion.

The term lamp refers to the light source employed. The efficiency of a lamp, expressed in lumens per watt, is the ratio of the total luminous flux to the total power input.

A luminaire is a complete lighting device consisting of a light source together with its direct appurtenances, such as globe, reflector, refractor, housing, and such support as is integral with the housing. The pole, post, or bracket is not considered a part of the luminaire. A lighting unit is the complete assembly of pole or post with bracket and luminaire.

The absorption factor is defined as the ratio of light flux absorbed by an object or surface to the light flux incident upon it. The reflection factor, or reflectance, is defined as the ratio of light reflected by a surface to the light incident upon it.

Application Requirements—There are a number of factors that contribute to the illumination level required in street-lighting installations. An important factor, common to all street and highway safety considerations, is the volume of vehicular and pedestrian traffic. As traffic volume increases, traffic interference and exposure to accidents also increase. Good visibility is more difficult to achieve in the confusion of moving vehicles and pedestrians, for it is against this background that the accident hazard must be discerned.

In order to make logical recommendations as to illumination levels required in street-lighting applications, it is necessary to classify streets with respect to vehicular and pedestrian traffic. Table 1[3] and Table 2[3] give classifications of vehicular and pedestrian traffic, respectively.

Table 1—Classification of Vehicular Traffic for Roadway Lighting Purposes

Classification	Volume of Vehicular Traffic (Maximum Night Hour Both Directions)
Very light traffic	Under 150
Light traffic	150–500
Medium traffic	500–1200
Heavy traffic	1200–2400
Very heavy traffic . . .	2400–4000
Heaviest traffic.	Over 4000

Table 2—Classification of Pedestrian Traffic

Classification	Pedestrian Volumes Crossing Vehicular Traffic Lanes
None	No pedestrians, as on express highways.
Light	As on streets in average residential districts.
Medium	As on secondary business streets.
Heavy	As on main business streets.

Table 3—Current Recommended Average Horizontal Footcandles*

(Lumens per Square Foot)

Pedestrian Traffic (Table 2)	Vehicular Traffic Classification (Table 1)			
	Very Light (Under 150)	Light (150–500)	Medium (500–1200)	Heavy to Heaviest (1200 and up)
Heavy	0.9	1.2	1.5	1.8
Medium	0.6	0.9	1.2	1.5
Light or None	0.3	0.6	0.9	1.2

*The recommended illumination values are for roadway surfaces having reflectances of the order of three per cent. These values should be treated as minimums after proper consideration has been given to both lamp and luminaire depreciation during operation, irrespective of the method employed in maintaining the lighting system and also to provide for probable pavement reflection characteristics.

The reflection factor, or reflectance, of the street surface has a definite effect on the effectiveness of a street-lighting installation. Consequently, the reflectance of the street and roadway surfaces should be evaluated. Table 3[3], which gives recommended illumination levels for street lighting, takes reflectance into account.

The foot-candle values given in Table 3 are current recommended minimum practice for average illumination on the traffic-used pavement between curb lines. The lowest foot-candle value at any point should not be less than one-fourth the average value given in Table 3, except in cases of very light vehicular traffic where the lowest foot-candle value at any point may be as low as one-tenth of that value.

Pavement brightness, for the achievement of satisfactory visibility by silhouette discernment, is dependent upon the light reflection characteristics of the pavement surface. The values in Table 3 are based on rather poor pavement reflectance in the order of three per cent. For streets and traffic conditions in which silhouette discernment is important, due allowance must be made for pavement reflectances which vary from the conditions assumed above. When reflectance is favorable (in the order of ten per cent), the illumination recommended may be reduced by 33 per cent. When reflectance is unusually high (20 per cent or more), the recommended values of Table 3 may be decreased by 50 per cent. In general, these corrections will apply more specifically to streets carrying a light traffic volume where the illumination recommended is less than 0.8 footcandle. On streets carrying a heavy traffic volume, and where 1.0 foot-candle or more is recommended, visibility is more apt to depend upon discernment by surface detail; hence, corrections for pavement reflectance becomes less important.

Intersections require higher illumination than that recommended in Table 3 for the approaching streets. The illumination at an intersection should be at least equal to the sum of the illumination values provided on the streets which form the intersection.

The color of light usually does not affect the level of illumination to be provided. Studies have shown that the visibility of objects on or near the roadway is substantially the same throughout the differences in color of light from sodium, mercury, fluorescent, and filament lamps, when the comparison is on the basis of equal amount of light and similar distribution.

3. Sources of Light

The primary purpose of a light source is the production of light, and the efficiency with which a source fulfills this purpose is expressed in terms of lumens emitted per watt of power consumed. If a source could be developed that would radiate all the input energy as monochromatic yellow-green light in the region of maximum sensitivity of the eye (5550 Angstroms), it would produce approximately 650 lumens per watt. A theoretical source of white light of maximum efficiency, emitting only visible energy without infrared or ultraviolet, would produce about 200 lumens per watt. Compared with these figures, the best available lamp efficiencies of today seem disappointingly low.

Incandescent or Filament Lamps—The filament lamp produces light by virtue of heating a wire, or filament, to incandescence by passing an electric current through it. An incandescent filament must operate in either a vacuum or an atmosphere of inert gas to prevent rapid disintegration due to oxidation.

The efficiency of filament lamps, while low compared to the theoretical values given above, has been vastly improved in the last 50 years by changing from carbon to tungsten as a filament material, by changing from vacuum to gas-filled construction, and by replacing straight filament wire with coiled, and then using coiled-coil filaments. However, the filament lamp has certain characteristics which make it inherently inefficient as a source of light, and although it is probable that efficiencies will still be raised slightly by further refinements in manufacturing processes, the maximum possible values have already been approached.

The most efficient incandescent lamps available for street-lighting purposes today have efficiencies in the order of 21 lumens per watt.

Both the life of a filament lamp and its light output are determined by its filament temperature. The higher the temperature for a given lamp, the greater the efficiency and the shorter the life. Hence, light output and life are interdependent. A lamp can be designed for long life at the expense of light output, or for high light output at the expense of life. In practice, the life for which a lamp is designed is an economic balance between the two factors, determined on the basis of the purpose for which the lamp is to be used.

Published data on lamp life refer to the average life of a group of lamps under specified test conditions, and are not intended as a guarantee of the performance of any individual lamp. As shown by the mortality curve of Fig. 1, in any large group of lamps, some will fail relatively early in life, whereas others will still continue to operate long after the end of rated life.

As a general rule, lamps should be operated at rated voltage. Overvoltage operation results in higher wattage, higher efficiency, and higher light output, but also in shorter lamp life. Undervoltage operation, while increasing lamp life, causes a reduction in wattage, in efficiency, and in light output. For example, operation of a lamp at 95 per cent of rated voltage results in a loss of light amounting to more than 16 per cent, with a saving in wattage of only 8 per cent. Since lamp cost is almost always compared with the cost of the power to operate the lamp, the increased lamp life which accompanies reduced voltage does not begin to compensate economically for the loss in light output. Maintenance of proper voltage is therefore an important factor in obtaining good performance from lamps operated on multiple systems. Characteristic curves for filament lamps operated on multiple circuits are shown in Fig. 2.

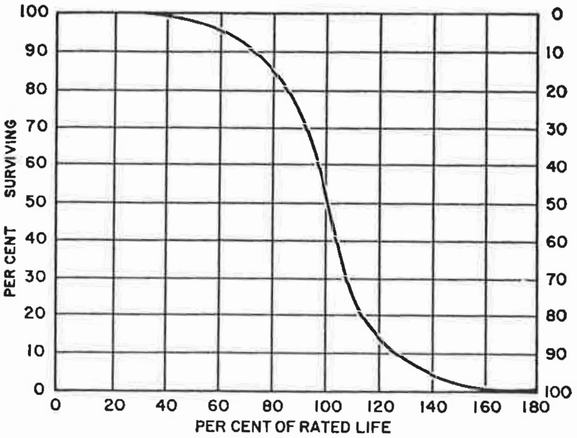


Fig. 1—Typical mortality curve for incandescent lamps.

As an incandescent lamp burns, the filament gradually evaporates, or sublimates, thus decreasing the diameter of the filament. The normal end of life is reached when the wire breaks or burns through at its thinnest spot. A reduction in light output results from the absorption of light by the sublimated tungsten which collects as a black deposit on the inner surface of the bulb. The lumen maintenance of series lamps (operated at constant current) is better than that of lamps operated on multiple circuits, because the wattage of the multiple lamps (which are held at a constant voltage) gradually decreases throughout life, whereas the wattage of a lamp held at constant current increases with life. This is because the resistance of the filament wire increases as its diameter decreases due to evaporation. At constant voltage, increased resistance results in a

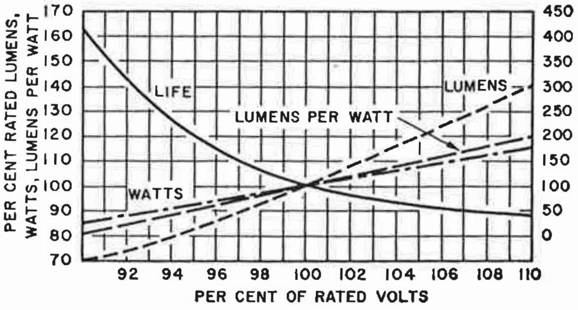


Fig. 2—Characteristic curves for incandescent lamps operated on a multiple circuit.

decrease in amperes, and accordingly, in watts. At constant current, increased resistance results in increased voltage, and a corresponding increase in watts which materially offsets the reduction in light output due to blackening of the bulb. Characteristic curves for series filament lamps are given in Fig. 3.

Fig. 4 shows two standard street-lighting luminaires that are commonly used with incandescent lamps.

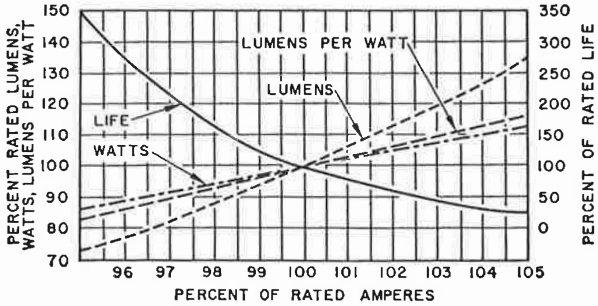


Fig. 3—Characteristic curves for incandescent lamps operated on a series circuit.

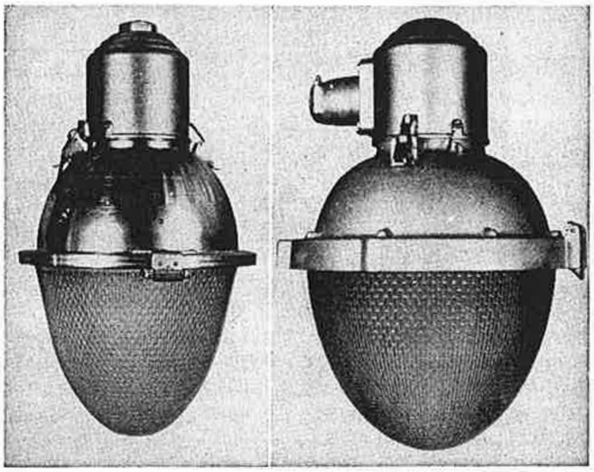


Fig. 4—Street-lighting luminaires designed for use with incandescent lamps, series or multiple, as well as type C-H5, F-H1, or E-H1 mercury lamps. (a) Type AK-10 for use with 2500- to 10,000-lumen incandescent lamps. (b) Heavy-duty type AK-14 for use with 10,000- and 15,000-lumen incandescent lamps.

Mercury Lamps—Mercury lamps belong to the general classification known as electric-discharge lamps. In this type of lamp, light is produced by the passage of an electric current through a vapor or gas rather than through a tungsten wire. The application of an electric potential ionizes the gas and permits current to flow between two electrodes located at opposite ends of the lamp. The electrons, which comprise the current stream or "arc discharge", are accelerated at tremendous speeds. When they collide with the atoms of the gas, or vapor, they temporarily alter the atomic structure. Light results from the energy given off as the disturbed atoms return to their normal state.

In mercury lamps, the "gas" utilized is vaporized mercury. Since mercury is a liquid at room temperature, a small amount of more readily ionized argon gas is introduced into mercury-vapor lamps to facilitate starting. The original arc is struck through the ionization of this argon gas. Once the arc strikes, the heat generated vaporizes the mercury. The electrodes used in mercury lamps are either of the activated type, with barium oxide as the electron-emissive material coated on a coil of tungsten wire, or of the non-activated thorium metal type. The impact of the arc heats the emissive material which supplies electrons to maintain the arc. The electrodes also act as terminals for the arc.

Mercury lamps are constructed with two bulbs: an inner bulb, or arc tube, which contains the arc, and an outer bulb which shields the arc tube from changes in temperature, and in some cases acts as a filter to remove certain wavelengths of the arc radiation. The outer bulb also carries the phosphor coating in fluorescent-mercury lamps. The arc tube is made of quartz in most lamps and of hard glass in a few of the older types. Quartz permits a more concentrated source of higher efficiency and also transmits the abundant ultraviolet radiation necessary for the fluorescent-mercury lamp. The outer bulb is of glass, the exact type determined by the application for which the lamp is designed, and the portion of the arc spectrum which it is desired to transmit. The space between the two bulbs is generally filled with inert gas.

Fig. 5 shows a number of mercury and fluorescent-mercury lamps designed for use in street-lighting luminaires.

The negative resistance characteristic of electric-discharge lamps makes it necessary to use a current-limiting device with these lamps. The device, or ballast, must provide the proper voltage to start the lamp and then limit the current through the lamp to the proper value.

Each ballast must be designed for the specific voltage, frequency, and lamp with which it will be used. An important advantage of mercury lamps is their ability to operate well over the range of input voltages for which the ballast was designed. Operation with input voltages above or below the ballast voltage range is not recommended. If the supply voltage is unusually low, the lamp may not start, or may require a longer time to warm up. When the supply voltage is too high, excessive lamp wattage may result. Fig. 6 shows the relationship of voltage, current, power, and light output for 400-watt E-H1 mercury lamps operated on typical ballasts.

The two-electrode type of mercury lamps requires starting voltages between 800 and 1200 volts to ionize the argon gas and permit the arc to strike. The more commonly used three-electrode type of lamp utilizes one electrode as a starting electrode. This starting electrode is placed close to the main electrode nearest the base of the lamp and makes it possible to start the lamp at a much lower voltage. The electrical field set up between these two electrodes causes an emission of electrons which develop a local glow and ionize the starting gas. The arc then starts between the two main elec-

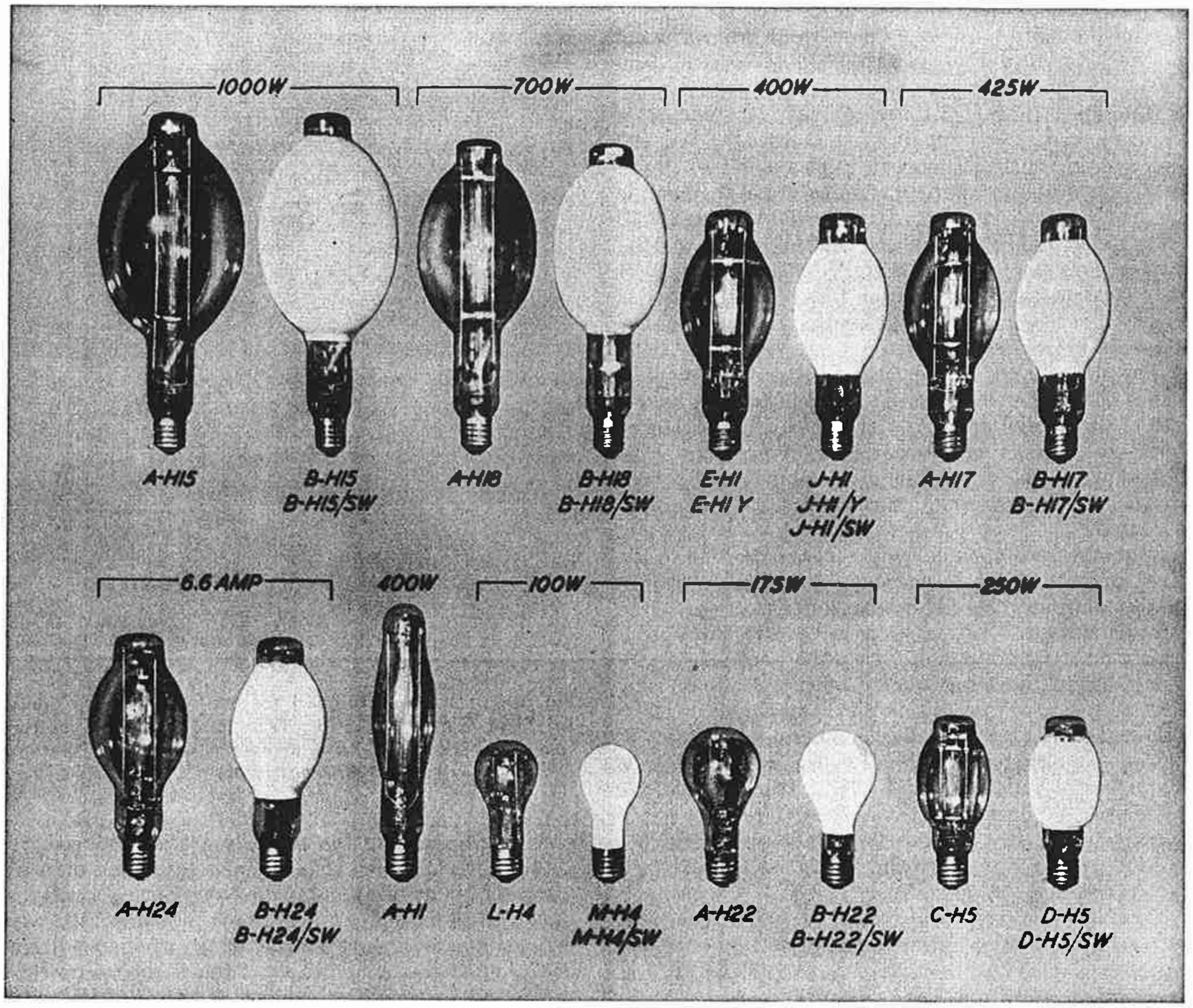


Fig. 5—Mercury and fluorescent-mercury lamps designed for use in street-lighting luminaires.

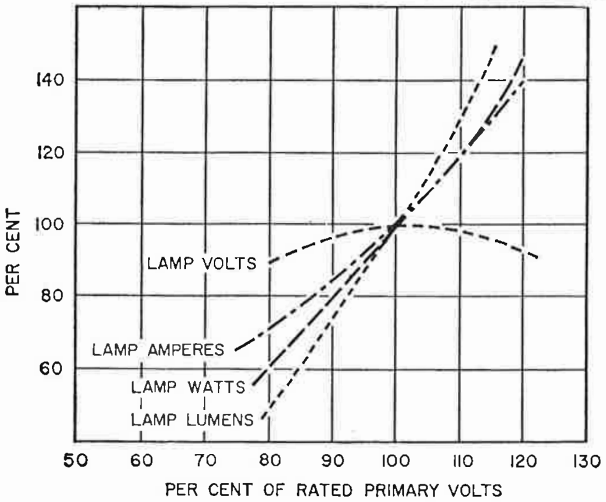


Fig. 6—Operating characteristics of 400-watt E-H1 mercury lamps with typical ballasts.

trodes, and the mercury gradually vaporizes and carries an increasing portion of the current. During this process, the arc stream changes from the diffuse bluish glow characteristic of the argon arc to the blue-green of mercury, increasing greatly in brilliance and becoming concentrated in the center of the tube. At the instant the arc strikes, the current is high and the voltage is low. Normal operating values are reached after a warm-up period of several minutes, during which time the current drops and the voltage rises until the arc attains a point of stabilization in vapor pressure.

An interruption in the power supply, or a sudden voltage dip of more than 15 to 30 per cent, may extinguish the arc. Before the lamp will re-light, it must cool sufficiently to reduce the vapor pressure to a point where the arc will restrike. During this time that the lamp is cooling, the ballast open-circuit or starting voltage is impressed on the lamp. The same condition exists when a lamp has failed or has been removed from the socket, except that a lamp replacement is necessary to correct the condition. This is termed open-circuit operation of the ballast, and the line current drawn by the ballast is termed the open-circuit line current. This operating condition does not harm the ballast.

The lumen output of a new mercury or fluorescent-mercury lamp is abnormally high. During the first 100 hours of operation, the output drops about 5 to 10 per cent. The drop during the remaining life of the lamp is gradual, as shown in Fig. 7, for the 400-watt and 250-watt lamps. Published values for initial lumens are the values obtained after 100 hours of operation. The deterioration that occurs after the 100-hour point is chiefly due to a gradual blackening of the inside of the arc tube throughout its life.

The higher initial efficiency and higher intrinsic brilliance obtained with the quartz type of lamp is the result of the smaller size arc, which has higher loading in terms of wattage per square inch of arc tube. The larger arc-chamber used in glass lamps results in a somewhat slower drop in lumen output over the life of the lamp.

With the barium-oxide type of electrode used in the glass arc-tube lamps, both life and lumen maintenance of the lamp are affected by the number of times the lamp is started. Each time the arc is struck, some of emission material is removed from the electrodes and is deposited on the inner surface of the glass arc-tube. This process results in eventual exhaustion of the emission material and blackening of the arc-tube.

The thorium electrodes used in the quartz arc-tube lamps are so little affected by lamp starting that the same average rated life and lumen maintenance apply for operating cycles of either 5 or 10 hours per start.

Fig. 8 shows two luminaires designed for use with mercury lamps.

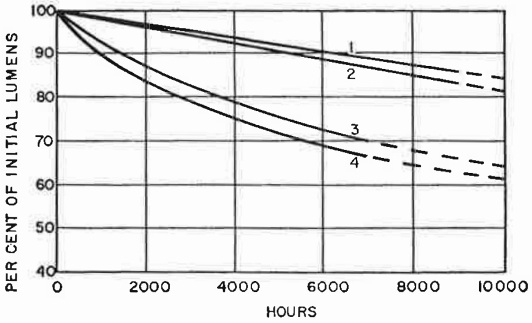


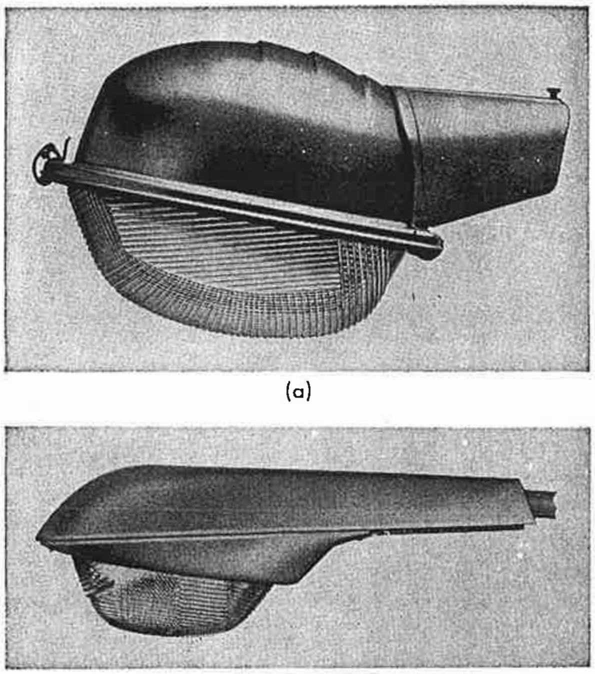
Fig. 7—Approximate lumen maintenance curves for several 400-watt mercury and fluorescent-mercury lamps.

Curve 1—Lifeguard lamps type E-H1-LG, P-H1-LG, P-H1/SW-LG, and P-H1/X-LG.

Curve 2—Lifeguard lamps type J-H1-LG, J-H1/S.W-LG, J-H1/X-LG, K-H1-LG, and L-H1-LG.

Curve 3—Standard lamps type E-H1, E-H1-WD, P-H1, and P-H1/SW.

Curve 4—Standard lamps type J-H1, J-H1-WD, J-H1/SW, J-H1/SW-WD, K-H1, and L-H1.



(a)

(b)

Fig. 8—Luminaires designed for use with mercury lamps. (a) Type OV-10 for 100-, 175-, and 250-watt mercury lamps. (b) Type OV-25 with built-in ballast for use with 400-watt, E-H1.

Fluorescent-Mercury Lamps—When an electric current is passed through vaporized mercury, the familiar blue-green-white light of the mercury arc is produced, together with a wealth of ultraviolet rays. The mercury arc can be controlled and made to produce a variety of bands of radiation. At low vapor pressures, the rays emitted consist almost entirely of the resonance line at 2537 Angstroms. An example of this is the bactericidal ray found in the Westinghouse STERILAMP which operates with a low vapor pressure of only a few microns. Westinghouse fluorescent lamps also operate at this low vapor pressure and use this radiation to excite the phosphor coating.

At medium vapor pressures, the radiations of longer wave lengths are strengthened, the energy emitted per inch of arc steam rises, and the increased energy in the visible lines results in high luminous efficiency. At higher vapor pressures, the color of the light becomes whiter, and the intensity of radiations emitted per inch of arc length rises so that these sources become invaluable where optical light control is required, such as in searchlight or projection service.

In the fluorescent-mercury lamp the medium pressure is used. This produces high luminous efficiency plus large amounts of ultraviolet energy. The ultraviolet is utilized to cause the phosphor coating (magnesium fluorogermanate) on the inside of the outer bulb to fluoresce red. This red light, added to the natural blue-green-white of the mercury arc, produces a golden-white color of light. The color of this light is approximately the same as that obtained with a mixture of equal wattages of mercury and incandescent lamps. Therefore, the use of a combination of mercury lamps and incandescent lamps to obtain white light is no longer necessary, and generally a system of fluorescent-mercury lamps is preferable.

Sodium Lamps—Sodium lamps are similar to mercury lamps in general principle, except that the arc is carried through vaporized sodium and the starting gas is neon. The vapor pressure at which the sodium arc operates is low, and the arc-tube must be enclosed in a vacuum flask to maintain the proper operating temperature. The starting time to full light output is 15 to 20 minutes, but the lamp will restart immediately after interruption of power supply.

The light produced by the sodium arc is almost monochromatic, consisting merely of a double line in the yellow region of the spectrum at 5890-96 Angstroms. Because all the energy emitted is so near the maximum of the eye sensitivity curve, efficiencies as high as 55 lumens per watt are obtained. The disadvantage of the limited spectrum is that all objects appear as yellow, or shades of yellow under the sodium lamp light. In addition, the large size and low brightness of the arc make accurate light control rather difficult.

The use of sodium lamps for street-lighting purposes never did gain great popularity in this country. Mercury and fluorescent lamps have practically eliminated the sodium lamp as a light source for street lighting. Sodium lamps are no longer stocked by any manufacturer and are available only on special orders of relatively large quantities.

Fluorescent Lamps—The fluorescent lamp is essentially an electric-discharge source. It consists of a tubular bulb with electrodes sealed into each end, and contains mercury vapor at low pressure with a small amount of argon for starting. The inner walls of the bulb are coated with fluorescent powders which give off light when activated by ultraviolet energy. When the proper voltage is impressed across the electrodes, a flow of electrons is driven from one electrode and attracted or pulled to the other. As the electrons move between the electrodes, they collide with the mercury atoms, causing a state of excitation which produces short-wave ultraviolet radiation (2537 Angstroms). The fluorescent powders, commonly known as phosphors, absorb this invisible energy and radiate visible light.

The type of electrode employed in most fluorescent lamps is the coated coiled-coil of tungsten wire. The coiled-tungsten-wire is coated with an emission material of barium and strontium oxide, which gives off emission because the electrons are emitted more as a result of the heat developed, than of the voltage applied. A hot spot is created on the cathode at the point where the mercury arc strikes, and a continuous stream of electrons is produced. This type of operation is characteristic of what is known as the "hot-cathode" lamp. As originally developed, it required a preheating of the cathodes to produce the necessary electrons to strike the arc. If a higher open-circuit voltage is applied to the lamp, the preheating of the cathode may be shortened as in the rapid-start type of lamp. If a still higher open-circuit voltage is applied to the lamp, the lamp can be made to start instantly without preheating.

Like all electric-discharge lamps, fluorescent lamps must have a ballast to limit the current and, in most cases, provide the necessary starting voltage. Each lamp requires a ballast specifically designed for its characteristics and for the service voltage on which it is to be operated. The chief differences among ballasts lie in the open-circuit voltages supplied to the lamp. Lamps with preheat cathodes require relatively low starting voltages, not over 200 volts. Instant-start lamps require from 450 to 750 volts, and rapid-start types require from 450 to 550 volts.

The life of a fluorescent lamp is affected by the voltage, the current, and the number of times it is started. Electron emission material is lost from the electrodes continuously during the operation of the lamp, and in larger quantities each time the lamp starts. Since the end of life is reached when the emission material is completely consumed for one of the electrodes, the greater the number of burning hours per start, the longer the life of the lamp. When the emission material is exhausted, lamps on a preheat type of circuit will blink on and off as the electrodes heat but the arc fails to strike. Lamps designed for instant or rapid starting will simply fail to operate. Blinking lamps should be removed from the circuit promptly to protect both the starter and the ballast from overheating.

The light output of a new fluorescent lamp drops off about five per cent during the first 100 hours of operation. Since the depreciation after this initial drop is much more gradual, fluorescent lamps are rated at the end of the 100 hour period. A typical lumen maintenance curve for a fluorescent lamp is shown in Fig. 9. The depreciation in light output is due chiefly to a gradual deterioration of the phosphor powders, and a blackening of the inside of the tube. The blackening of the tube is produced by the electrode material deposited on the inner surface of the tube, and is therefore more pronounced at the ends of the lamp.

The voltage at the luminaire should be kept well

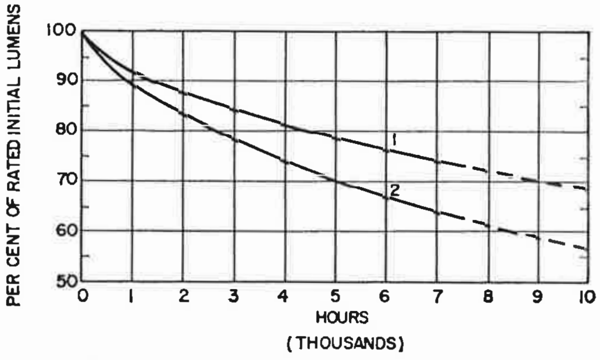


Fig. 9—Typical lumen maintenance curve of Westinghouse type HO and SHO fluorescent lamps normally used for street-lighting applications.

Curve 1—Medium loading of approximatety 800 milliamperes.

Curve 2—Heavy loading of 1000 to 1500 milliamperes.

within the normal operating range for the ballast. Low voltage, as well as high voltage, reduces efficiency and shortens lamp life. This is in contrast with filament lamps, where low voltage reduces efficiency but prolongs the life of the lamp. Low voltage may also cause instability in the arc, and starting difficulty.

On voltages above the specified range, the operating current becomes excessive and may not only overheat the ballast, but may also cause premature end-blackening and early lamp failure. Voltages below the specified range may lower the preheat current to a point where the electrodes fail to emit a sufficient number of electrons to permit starting the lamp. If the lamps do start, the emission material may waste away too rapidly, with consequent shortening of lamp life.

Fig. 10 shows a four-tube fluorescent luminaire, with cover cutaway, that is used in applications where relatively high illumination levels are required. This unit is normally mounted perpendicular to the axis of the roadway. The luminaire shown in Fig. 11 is also used for high illumination levels, but this unit is mounted parallel to the axis of the roadway.

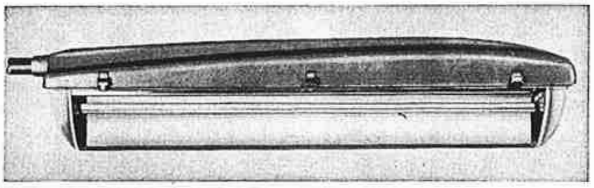


Fig. 10—Type 4FSL-72 fluorescent luminaire which uses four six-foot, 5300-lumen fluorescent lamps.

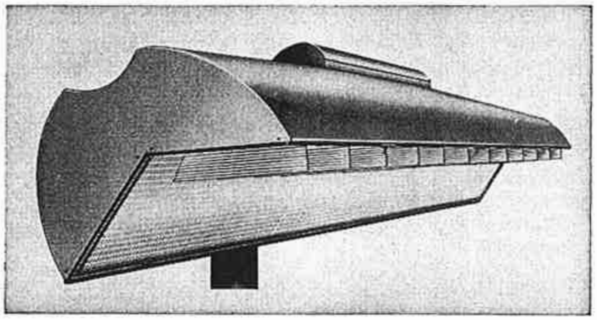


Fig. 11—Type 2HUS-72 "Mainstreeter" fluorescent luminaire which uses two six-foot, 5300-lumen fluorescent lamps.

II. SERIES SYSTEM

4. Description of Series System

As the name implies, all of the lamps in a series street-lighting system are connected in series in the lighting circuit. A constant current is maintained in the circuit, and consequently through all of the lamps, by means of a constant-current transformer.

Method of Supply—Two supply circuits are required for a series street-lighting system. One supply circuit is the high-voltage circuit for the constant-current transformer, and the other is the low-voltage circuit for the control circuit. The high-voltage supply is usually a single-phase tap from a primary feeder that exists in the area to be lighted. The low-voltage supply for the con-

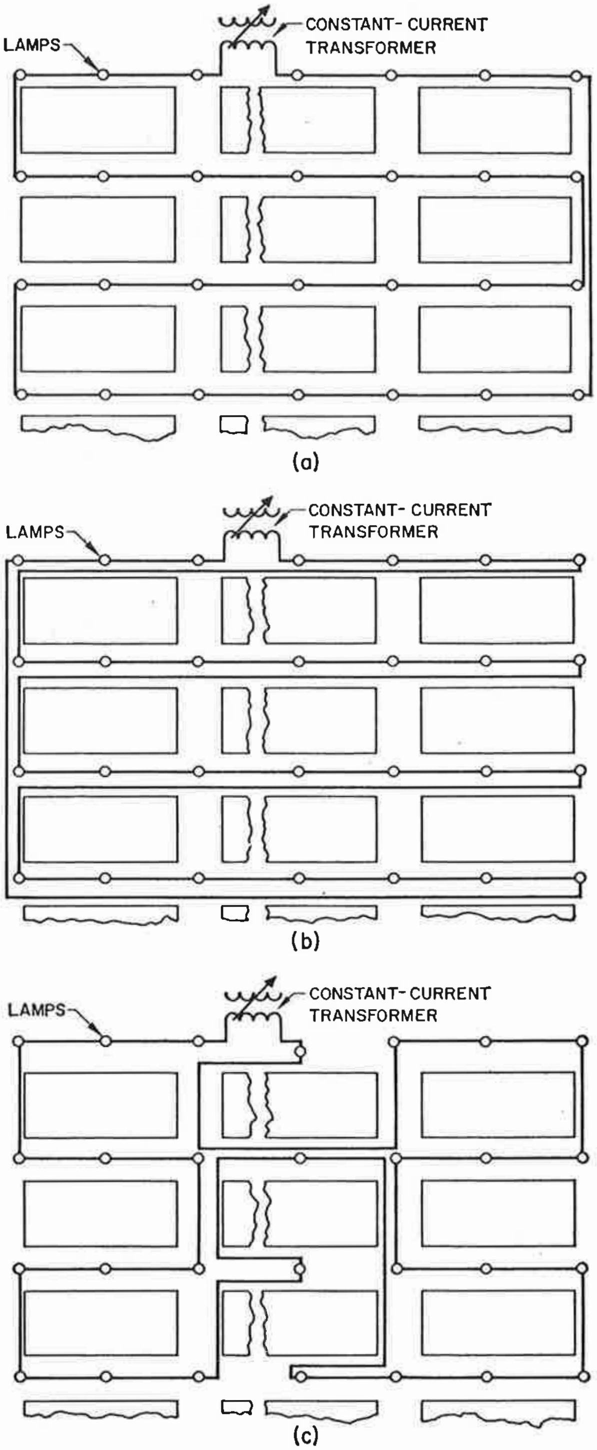


Fig. 12—Several possible series circuit arrangements to serve a given area. (a) Minimum conductor length—most difficult to test for open-circuit condition. (b) Maximum practical conductor length—easiest to test for open-circuit condition. (c) Compromise between conductor length and ease of open-circuit testing.

trol circuit is taken from a nearby 120/240-volt secondary circuit. If no secondary circuit exists close to the constant-current transformer location, a source of low-voltage supply for the control can be established through the installation of an instrument transformer or a distribution transformer having a relatively low kva rating.

Layout—Several simplified series street-lighting circuits are shown in Fig. 12. These different circuit arrangements illustrate the compromise that is made between circuit length and ease of testing under open-circuit conditions. Fig. 12(a) shows an arrangement that provides minimum conductor length but is very difficult to test for an open-circuit condition. Fig. 12(b) shows the other extreme, where testing is greatly simplified, but conductor length is at a maximum. Fig. 12(c) is a compromise between (a) and (b), in which the conductor length is greater than in (a), but less than in (b); and the ease of testing is better than in (a), but poorer than in (b).

The voltage drop across each lamp must be the rated voltage of the lamp in order to obtain rated lumen output. The voltage applied to the circuit must then equal the sum of the voltage drops across each of the lamps and the voltage drop in the circuit conductors. Consequently, the source voltage must be variable to permit variations in the number of lamps and in the length of the circuit. The voltage impressed upon the circuit by the constant-current transformers may vary from a few hundred volts to approximately 4500 volts, depending upon the number of lamps and the length of the circuit. However, when an open-circuit condition exists, the voltage can reach 6000 volts. The transformer automatically adjusts itself to maintain the desired current through the circuit for load conditions within its rated capacity. Changes in the impedance of the circuit due to lamp burnout, or extension of the circuit, are automatically compensated for by the constant-current transformer.

Where Applicable—The main area of application of series street-lighting systems is where illumination level requirements are relatively low and luminaires are relatively far apart. For the most part, this is brought about by the savings that can be made through the use of small conductors at the high voltage. Series systems are used almost exclusively in areas where secondary distribution circuits are not available, such as on parkways, highways, and in rural areas. Series street-lighting applications also predominate in residential areas.

The use of a series system is more attractive to operating companies if they are operating series systems and do not have to change the inventory of street-lighting equipment maintained in stock. Significant savings are available if local regulations and code do not require that insulating transformers be used with each luminaire. Another factor that indicates that series circuits probably should be used in expanding street lighting is that a considerable amount of constant-current transformer capacity is available. Having personnel available that are qualified to operate and maintain the high-voltage series systems is also important.

Limitations—Series street-lighting circuits are generally not used in commercial areas where secondary circuits exist at almost all points where a luminaire might be installed. This is particularly true in areas where secondary-network systems exist.

The main disadvantage of the series street-lighting circuit is that high voltages are present in the case of an open-circuit condition unless a series transformer is used. In addition to presenting a safety hazard to maintenance personnel, this results in increased investment in equipment that must withstand these high voltages.

5. Selection of Current Rating

Current Ratings Available—Series street-lighting circuits have constant-current ratings of 3.3, 6.6, 7.5, 15, and 20 amperes. The most commonly used of all of these constant-current ratings are the 6.6-ampere and the 20-ampere ratings.

The 6.6-ampere rating is a carry-over from the days of the magnetic-arc lamps. The 6.6-ampere constant-current transformers used for the arc lamps were standard equipment, and filament lamps were designed for use with these transformers.

The 7.5-ampere rating is also a carry-over from the days of the arc lamp. However, the 7.5-ampere rating makes up only a very small percentage of all installations.

The 15-ampere and 20-ampere ratings came into use through several advantages that they offer over the 6.6-ampere rating. First of all, in most cases the size of the circuit conductors in a series circuit is determined by the mechanical strength of the conductor. This means that the current-carrying capacity of the conductor used for a 6.6-ampere circuit is considerably in excess of the current that it has to carry. The 15- and 20-ampere circuits permit taking better advantage of the current-carrying capacity that is available in the conductor. Another advantage of the higher amperage circuits is that the circuit voltage is reduced to approximately one-third that of a 6.6-ampere circuit. Or, looking at it another way, for the same maximum voltage at either 6.6 amperes or 20 amperes, the number of lamps in a 20-ampere circuit may be approximately three times the number on a 6.6-ampere circuit.

The 3.3-ampere rating has come into use with mercury lamps. The 6.6- and 20-ampere rating had been very nearly standardized upon by the time that the mercury lamps were introduced. Since each mercury lamp type required a different operating current, it became common to restrict the open-circuit voltage at the luminaire through the use of a two-winding current transformer with an air gap in the core. The one type of mercury lamp that predominates among the mercury installations requires 3.3 amperes. Since this condition has come about, a 3.3-ampere constant-current system has been developed to use these lamps. This system eliminates the use of a small current transformer or series-mercury transformer at each lamp, but requires the use of a non-standard constant-current transformer for the lighting circuit.

There are a number of factors that influence the decision as to which of the current ratings is to be used in a new installation. Established practice is usually the determining factor. However, when future planning is taken into account, the continuation of existing practice may not be the most economical answer.

Local codes, safety to maintenance personnel, and local rates for street lighting also influence the choice of current rating for a series circuit.

6. Description of Equipment for Series System

Fig. 13 shows in detail the equipment used in a series street-lighting circuit. At the left of the figure are the two sources of supply that serve the system. The primary feeder tap supplies power for the lights, and the 120-volt tap supplies power to the control circuit.

Constant-Current Transformers—To obtain full or rated lumen output from the lamps in a series street-lighting circuit, the current flowing through the lamps must not be lower than the rated current of the lamps. To avoid serious reduction in lamp life, the current must not be allowed to increase above the rated value. Therefore, it is desirable that a current equal to the rated current of the lamps flow in the circuit, regardless of the number of lamps on the circuit or the length of the circuit.

Since electric energy is generated at constant potential, these series systems require an intermediate device to transform the energy from a constant potential to a constant current. The device which is economical and most desirable, because it gives the closest current regulation for all loads, is the moving-coil constant-current transformer. These transformers are designed to convert a constant-potential value (ranging from 2.4 kv to 13.2 kv) to a constant-current value of 3.3, 6.6, 7.5, 15 or 20 amperes.

The early constant-current transformers were all of the air-cooled, open-construction design for indoor applications. Since most of the early street-lighting circuits originated at an attended station, the constant-current transformer could conveniently be installed indoors. Increased use of street lighting made it necessary to develop oil-insulated, pole-type, and subway-type units that could be installed throughout the system. Present day pole-type units are available with added built-in features for complete protection against lightning, against faults in the primary winding, and against open-circuit conditions on the lighting circuit.

The discussion given below describes the theory and principles of operation of constant-current transformers. In particular, this discussion refers to the open station-type unit. While the construction of the pole- and subway-types of constant-current transformer are slightly different, the same theory of operation applies to each type.

The constant-current transformer is a two-winding transformer with one coil which is movable with respect to the other. The movable coil is balanced by a counterweight, and its position is determined by the electromagnetic force between the coils.

In Fig. 14(a) and (b), P is the primary coil, S is the secondary coil, W is the wheel or lever arrangement used to suspend the moving coil, and C is the counterweight. Assume that a voltage is applied to P while the circuit of S is open. An exciting current will flow and a magnetic flux will be induced through the primary coil and up the middle leg of the iron to the top. Here the total flux will divide, and one-half will return down each of the outer legs to the primary coil. The amount of flux through P is determined from the transformer formula, $E=(k)\ (f)\ (A)\ (N)\ (B)$; where E=voltage, k=a con-

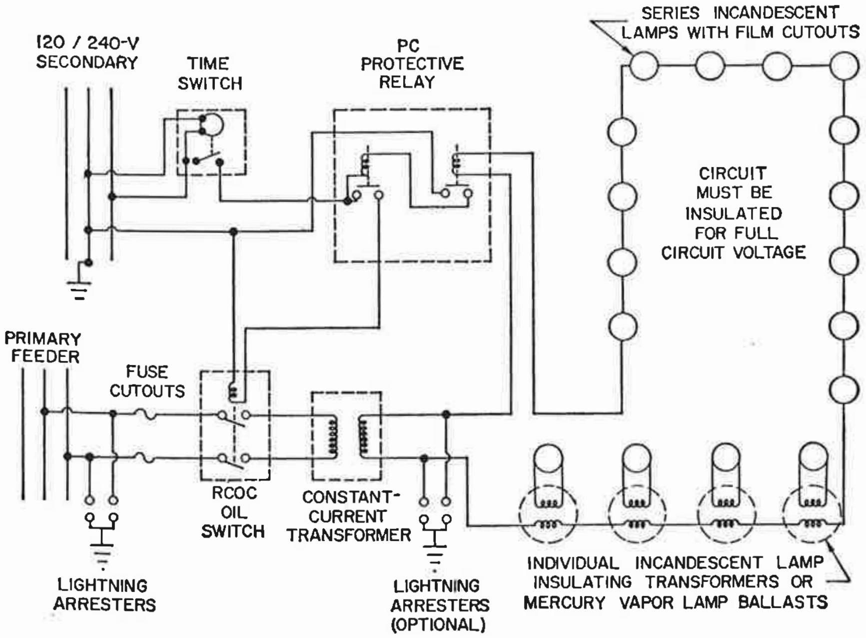


Fig. 13—Schematic diagram of a series street-lighting circuit.

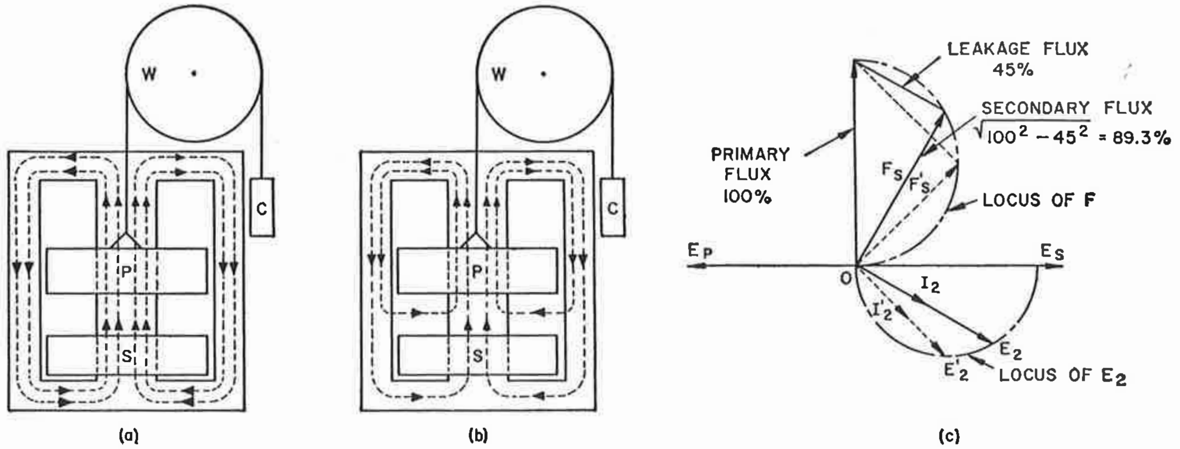


Fig. 14—Magnetic circuit and flux path of a movable-coil constant-current transformer. (a) With secondary open. (b) With secondary closed through load circuit. (c) Vector diagram of primary and secondary voltages and flux with secondary closed through load circuit.

stant, A = area of core, N = number of turns, B = flux density, and f = the frequency in cycles per second.

The flux in the iron induces a voltage in the secondary coil, and, if the circuit is completed, a current will flow. The current in S sets up a magneto-motive force opposed to that of P, and a part of the magnetic flux through P will be forced across the opening between P and S, instead of following the iron circuit. This has two results. First, the voltage in S will be reduced because of the reduced flux which links it; and second, there will be an electromagnetic force on P tending to raise it. This force is caused by the reaction of the leakage flux on the current in S. The counterweight is normally adjusted so that the weight of the coil is just equal to the counterweight plus the electromagnetic force when the coil is carrying the desired current.

If a part of the load is suddenly short-circuited, there will be an instantaneous rise in the secondary current, and consequently in the leakage flux. This results in an increased force between coils, and the primary coil moves upward. The leakage space between the coils is thus increased, and the secondary voltage is diminished to a point where it will again send only the desired current through the circuit.

The relation of the various quantities is shown by the vector diagram, Fig. 14(c). For the sake of simplicity, the losses in the transformer are neglected, and it is assumed that the secondary load has a power factor of 100 per cent. If OE_p is the voltage applied to the primary coil, OF will be the flux which links this coil. OE_s, exactly opposite to OE_p, would be the voltage induced in the secondary if there were no magnetic leakage—that is, if the secondary coil were open circuited. At full load on the secondary, there will be a normal leakage between the primary and the secondary amounting to 45 per cent of the primary flux, more or less; and since this leakage flux is in phase with the secondary current, it will be perpendicular to the flux through the secondary coil, which produces the secondary voltage. Therefore, on OF as a hypotenuse, construct a right triangle with one side equal to 45 per cent of OF, and the other side equal to $\sqrt{100^2-45^2}=$ 89.3 per cent of OF. OF_s is the flux which induces the secondary voltage, and it leads the secondary voltage by 90 degrees. The secondary voltage at the load is OE_2, and the secondary current will be in phase with OE_2, since the load power factor is 100 per cent.

If a part of the load is short-circuited, the coils will move apart as explained above. This will cause the vectors to take the position shown by the dotted lines, increasing the leakage flux and decreasing the flux through the secondary coil, with a consequent reduction of the secondary voltage. The secondary current is thus brought back to its normal value. Constant-current transformers are usually designed so that, with normal voltage and frequency on the primary, and with the secondary short-circuited, normal secondary current will not quite cause full separation of the coils.

It is interesting to trace the effect of a change in the primary voltage or frequency when the secondary load is not changed. An increase in the primary voltage will cause an increase in the primary flux. Since the secondary flux remains the same for the same load, the coils move apart so as to increase the per cent leakage. This lowers the primary power factor. It may also cause an increase in the short-circuit current of the secondary coil if the moving coil reaches the top of the opening.

An increase in the primary frequency, without a corresponding change in voltage, decreases the primary flux. The secondary flux decreases in the same proportion. The leakage flux also decreases in the same proportion, and the coils therefore must move closer together. The frequency can be varied only within rather narrow limits without changing the voltage. If it becomes too low, the magnetic density in the iron becomes too high. If the frequency is too high, the per cent leakage becomes high and the transformer has reduced capacity and poor power factor.

The primary windings of constant-current transformers are usually provided with taps, and, from what has gone before, it will be easy to see the effect of using the taps. If 2200 volts is applied to the 2400-volt connection on the transformer, the volts-per-turn, and consequently the flux through the primary coil, is decreased. For any given output therefore, the coils are closer together, the leakage is less, and the power factor is higher. If 2600 volts is applied to the 2400-volt connection, the effect is the reverse. For a given output, the coils are farther apart, and, if the secondary is short circuited, there may be a rise of current because the coils may not be able to move far enough apart.

The current regulation of a constant-current transformer is quite accurate. The moving parts are supported on ball bearings and, if the transformer is mounted reasonably level so that the coil travels freely, the current should not vary more than one per cent from its rated value.

This type of transformer cannot be overloaded, because the secondary current will decrease if the load capacity of the regulator is exceeded. The no-load condition corresponds to a short-circuit on the secondary load terminals and, under this condition, the position of the movable coil approaches that of maximum separation. At full load, the coils are at nearly minimum separation. If the load is increased beyond the full-load value, the coil separation is further decreased until the bumper-stop is reached. Beyond this point, any increase in load will result in a corresponding decrease in secondary current.

Because of the constant-current characteristic, the I^2R loss in this type of transformer remains constant for all load values, but the stray loss increases with a decrease in load. Consequently, the total loss increases with decrease in load and is maximum at no-load. The operating temperature is therefore lower when operating at nearly full load than when operating at only a fraction of the full-load rating.

The constant-current transformer will operate correctly as long as the variation in the primary supply voltage is not greater than five per cent above or below the rated tap voltage, and provided the secondary is not loaded above the rated load for the particular transformer. For example, the 4800-volt tap accommodates voltages ranging from 4560 volts to 5040 volts. A 4320-volt tap on the transformer provides for voltages ranging from 4100 volts to 4540 volts.

There are two basic types of pole-type constant-current transformers and one subway-type which are manufactured by Westinghouse. These units are available in standard kw ratings of 10, 15, 20, 25, and 30 kw with single-voltage primaries for 2400, 4800, or 7200 volts, and dual-voltage primaries for either 2400 or 4800 volts. The standard rated current for the secondary windings of constant-current transformers are 6.6 or 20 amperes. These units are designed in accordance with AIEE, ASA, and EEI-NEMA Standards, and, in line with these standards, deliver rated output at secondary terminals to a 99½ per cent power-factor load at 95 per cent of rated primary voltage. Temperature rise in the windings does not exceed 55C above a 40C ambient temperature when operated at 50 per cent of rated load for eight hours. These transformers have 48 per cent minimum inherent impedance to prevent excessive current inrush to the lamps when the circuit is energized. The transformers are subjected to the dielectric tests given in Table 4.

Table 4—Constant-Current Transformer Dielectric Tests

Rated Circuit Voltage In Volts	Impulse Test Full Wave Crest-Kv	60 Cycle Test-Kv
2400/4160Y	60	19
4800/8320Y	75	26
4800/2400	75	26
7200/12470Y	95	34

The pole-type CPH constant-current transformer shown in Figs. 15 and 16 has the operating characteristics outlined above. The type CPH transformer with cover-mounted bushings is available with primary voltages from 7200 volts through 13.2 kv. It is not available with primary voltages below 7200 volts, nor with lightning arresters. The type CPH transformer with wall-mounted bushings and de-ion arresters provides protection against lightning surges between the primary and core or tank, between the secondary and core or tank, and between the primary and secondary windings.

The pole-type CSPH constant-current transformer is a self-contained "package unit" that includes an oil switch, a type PC protective relay, de-ion arresters,

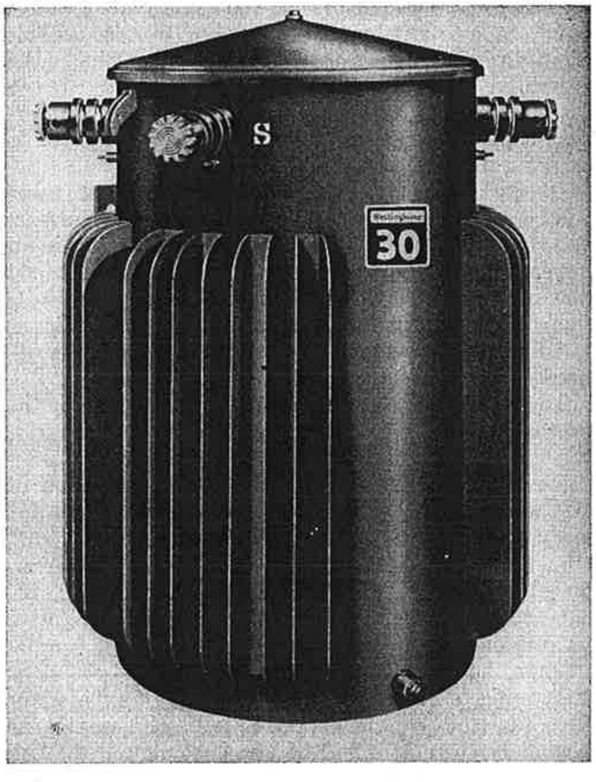


Fig. 15—Westinghouse pole-type CPH constant-current transformer for series street-lighting circuits.

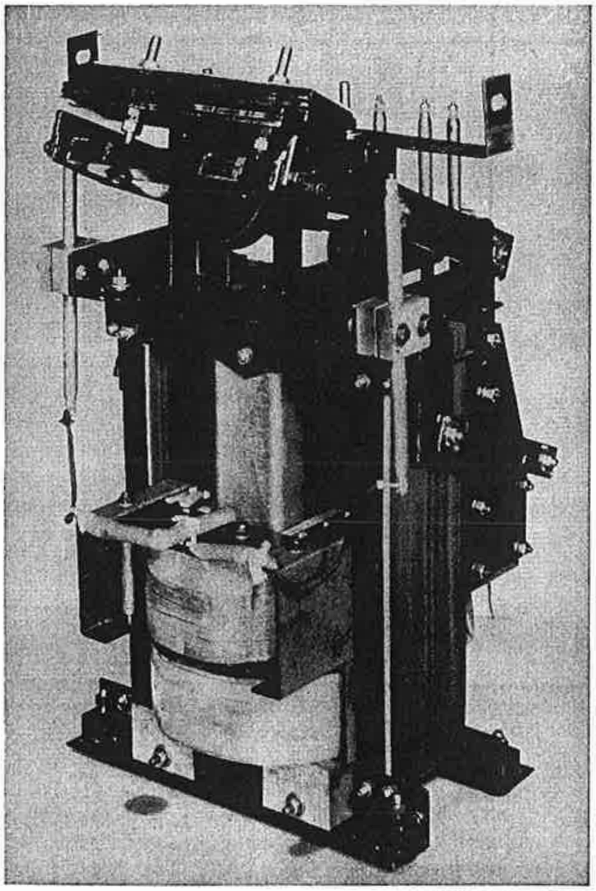


Fig. 16—Core and coil assembly of Westinghouse pole-type CPH constant-current transformer.

fusible protective links, and the core and coil assembly, housed in one tank.

The type CSPH transformer is also available with shunt capacitors mounted externally on the tank to correct the normal power factor to a high power factor for all conditions of load within the capacity and rating of the unit. This unit is designated as type CSPH-C.

The type CSPH-K differs from the CSPH unit in that it includes a series-cascade controlled oil switch and protective relay. This unit is designed specifically for series-cascade installations.

The subway-type constant-current transformer, designated type CMH, is a waterproof unit designed for operations in vaults and manholes.

Table 5 gives the electrical characteristics and performance data for all of the pole-type constant-current transformers described above, with the exception of the CSPH-C unit. The same type of information for the CSPH-C unit is given in Table 6.

Circuit Switch and Controls—Lamps on series street-lighting circuits are turned on and off through the action of a switch in the high-voltage circuit that supplies the constant-current transformer. The switching operation may be initiated by any one of several types of controls available. The type of control used will depend upon the location of the street-lighting circuit, the specific purpose of the lights, the time cycle of operation for the lights, etc. Among the most common control methods are manual control, time switches, and photoelectric cells. A discussion of the characteristic and operation of these controls appears elsewhere in this chapter.

The switch used to energize or de-energize the constant-current transformer can be almost any type of air or oil circuit breaker, as long as the switch selected has the necessary voltage, current, and interrupting ratings. This is particularly true if the street-lighting circuits terminate at an attended substation and the circuit is switched manually. Most circuits, however, are remote from an attended substation and remote switching is necessary.

The most common type of switch for remote operation is a pole-mounted, two-pole, oil-filled switch.

Schematic diagrams of the type RCOC oil switch are shown in Fig. 17. The diagram in Fig. 17(a) has a shunt operating coil rated at 120 volts at 60 cycles. This coil is energized from the low-voltage supply circuit through the circuit control. The diagram in Fig. 17(b) is for a switch used in a series-cascade circuit arrangement. Instead of a 120-volt coil, this switch has a 6.6-ampere constant-current coil which is energized from a 6.6-ampere series street-lighting circuit.

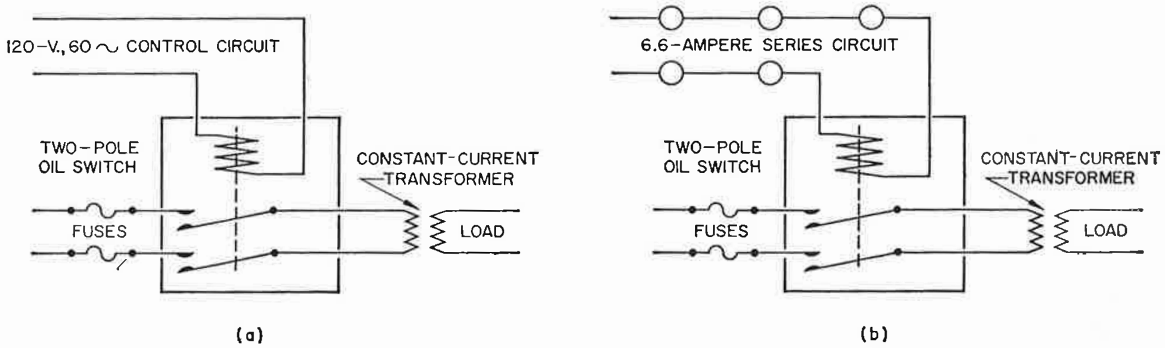


Fig. 17—Schematic diagram of two types of RCOC oil switches. (a) Switch with control circuit energized from 120-volt circuit. (b) Switch with control circuit energized from 6.6-ampere series street-lighting circuit for cascade operation.

Table 5—Electrical and Performance Data For All Westinghouse Pole-Type Constant-Current Transformers Except Type CSPH-C

Kw Rating	Approx. Primary Amps. at All Loads	Approx. Kv-a Input at All Loads	Secondary Open Circuit Voltage	Secondary Normal Load Voltage	Approx. Max. Output at Unity Pf-Kw	Efficiency▲ Full Load	Efficiency▲ ¾ Load	Efficiency▲ ½ Load	Efficiency▲ ¼ Load	Primary Power Factor (%) Full Load	Primary Power Factor (%) ¾ Load	Primary Power Factor (%) ½ Load	Primary Power Factor (%) ¼ Load
2400 Volts Primary – 6.6 Amperes Secondary													
10	5.87	14.1	2090	1515	11.30	95.1	93.5	90.4	82.2	75	56	38	20
15	8.75	21.0	3090	2270	16.95	95.8	94.3	91.7	84.3	75	56	38	20
20	11.6	27.8	4090	3030	22.6	96.2	95.0	92.5	85.9	75	56	38	20
25	14.4	34.6	5110	3790	28.3	97.0	95.9	93.7	87.5	75	56	38	20
30	17.3	41.5	6130	4550	33.9	97.0	96.0	93.9	88.5	75	56	38	20
2400 Volts Primary – 20 Amperes Secondary													
10	5.87	14.1	690	500	11.30	95.1	93.5	90.4	82.2	75	56	38	20
15	8.75	21.0	1020	750	16.95	95.8	94.3	91.7	84.3	75	56	38	20
20	11.6	27.8	1350	1000	22.6	96.2	95.0	92.5	85.9	75	56	38	20
25	14.4	34.6	1690	1250	28.3	97.0	95.9	93.7	87.5	75	56	38	20
30	17.3	41.5	2020	1500	33.9	97.0	96.0	93.9	88.5	75	56	38	20
4800 Volts Primary – 6.6 Amperes Secondary													
10	2.93	14.1	2090	1515	11.30	95.1	93.5	90.4	82.2	75	56	38	20
15	4.37	21.0	3090	2270	16.95	95.8	94.3	91.7	84.3	75	56	38	20
20	5.80	27.8	4090	3030	22.6	96.2	95.0	92.5	85.9	75	56	38	20
25	7.20	34.6	5110	3790	28.3	97.0	95.9	93.7	87.5	75	56	38	20
30	8.65	41.5	6130	4550	33.9	97.0	96.0	93.9	88.5	75	56	38	20

4800/2400 Volts Primary – 6.6 Amperes Secondary	4800 Volts	2400 Volts												
10	2.93	5.87	14.1	2090	1515	11.30	95.1	93.5	90.4	82.2	75	56	38	20
15	4.37	8.75	21.0	3090	2270	16.95	95.8	94.3	91.7	84.3	75	56	38	20
20	5.80	11.6	27.8	4090	3030	22.6	96.2	95.0	92.5	85.9	75	56	38	20
25	7.20	14.4	34.6	5110	3790	28.3	97.0	95.9	93.7	87.5	75	56	38	20
30	8.65	17.3	41.5	6130	4550	33.9	97.0	96.0	93.9	88.5	75	56	38	20

7200 Volts Primary – 6.6 Amperes Secondary													
10	1.96	14.1	2090	1515	11.30	95.1	93.5	90.4	82.2	75	56	38	20
15	2.92	21.0	3090	2270	16.95	95.8	94.3	91.7	84.3	75	56	38	20
20	3.86	27.8	4090	3030	22.6	96.2	95.0	92.5	85.9	75	56	38	20
25	4.80	34.6	5110	3790	28.3	97.0	95.9	93.7	87.5	75	56	38	20
30	5.77	41.5	6130	4550	33.9	97.0	96.0	93.9	88.5	75	56	38	20

▲Conventional efficiency based on I^2R loss at 75°C and measured core loss at normal primary voltage with secondary open.

Table 6—Electrical and Performance Data For Westinghouse Pole-Type CSPH-C Constant-Current Transformers

Kw Rating	Approx. Primary Amps. at Full Load	Approx. Primary Kv-a Input at Full Load	Secondary Open Circuit Voltage	Secondary Normal Load Voltage	Approx. Max. Output at Unity Pf-Kw	Efficiency (%)♦ Full Load	Efficiency (%)♦ ¾ Load	Efficiency (%)♦ ½ Load	Efficiency (%)♦ ¼ Load	Primary Power Factor (%)▲ Full Load	Primary Power Factor (%)▲ ¾ Load	Primary Power Factor (%)▲ ½ Load	Primary Power Factor (%)▲ ¼ Load
2400 Volt Primary – 6.6 Amperes Primary													
15	6.58	15.8	3090	2270	16.95	95.8	94.3	91.7	84.3	100	98	89	64
20	9.13	21.9	4090	3030	22.6	96.2	95.0	92.5	85.9	–97	100	99	92
25	10.8	26.0	5110	3790	28.3	97.0	95.9	93.7	87.5	100	98	89	64
30	13.0	31.1	6130	4550	33.9	97.0	96.0	93.9	88.5	100	98	89	64
4800 Volt Primary – 6.6 Amperes Secondary													
15	3.29	15.8	3090	2270	16.95	95.8	94.3	91.7	84.3	100	98	89	64
20	4.56	21.9	4090	3030	22.6	96.2	95.0	92.5	85.9	–97	100	99	92
25	5.40	26.0	5110	3790	28.3	97.0	95.9	93.7	87.5	100	98	89	64
30	6.50	31.1	6130	4550	33.9	97.0	96.0	93.9	88.5	100	98	89	64

♦Conventional efficiency based on I^2R loss at 75°C and measured core loss at normal primary voltage with secondary open.
▲As corrected with capacitors.

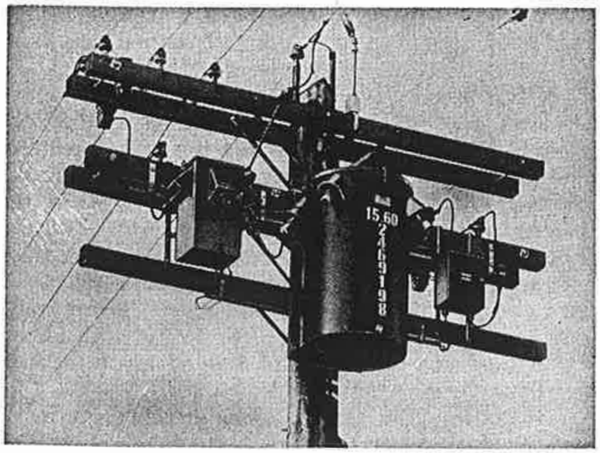


Fig. 18—Series street-lighting installation showing a type AN oil switch, a constant-current transformer, and a type PC protective relay.

A typical pole-type installation of an oil switch, a constant-current transformer, and a protective relay are shown in Fig. 18.

Standard oil switches have interrupting ratings of 50 amperes at 2500 volts, 35 amperes at 5000 volts, and 15 amperes at 7500 volts line-to-line, for use on 5.0/8.66-kv systems, and for line-to-neutral supply of an 8.66/15-kv wye class system. Other ratings are available, but the above ratings are the most commonly used. All units have auxiliary hand levers for manual operation.

In the case of the type CSPH constant-current transformers, the switch is included as an integral part of the packaged unit and is located in the same tank with the transformer. A wiring diagram of these packaged units is shown in Fig. 19 for both the 120-volt control and the series-cascade control.

Film Cutouts—Film cutouts are used with individual lamps in series circuits to insure continuity of the circuit after a lamp failure. The film cutout is inserted between the series socket prongs of the series luminaire. This puts the cutout in parallel with the lamp. At voltages somewhat higher than the normal lamp voltage, the cutout acts as an insulator. Upon failure of the lamp, it breaks down at a value below the open-circuit voltage of the line.

Film cutouts are an important connecting link in the system, and their failure to operate properly may cause expensive and serious lamp outages, possible damage to equipment, and both radio and telephone interference due to harmonic voltages.

For correct operation, the film cutout must function in the following manner:

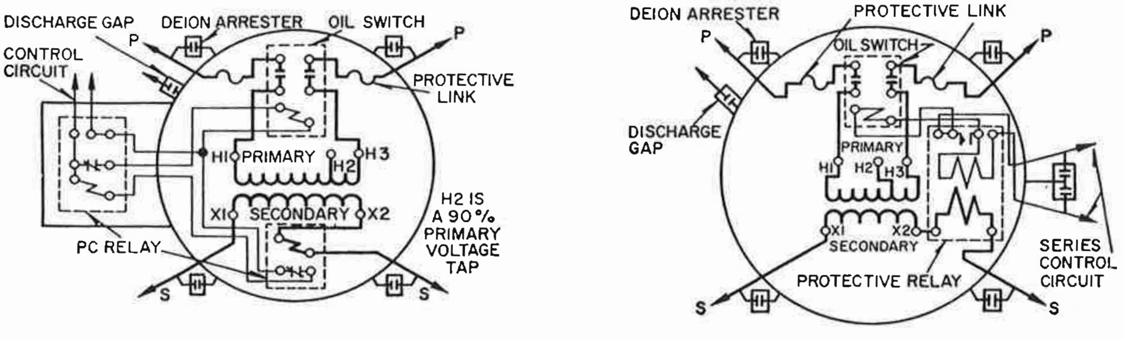
1. It shall break down immediately upon failure of the lamp filament (due to burnout or mechanical damage), and insure continuity of the circuit by short circuiting the socket prongs.
2. The short-circuit established by the film cutout shall be positive and permanent. Its current-carrying capacity should be sufficient to avoid excessive voltage drop, thus eliminating unnecessary line losses, radio and telephone interference, and overheating of the socket and receptacle.

There are three different film cutouts that are used in series circuits. They are designated as low-voltage, intermediate-voltage, and medium-voltage film cutouts. The low-voltage and intermediate-voltage cutouts consist of two thin aluminum discs, three-quarters of an inch in diameter, which are separated by means of a thin asbestos washer. The hole in the center of the asbestos washer is filled with finely divided aluminum powder. The aluminum discs and the asbestos washer are firmly cemented together.

The medium-voltage film cutout consists of two aluminum discs coated on the inside with a mixture of graphite and aluminum powder. The discs are firmly cemented to an asbestos washer, which acts as a heat-resisting spacer.

Table 7 gives the area of application of these three types of film cutouts.

Conductors—Weather-proof conductors are normally used on overhead series street-lighting circuits. Bare conductors may be used where local codes permit, and where sufficient spacings between street-lighting circuits and primary feeder circuits are practical to avoid



(a) (b)

Fig. 19—Schematic diagram of two types of packaged unit constant-current transformers. (a) Type CSPH constant-current transformer with 120-volt control circuit. (b) Type CSPH-K constant-current transformer with control circuit that is directly in series with a series lighting circuit supplied from another transformer.

Table 7—Application of Film Cutouts for Incandescent Lamps Used With or Without Insulating Transformers

Film Cutout Designation	Breakdown Voltage In Volts			Lamp Rating	
	Min.	Max.	Avg.	Lumens	Amperes
Low (L)	40	100	60	1000	6.6
				1000	7.5
				2500	15.0
				4000	15.0
				4000	20.0
				6000	20.0
Intermediate (B)	75	150	100	2500	6.6
				2500	7.5
				4000	6.6
				4000	7.5
				10000	20
				15000	20
Medium	100	400	250	6000	6.6
				6000	7.5
				25000	20

contact between the conductors. Since the current flowing in a series circuit is relatively low, the conductor size is usually determined by mechanical strength. In most cases, No. 8 or No. 6 copper conductors are used.

The selection of conductors for use in underground lighting circuits is somewhat complicated by the fact that these conductors may be installed in duct banks with distribution circuits, in separate ducts, or directly buried in the earth.

In the downtown areas of large cities, the distribution system is normally underground with the cables installed in multiple duct banks. In many cases, there are spare ducts available that can be used solely for street-lighting circuits. Practice over the years has been to install varnished-cambric, paper, or rubber-insulated cable with lead sheath in these ducts. The grounding of the sheath and the wiping of all splices and terminations have given this type of cable an excellent operating record. In recent years there has been an increase in the use of synthetic materials in this type of application, with rubber-insulated neoprene-jacketed cables also giving excellent performance.

A survey of utility practice, where separate conduits are used for street-lighting circuits, shows that the large majority of companies prefers rubber or rubber-like insulation covered by a neoprene jacket. Single-conductor No. 8 or No. 6 with 5-kv insulation is usually used.

Direct burial of cables for street-lighting service presents a few problems that are not present when ducts are used. The cables are usually more exposed to mechanical damage, plus the fact that when a fault occurs it usually costs more to locate and eliminate the trouble. For these reasons, many companies use lead-covered cables or parkway-type cables to minimize troubles. In many cases, the use of rubber-neoprene cables with or without some mechanical protection above the cable is believed to be adequate for this type of installation. Single-conductor No. 8 or No. 6 copper cables are normally used for directly-buried circuits.

7. Cascading

Description—Series-cascading of street-lighting circuits is accomplished by inserting the control relay of one constant-current transformer into the load circuit of another constant-current transformer. When the parent circuit is energized, the control in the load circuit closes and energizes the cascaded circuit. A third circuit can be controlled by putting its control in the load circuit of the first cascaded circuit. Theoretically, any number of circuits could be controlled in this manner by inserting the control of each circuit in the load circuit of the adjacent cascaded circuit.

Application—This type of street-lighting control is used primarily where economy can be achieved through elimination of time-clock or photo-electric control for the new circuits.

Cascading has a definite disadvantage in that each cascaded circuit is dependent upon all of the circuits between it and the parent control. If there were a fault in any of these circuits, or if any control relay failed to close, then all of the cascaded circuits beyond the trouble spot would not be energized.

Constant-Current Transformers—The type CSPH-K constant-current transformer is designed for installations where it is preferable to use an existing, conveniently located series-lighting circuit to control the operation of the primary oil switch in order to obtain an identical switching schedule for the new series circuit.

Fig. 19(b) shows the schematic wiring diagram of the CSPH-K constant-current transformer. The series control circuit of the CSPH-K is inserted in the load circuit of the controlled series circuit. When the controlled series circuit is energized, the series control in the CSPH-K causes the series-cascade controlled type AN oil switch to operate to close the primary circuit of the constant-current transformer.

8. Protection

Open-Circuit Protection—It is necessary to provide protection against the hazards of open-circuit voltage on a series-lighting circuit. The type PC series open-circuit relay provides this protection. The constant-current transformer regulates the voltage across the secondary terminals to give rated constant current in the connected series lamp circuit. Should a conductor break, or a film cutout fail to breakdown upon lamp failure, full open-circuit voltage is established across the break or across the lamp, as the case may be. The value of the open-circuit voltage is proportional to the transformer constant-current and kw rating. (See tables 5 and 6.) The type PC protective relay operates to de-energize the operating coil of the normally-open remote control oil switch and thus disconnects the primary of the constant-current transformer when open-circuit conditions exist in the series lamp circuit.

The type PC protective relay has internal connections as shown in Figs. 20 and 21. Under normal circuit conditions, the air dashpot delays action of the control

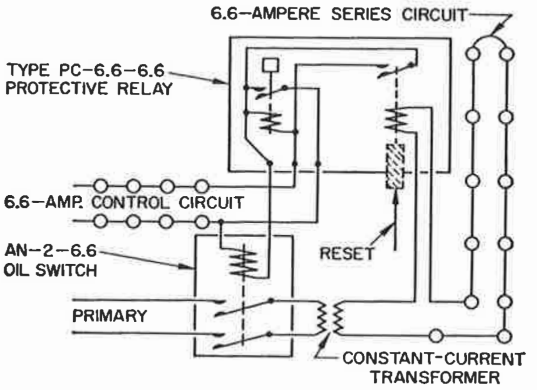


Fig. 20—Connections for type PC-6.6-6.6 protective relay with 6.6-ampere series control circuit rating and a 6.6-ampere series protected circuit rating.

circuit element for one-half second. This delay permits the series-protected circuit element to actuate contacts to de-energize the coil of the control circuit element. Normal operation requires only 40 volt-amperes continuous power to the series-protected circuit coil. An open-circuit fault de-energizes the series-protected circuit relay coil, which actuates contacts to energize the coil of the control circuit element. The control circuit element de-energizes the primary oil switch operating coil to disconnect the connected load. The type PC protective relay series-circuit operating coils are insulated for series-lighting circuits on which the open-circuit voltages do not exceed 8000 volts.

Lightning Protection—Series street-lighting circuits in most areas are generally well shielded by buildings, structures, and other electrical circuits, and as a result are not subject to much trouble caused by lightning strokes. For this reason, there is not much operating experience with lightning arresters applied to series street-lighting circuits. Practice with respect to lightning protection of street-lighting circuits trends toward minimum protection, unless operating experience indicates otherwise.

When a direct stroke hits a series street-lighting circuit, there generally is a flashover at one of the insulators or at the porcelain socket of one of the lamps. Therefore, the surge current usually travels for only a short distance along the circuit. It is possible that, if a flashover occurs at a luminaire socket, the lamp involved will burn out.

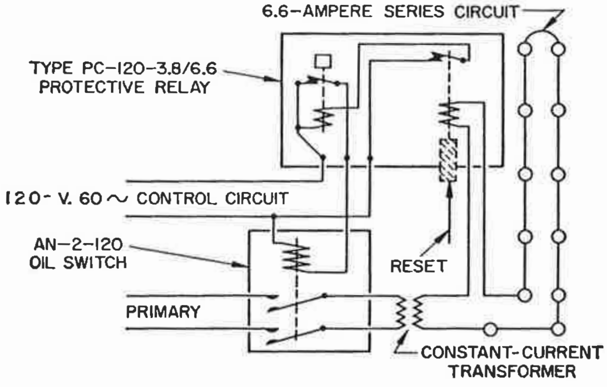


Fig. 21—Connections for type PC-120-3.8/6.6 protective relay with 120-volt, 60-cycle control circuit rating and 3.8/6.6-ampere series protected circuit rating.

When direct strokes to the street-lighting circuit do occur frequently, as indicated by excessive lamp failures or breakdown of film cutouts, there are several steps that can be taken. The most effective protection for exposed series circuits is to run a grounded shield wire over the entire length of the circuit. This protects all lamps in event of a direct stroke, but is more expensive than applying a few lightning arresters to confine outages to four or five lamps. On these exposed circuits, it is recommended that standard type LV lightning arresters be placed on the lines at a distance of approximately 1500 feet from the regulator. If lamp or film cutout failures are excessive, additional lightning arresters can be added along the line.

Constant-current transformers of the CSP type are equipped with type LXT lightning arresters. For constant-current transformers that are not of the CSP type, it is recommended that either type LXT or LVT arresters be applied.

Transformers with a single-circuit secondary require two arresters for the secondary. An arrester should be applied to each line on the primary side of the regulator. These arresters should be located on the source side of the oil switch and the power-factor correcting capacitor, if one is used. In selecting the proper voltage rating of arresters for the primary circuit, consideration should be given to the circuit voltage and normal arrester application procedure should be followed. Under certain conditions on grounded-neutral systems, it is desirable to apply grounded-neutral arresters having an 80 per cent rating, since these arresters will provide a greater margin of protection.

The recommended ratings for lightning arresters applied to the secondary circuits of constant-current transformers are based on the open-circuit voltage. Recommended arrester ratings for 6.6-ampere and 20-ampere series circuits are given in Table 8.

9. Grounding

The high voltages used in series street-lighting circuits present a possible hazard to the public and maintenance personnel in the case of failure of insulation somewhere on the system. For this reason, it is recommended that all equipment cases, tanks, housings, metallic poles, and conduits be effectively grounded. The frame and one of the secondary conductors of an insulating transformer should also be grounded, if the secondary is to be treated as a low-voltage circuit.

Since the current is limited in a series street-lighting circuit, grounding conductors generally are not subjected to a current flow of more than about 20 amperes. Therefore, the mechanical strength of the conductor becomes the determining factor, and conductor sizes ranging from No. 8 to No. 4 copper are normally used.

Table 8—Recommended Lightning Arrester Ratings for 6.6-Ampere and 20-Ampere Series Street Lighting Circuits

KW Rating of Regulator	Arrester Maximum Rating In Kv	
	6.6-Ampere Secondary	20-Ampere Secondary
2	0.50	0.50
3	0.75	0.50
5	3.0	0.50
7½	3.0	0.75
10	3.0	0.75
15	3.0	3.0
20	6.0	3.0
25	6.0	3.0
30	6.0	3.0
40	9.0	3.0
50	12.0	6.0
60	12.0	6.0
70	15.0	6.0

In many cases where series circuits are underground, an intentional ground is established at the electrical midpoint of the circuit. This effectively reduces the normal stress on the insulation to one-half of the normal load voltage of the constant-current transformer. If an open-circuit condition occurs on a circuit grounded in this manner, the cable on the ungrounded side of the open point is subjected to full open-circuit voltage to ground. If an open-circuit protective relay is used with the transformer, the duration of the overvoltage is in the order of less than a second. If the protective relay is not used, the cable is subjected to the open-circuit voltage until the situation is recognized and corrected. This may be a matter of hours, or even days.

Some companies place an intentional ground on the circuit at or near one of the transformer terminals. This has the advantage of making it convenient to remove the ground for test purposes, but, at the same time, it increases the normal stress on the conductor insulation near the other terminal of the transformer.

When an accidental ground occurs on a series circuit on which an intentional ground exists, the portion of the circuit between the two grounds is essentially shorted out, and the lamps go out or burn dimly. This condition gives an excellent indication as to the location of the accidental ground point.

While a large number of series circuits are operated with intentional grounds, probably the majority of the series circuits are ungrounded. This is true of both overhead and underground circuits. The ungrounded circuit will continue to operate with one accidental ground.

III. MULTIPLE SYSTEM

10. Description of System

Voltages—In a multiple street-lighting system, the lamps are served over low-voltage circuits, as opposed to the high-voltage circuits used in the series system. The most common multiple system voltages are 120/240 volts, single-phase, three-wire, or 120 volts, single-phase, two-wire. Systems operating at 120/208 volts, three-phase, four-wire are used in some commercial areas and 480-volt systems are becoming popular.

Layout—The multiple system may take several forms. Because low-voltage secondary circuits exist in the great majority of the areas where street lights are installed, individual multiple lamps can be supplied directly from the existing secondaries. When this type of system is used, each lamp requires an individual control. In another form of the multiple system, a separate secondary circuit is installed for the sole purpose of serving multiple street lights. The power supply to this secondary circuit is accomplished by one of two methods. See Fig. 22. Both methods utilize standard, pole-type distribution transformers and may use the same type of control for switching intelligence.

The difference between the two methods lies in the actual switching. In one method, the primary of the distribution transformer is directly connected to the available primary circuit, and the switching operation is performed by a multiple relay that is located between the secondary terminals of the transformer and the multiple circuit. In the other method, the secondary of the distribution transformer is directly connected to the multiple circuit, and the switching is performed by an oil switch on the primary side of the transformer.

Advantages—Multiple street-lighting applications are increasing, due to a number of advantages that they offer. In new areas where street lighting has not existed, the individually controlled multiple units eliminate the need for a separate system in addition to the distribution circuits. The fact that the lamps operate at low-voltage makes them safer to maintain and does not require maintenance personnel who are qualified to work on high-voltage circuits. The equipment used for the multiple system is essentially the same as used on other distribution circuits. All of these factors usually add up to a cost advantage over series street-lighting circuits.

Limitations—Multiple street lighting also has some disadvantages that should not be overlooked. The main disadvantage of multiple circuits which are separate from the low-voltage distribution circuits is that large conductors must be used when long circuit runs or large loads are involved. The installed cost of these conductors becomes an important factor in the overall economics.

11. Description of Equipment for Multiple Systems

Transformers—One of the big advantages of the multiple system is that standard pole-type distribution transformers are used. This makes it possible and practical to install a multiple lamp or lamps on existing low-voltage secondary circuits without having to install additional transformer capacity, in the great majority of cases. However, since there will be a number of days during the year when the street lights will be on at time of peak load on the distribution transformers in some areas, the street-lighting load must be taken into account in determining the necessary distribution transformer capacity.

Another advantage of the use of standard pole-type

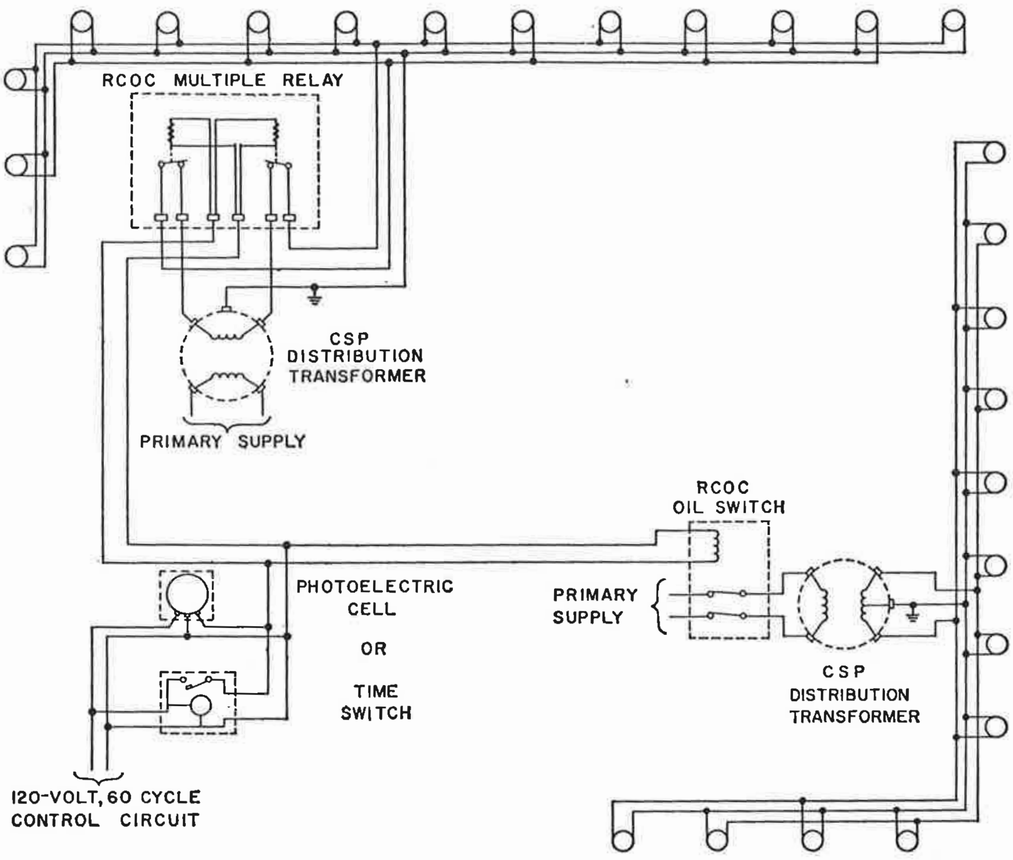


Fig. 22—Two different methods of serving multiple street lighting circuits. In one method the switching is accomplished on the high-voltage side of the distribution transformer, and in the other the switching is performed at low voltage.

distribution transformers and the multiple system concerns the starting requirements of mercury lamps. In series systems it is sometimes necessary to install the constant-current transformer on the basis of the starting requirements of the mercury lamps, rather than on normal operation requirements. This results in two disadvantages. One is the relatively high investment in constant-current transformer capacity. The other is the resulting low power factor operation of the transformer, due to the fact that under normal operation the load on the transformer is well below its rated output. This usually indicates that the installation of shunt capacitors on the primary side of the constant-current transformer is necessary.

The thermal capabilities of standard distribution transformers are such that the high starting currents drawn by the mercury lamps usually do not present a problem. At least, in the majority of cases, the starting requirements of mercury-vapor lamps on multiple systems do not necessitate more transformer capacity than needed for normal operation.

The fact that standard pole-type distribution transformers are used for multiple systems somewhat simplifies the problems of planning, ordering, and stocking transformers to serve street-lighting systems.

Circuit Switch—When the switching of multiple circuits is accomplished by switching the primary supply to the transformers, the type R-C-O-C oil switch is normally used. Automatic switching with this device is accomplished by energizing the control circuit to the 120-volt, 60-cycle, shunt operating coils of the switch with a low-voltage time switch or photoelectric control.

The operating characteristics of R-C-O-C oil switches for multiple system applications are given in Table 9, and the interrupting ratings are given in Table 10.

All of the switches listed in these two tables have an auxiliary hand lever on the tank, with the exception of the type CP oil switch. This lever permits manual or automatic operation of the switch. When the hand lever is set in the AUTO position, energizing the control circuit either opens or closes the switch load contacts, as indicated in Table 10.

When multiple circuit switching is accomplished by switching the circuit on the low-voltage side of the supply transformer, the type MR multiple relay is used. The load contacts of the multiple relay are actuated by

Table 9—Operating Characteristics of R-C-O-C Oil Switches For Multiple Street Lighting Applications

R-C-O-C	Coil Rating	Pull-In Voltage in Volts	Maximum Drop-Out Voltage in Volts	In-rush Amperes	Continuous Current Rating in Amperes	Voltage Rating in Volts
AN	120-volt, 60-cycle	90	65	5.0	1.5	120
ANH	120-volt, 60-cycle	90	65	5.0	1.5	120
ANR	120-volt, 60-cycle	95	65	7.3	3.7	120
CP	120-volt, 60-cycle	90	70	12.0	1.4	120
CPM	120-volt, 60-cycle	90	70	12.0	1.4	120

Table 11—Operating Characteristics of R-C-O-C Multiple Relays with 120-Volt, 60-Cycle Coils

R-C-O-C Type	Number of Poles	Load Rating in Amperes	Pull-In Voltage in Volts	Maximum Drop-Out Voltage in Volts	Inrush Ampere Rating	Continuous Power	
						Current Rating in Amperes	Watts
MR	1	15	75	65	.140	.055	4
MR	1	30	85	70	.310	.080	6
MR	1	60	85	70	.800	.160	12
MR	2	30	85	70	.620	.160	12
MRR	1	15	75	65	.115	.055	4
MRR	1	30	80	65	.285	.080	6
MRR	1	60	80	65	.850	.160	12
MRR	2	30	80	65	.570	.160	12

energizing the control circuit to the relay operating coil. The operating characteristics of the multiple relays are given in Table 11. The load contacts of the type MR multiple relay are normally open with the operating coil de-energized. The type MRR multiple relay contacts are normally closed with the operating coil de-energized. This relay is usually specified for applications requiring positive control of the 'ON' schedule, as a fault in the control circuit will de-energize the relay operating coil and close the load contacts.

In areas where there are a number of multiple circuits using low-voltage switching, a single time clock or photo-electric control can be used to energize a large number of type MR multiple relays.

Table 10—Interrupting Ratings of the Type R-C-O-C Oil Switches for Multiple Street Lighting Applications

R-C-O-C Type	R-C-O-C Specification Number	Number of Poles	Amperes at Line-to-Line Voltage			
			15000 Volts	7500 Volts	5000 Volts	2500 Volts
CONTACTS NORMALLY OPEN WITH 120-VOLT, 60-CYCLE COIL DE-ENERGIZED						
AN-1-120	6120+	1	—	15	35	50
AN-1-120	6122+	1	—	15	35	50
AN-2-120	6121+	2	—	15	35	50
AN-2-120	6123+	2	—	15	35	50
CONTACTS NORMALLY CLOSED WITH 120-VOLT, 60-CYCLE COIL DE-ENERGIZED						
ANR-1-120	6130*	1	—	—	35	50
ANR-2-120	6131*	2	—	—	35	50
CONTACTS NORMALLY OPEN WITH 120-VOLT, 60-CYCLE COIL DE-ENERGIZED						
CP-2-120	6091++	2	10	20	30	60
CP-3-120	6059+	3	—	20	30	60
CPM-2-120	6092++	2	10	20	30	60
CPM-3-120	6069-A+	3	—	20	30	60
CPM-3-120	6075-A+	3	—	20	30	60

+Recommended for phase-to-neutral switching applications on an 8.66/15-Kv system.
*Recommended for phase-to-neutral switching applications on a 5.0/8.66-Kv system.
++Recommended for use on an 8.66/15-Kv system.

Ballasts—A ballast is required to start and operate a mercury lamp on a multiple street-lighting system. The ballast is used to provide the higher voltages required for starting, and to limit the current flow once the arc has been established.

The "reactor" type of ballast may be used to limit the flow of current in the lamp. This type of ballast, which is a simple inductance, is used where the voltage of the multiple circuit is correct for starting the lamp.

Where the circuit voltage is not correct for starting the lamp, an autotransformer is included in the ballast to provide the proper voltage. This type of ballast is called a "high-reactance" ballast.

The reactor type and high-reactance type of ballasts are recommended for use on multiple circuits where the line voltage available at the ballast does not vary more than ±5 per cent from the rated top voltage. Where the ballast will be subject to greater voltage variations, the "regulated-output" ballast should be used. This ballast is of recent design and is a variation of the high-reactance type of ballast. It incorporates a saturable iron element and will operate the lamp over a 12 or 13 per cent voltage variation on multiple circuits. Another advantage of this regulated-output type of ballast is that there are no voltage taps to complicate their installation on the system.

While it is not essential for proper operation, most reactor and high-reactance ballasts contain a capacitor to correct the input power factor to 90 per cent or more. The normal power factor for an uncorrected ballast is approximately 50 to 60 per cent. All regulated-output ballasts have a power factor of 95 per cent or above, since a capacitor is an essential part of their design.

The starting and operating characteristics of mercury lamps are quite different from those of incandescent lamps. The line starting current for each type of lamp and ballast will vary in maximum value as well as in duration. It may vary from less than normal to 75 per cent greater than normal for different lamp-ballast combinations.

In general, the higher the ratio of secondary short-circuit current to lamp operating current, the shorter is the lamp starting time for a given type of lamp. The high-pressure, short-arc lamps usually reach stable operating conditions faster than the longer-arc lamps.

Conductors—When multiple street lighting is used in overhead distribution areas, existing secondary circuits may be used as the source of power supply to the lamps. In the great majority of cases where existing secondaries are utilized, the lengths of the secondaries are usually only three or four pole spans long. This limits the number of lamps per secondary to a small number, due to physical spacing of the lamps. As a result, the fact that the lamps are supplied directly from the secondary has little or no influence in the determination of secondary conductor size.

When separate circuits are used for multiple street lighting, it is to be expected that the conductor runs will be relatively long, taking transformer-secondary combination economics into account. Voltage drop normally determines the conductor size for a given circuit length and number of lamps.

There is a definite trend to the use of rubber or rubber-like insulation with neoprene or comparable jacket in multiple circuits that are installed underground. The cable normally used for multiple circuits has insulation rated for 600 volts and below.

In the downtown areas of cities, these cables are normally installed in available ducts. These cables should not be in the same duct with high-voltage cables.

In residential areas, underground multiple circuits are normally buried directly in the ground without the use of duct or mechanical protection. Burial depth varies between one and two feet. Ducts are normally used with direct-buried installations where the cables pass under streets and sidewalks.

The conductors used in underground circuits normally range from No. 8 to No. 2 copper.

12. Protection

The problem of providing protection for multiple street-lighting circuits is simpler than for series circuits. The main reason for this is that the low-voltage multiple circuits are not exposed to as much possible trouble as series circuits are. The multiple circuits are not on the same crossarm with primary distribution circuits, and consequently are not subject to contact with those conductors due to wind and trees. The fact that the multiple conductors are installed below the primary circuits affords them shielding from lightning strokes.

If CSP distribution transformers are used to supply multiple circuits, overload and fault protection are provided by the secondary breakers in the transformers. The lightning arrester on the transformer provides protection against surges on the primary circuit which might get into the secondary. If conventional distribution transformers are used, the same degree of protection cannot be provided as with the CSP transformer. Lightning arresters and primary fuse cutouts are normally installed with the conventional transformers.

IV. SERIES-MULTIPLE SYSTEM

13. Description of Series-Multiple System

Where Applicable—In cases where a new group of street lights are necessary in an area served by series street-lighting circuits, a series-multiple system arrangement may be used. The decision to use the series-multiple system may be based on one or more of several reasons. Most series-multiple systems are used because the existing series circuits do not have sufficient capacity to handle the additional load. Assuming that the lighting schedule for the series circuit is satisfactory for the multiple circuit, a series-multiple relay is inserted in the series circuit to control the multiple lamps. When the series circuit is energized, the series-multiple relay operates to actuate a contactor, or pilot-wire control, to energize the multiple lamps. The supply circuit to the multiple lamps may be a tap off of an existing secondary circuit, or may be a separate circuit with its own distribution transformer.

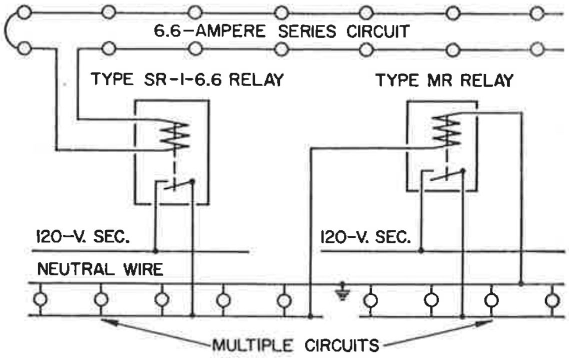


Fig. 23—A series-multiple street-lighting system using a type SR-1-6.6 series-multiple relay to switch the multiple lamps, and a type MR multiple relay to switch additional multiple lamp groups.

The decision to use the series-multiple arrangement may also stem from the fact that the use of high-voltage circuits is undesirable in the new installation. It may also be used to eliminate the cost of control in a multiple system, or to eliminate the cost of a constant-current transformer in a series system.

Layout—Two possible circuit arrangements for series-multiple systems are shown in Fig. 23 and Fig. 24. In Fig. 23, the type SR series-multiple relay closes its normally-open contacts when the 6.6-ampere series circuit

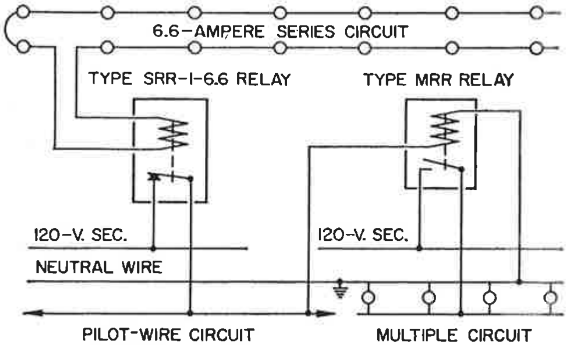


Fig. 24—A series-multiple street-lighting system using a type SRR-1-6.6 series-multiple relay to initiate pilot wire switching through the use of a type MRR multiple relay.

is energized. When the relay contacts close, the multiple circuit is energized from the 120-volt supply circuit. Other multiple circuits may also be controlled from the one series-multiple relay through the use of type MR multiple relays as shown. In Fig. 24, the type SRR series-multiple relay opens its normally-closed contacts when the 6.6-ampere series circuit is energized. This operation de-energizes the pilot-wire circuit and causes the type MRR relay to close its contacts and thereby energize the multiple lamps.

Limitations—The series-multiple system has the same major disadvantage of the series-cascade system, in that a failure in the series system or in the series system control will prevent energization of the multiple lamps.

14. Description of Equipment for Series-Multiple System

The series-multiple system provides a convenient means of using a series-lighting circuit to control a multiple lighting circuit requiring an identical lighting schedule. With the exception of the series-multiple relay used to tie the series system to the multiple system, the equipment used in the series system and the multiple system is the same as used in other series and multiple systems.

Series-Multiple Relays—Series-multiple relays are basically a solenoid-actuated contactor. They may be single or two pole devices, and may be either normally open or normally closed with the coil de-energized. Series-multiple relays are available with either 6.6-ampere or 20-ampere coil ratings and either 125- or 250-volt load ratings. Table 12 gives the designation and ratings of series-multiple relays.

Table 12—Series-Multiple Relay Ratings

R-C-O-C Type	Number of Poles	Coil Rating in Amperes	Normal Contact Position	Load Rating Per Pole	
				Amperes	Volts
SR-1-6.6	1	6.6	Open	40	125
SR-1-20	1	20	Open	40	125
SR-2-6.6	2	6.6	Open	20	250
SR-2-20	2	20	Open	20	250
SRR-1-6.6	1	6.6	Closed	40	125
SRR-1-20	1	20	Closed	40	125

V. STREET-LIGHTING CONTROL

15. Manual Controls

Street lights are turned on and off through the use of several types of controls. The oldest, and simplest, control scheme employs manual control. Manual control dates back to the early days of electric street lighting when all lighting circuits originated at attended stations. Circuits are still switched manually today at attended substations. However, the extensive street-lighting systems of today have made remote controls necessary and, for the most part, have eliminated manual controls. The relatively low cost and the reliability of modern remote controls make it difficult to justify manual switching in some attended stations where street-lighting circuits originate.

16. Photo-electric or Light-sensitive Controls

There are three general types of light-sensitive devices used to control street lights. One type utilizes a photo-tube, an amplifier tube, a time-delay network, a power tube, and a relay or contactor. A second type employs a self-generating, or photo-voltaic, photocell of the barrier-layer cell type, a relay, a small motor, and a sealed mercury switch. The third type has as its primary features a broad-area cadmium sulfide photoconductive cell and a special full-wave rectifier type relay.

The phototube type requires from 3.5 to 11 watts during the daytime and from 1.5 to 7 watts during the night. The barrier-layer cell type draws no current between turn-on and turn-off operations. Each complete on-off cycle of operation requires only 4 watts for one minute, generally once a day. The cadmium sulfide type of control requires a maximum of 0.9 watt in the daytime and a maximum of 0.6 watt at night.

The phototube type of control is available in two ratings with respect to the contacts. Contact ratings are 575 watts and 3000 watts. The 575-watt rating is used for single-lamp control, or for control of a pilot-wire control circuit. The 3000-watt rating is used to control a group of lamps. The mercury switch in the barrier-layer cell type of control is rated 30 amperes at 120 volts. The cadmium sulfide control is rated for a maximum direct lamp load of 1000 watts.

These controls are normally aimed to the north, and are preset to turn on and off based on the illumination of the north sky. The control can be adjusted to turn the lights on over a range of 0.5 to 5.0 foot-candles.

Care must be exercised in the installation of these light-sensitive devices so that artificial light of an intensity above the turn-on value will not strike the light-sensitive cell. This would prevent the desired operation of the control.

The phototube type of control has a time-delay circuit which provides a four to six second delay at turn-off. This prevents false operation of the control due to transient lights, such as from the headlamps of passing automobiles.

From the standpoint of having street lights turned on when they are needed, the light-sensitive type of control provides the best operation. The curve in Fig. 25 shows the turn-on and turn-off characteristics of photoelectric lighting controls.

When light-sensitive controls are used to control mercury- or sodium-vapor lamps, it is recommended that the turn-on setting be increased by 4.0 or 5.0 foot-candles. This will cause the lamps to be energized about 7 or 8 minutes earlier, thus insuring that the lamps will be up to full brilliance when natural daylight has dropped to one foot-candle.

The greatly increased use of multiple circuits has also increased the use of photoelectric type controls. The economics of using this type of control, along with the economics and flexibility of the multiple system, have made it practical for some operating companies to standardize on the use of multiple circuits with an individual control for each lamp.

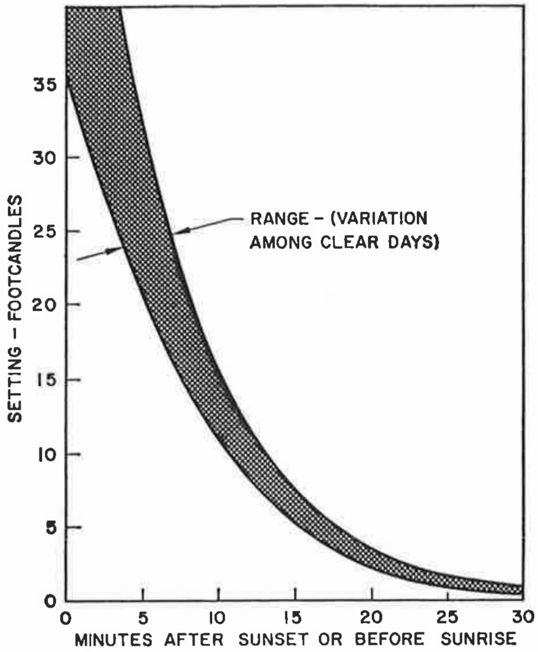


Fig. 25—Approximate relationship between the operating points of a photo-electric lighting control in foot-candles and either the turn-on in minutes after sunset or the turn-off in minutes after sunrise on a clear day.

17. Time-Clock Controls

Time-clock controls offer one of the least expensive methods of controlling street lights. The basic time-clock unit consists of an astronomical-dial clock driven by a synchronous motor, and a set of contacts. This type of clock automatically adjusts the contact operations to meet the day-to-day variations in sunrise and sunset.

One major disadvantage of this type of control is that outages on the circuit supplying power to the clock will cause the clock, and consequently the street light operation, to be off schedule. This problem can be avoided, at least for outages of short duration, through the addition of a mechanical timer that will continue to operate the clock until electric power is restored. The addition of the mechanical timer makes the control more complex and of course increases the cost, but, it does eliminate the necessity of having to reset time clocks following an extended service outage.

Time clock controls can be used for either series or multiple circuits to good advantage.

18. Pilot-Wire Control Systems

One of the most common methods of controlling street lights has been accomplished through the use of an a-c pilot-wire system. As the name pilot wire implies, a wire is run from a master control to each lamp or group of lamps to be operated from the master control. The master control can be a time clock, a light-sensitive device, or manual control. The pilot wire itself is usually a No. 8 or No. 6 conductor. A relay is installed at each lamp, or group of lamps, to be operated. The relays may be operated in one of two ways. The most popular operation is to energize the pilot wire and the relays in the daytime. De-energization of the pilot wire and the relays causes the lamps to be connected to the power supply. The other method of operation is to energize the pilot wire and relays when the lights should be turned on.

The former of the two methods offers the advantage that should there be a failure in the master control, the pilot-wire circuit, or any relay, the lights will come on. The fact that the lights are on day and night will indicate a control failure, but, will provide light when it is needed. The latter method does not operate any of the lamps when a failure occurs, and no lighting is provided until the necessary maintenance is performed.

The pilot-wire system of control is applicable to both series and multiple circuits, but is used more on the multiple systems.

VI. SELECTION OF SYSTEM

19. General Discussion of Series and Multiple Systems

There are many factors that should be considered in the planning of any street-lighting installation. The desired level of illumination can be achieved through the use of many combinations of lamps, luminaires, luminaire spacings, light distribution patterns, and circuit arrangements. The final decision as to the installation is usually based on initial costs and annual operating costs, with the exception of cases where appearance of the installation is of particular importance.

In many cases, existing equipment and circuits will greatly influence what combination of equipment and circuits will be used. This is particularly true of the circuits. However, if a completely new installation is to be made, including a new circuit to be used only for street-lighting purposes, then the advantages and disadvantages of a number of possible combinations of systems and equipment should be considered.

If a series circuit is to be used, the equipment necessary consists of a constant-current transformer, a primary remote-control oil switch, control equipment, film cutouts, and surge and short-circuit protection. Other equipment that might be used are capacitors for power-factor correction, a protective relay to cause the oil switch to operate to de-energize the circuit in the event of an open-circuit condition, and series-mercury transformers.

In some cases, where safety and local codes require it, insulating transformers are used to insulate the luminaire from the high voltage of the series circuit. When insulating transformers are used, the primary of the transformer is inserted in the series loop and the lamps are operated from the secondary of the transformer. The voltage at the luminaire is limited by the air gap in the insulating transformer.

Until recently, mercury lamps could not be operated from a series circuit without using a series-mercury transformer. The series-mercury transformer trans-forms the current from the normal 6.6 or 20 amperes supplied by the constant-current transformer to the 3.3 amperes required by the lamp. It is essentially a current transformer, but does have a slight air gap to limit the peak open-circuit voltage developed to a value sufficiently low enough to prevent internal arc-over in the lamp. In order to operate mercury lamps without using series-mercury transformers, a 3.3-ampere series circuit was developed to operate type E-H1 mercury lamps. As another approach to the elimination of the series transformer, a 6.6-ampere mercury lamp was developed.

When mercury lamps are operated on a series circuit without the use of series-mercury transformers, the equipment previously mentioned is necessary, plus a film cutout for each lamp, a potential transformer, and a time-delay relay. This additional equipment is required so that in case of a power dip or outage, which extinguishes the lamps, the circuit will be de-energized for a sufficient length of time to permit the lamps to cool and then restrike in the normal manner. If this is not done, the arc in the lamps will not restrike and the film cutouts will break down, the same as if the lamps had failed.

The 3.3-ampere system requires a special constant-current transformer, but uses standard type E-H1 mercury lamps. The 6.6-ampere system uses a conventional constant-current transformer, but requires the type A-H24 mercury lamp which has a 6.6-ampere rating.

If multiple street lighting is to be used, existing secondary circuits can be used without the need of a separate street-lighting circuit. The lamps served from the existing secondaries can be controlled individually by photoelectric cells, or by a pilot-wire relay scheme.

If a separate circuit is to be used for the multiple system, then the equipment necessary for such a circuit is a standard pole-type distribution transformer, a remote-controlled primary oil switch, or a multiple relay, and some device to provide switching intelligence to the primary switch or multiple relay.

Mercury and fluorescent lamps operated from a multiple circuit require a ballast in order to provide proper voltage to start the lamp, and then to limit the current to a proper value once conduction has started.

Advantages and Disadvantages of Each System—The advantages of each type of system are both tangible and intangible. Local conditions will determine how much weight is given to each of the advantages and disadvantages.

The series circuit permits better control of light due to the smaller light source in a series incandescent lamp. The lamps are more efficient and maintain close to initial lumen output over a relatively long period of the life of the lamp. As a rule, the lamps are more rugged than the incandescent lamps used on multiple circuits.

Series-circuit control equipment is less complicated than corresponding multiple control equipment, and series circuits are more adaptable to simple methods of control.

Outages on the distribution circuits serving the area will not affect the separate series street-lighting circuits.

In rural areas, along arterials and highways, where long circuit runs may be required, the series circuit permits the use of more economical conductor sizes.

The multiple system offers the advantage of having a relatively low voltage at the luminaire. This permits the use of lower cost lamps, and makes it safer to replace lamps or to perform maintenance work on the luminaire. The constant-potential multiple system eliminates the need for special equipment such as the constant-current transformer, the type PC relay, and film cutouts.

Since the multiple system does not operate at primary voltages, the conductors need not be installed on crossarms. This somewhat simplifies the operating and maintenance problems. Since multiple system conductors need not be on the same crossarm with primary circuits, the problem of the street-lighting circuit conductors swinging into primary circuit conductors is eliminated. However, a broken primary conductor could fall into the multiple circuits which are installed below them. With the present trend to distribution voltages in the 15-kv class, if the street-lighting conductors are installed on the same crossarm with the primary circuit, the crossarm must be made longer. Consequently, the tree trimming problem may become more severe in some areas. Multiple circuits avoid complicating these problems.

The multiple system does not require power-factor correction in most cases, as contrasted to the series system with its relatively low power factor.

The main disadvantage of the multiple system is that it requires relatively large conductors to serve large loads or long runs. However, the use of a 480-volt multiple system permits the use of smaller conductors for these large loads, or long runs than could be used with the more commonly used 120/240-volt multiple system.

20. Calculation of Constant-Current Transformer Loading

The rating of a constant-current transformer is expressed in kw output at the secondary terminals at rated voltage and frequency, and with rated secondary current and power factor. In accordance with ASA standards, constant-current transformers are designed to deliver rated kw output at 95 percent of rated primary voltage, with a load power factor of 99.5 percent.

To determine the required rating of a constant-current transformer for a given installation it is necessary to know: the type and number of lamps to be served; the characteristics of any insulating transformers or series-mercury transformers; conductor size, length, and spacing; ampere rating of protective relay; and the lowest ambient temperature expected.

Incandescent Lamp Load—Straight series operation of incandescent lamps approaches the condition of a 99.5 percent power factor load. The total load kw seen by the constant-current transformer is the lamp load plus the kw losses in the circuit. This total kw must not exceed the kw rating of the constant-current transformer as shown by the loading curves of Figs. 26 and 27. These curves are based on 95 percent

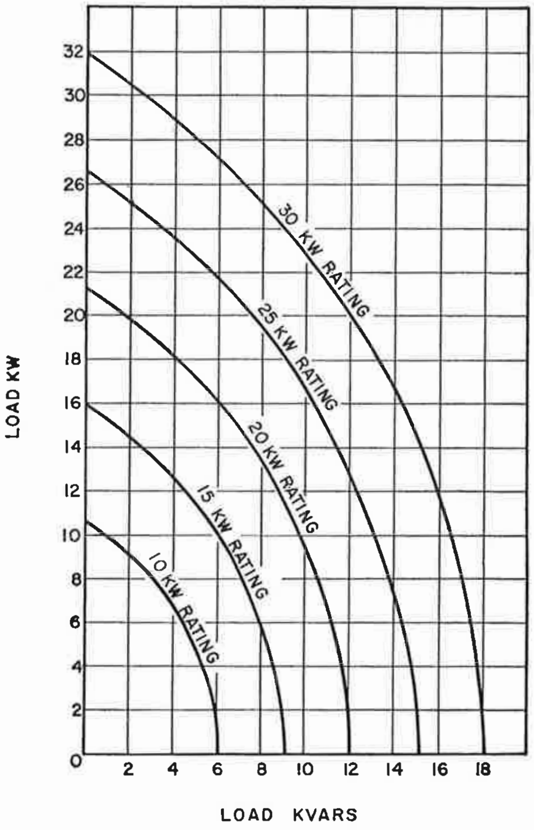


Fig. 26—Relationship of kilowatt and kilovar loading of types CPH, CSPH, and CMH constant-current transformers with 95 per cent of rated primary voltage applied.

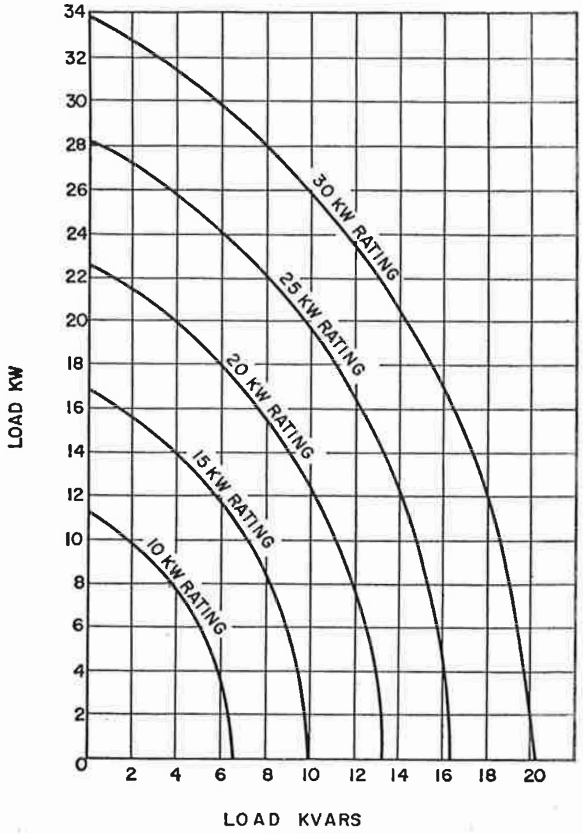


Fig. 27—Relationship of kilowatt and kilovar loading of types CPH, CSPH, and CMH constant-current transformers with 100 per cent of rated primary voltage applied.

and 100 percent of rated primary voltage, respectively. Table 13 shows the kw required by incandescent lamps.

Table 13—Data for Incandescent Lamps

Lamp Rating		2000-Hour Lamps				3000-Hour Lamps			
		Straight Series		Insulating Current Trans-formers		Straight Series		Insulating Current Trans-formers	
Lumens	Amperes	kw	kvar	kw*	kvar	kw	kvar	kw*	kvar
1000	6.6	0.065	0	0.077	**	0.0695	0	0.082	**
2500	6.6	0.150	0	0.167	**	0.160	0	0.178	**
4000	6.6	0.220	0	—		0.231	0	—	
4000	15	—	—	0.236	**	—	—	0.248	**
4000	20	0.221	0	—		0.231	0	—	
6000	6.6	0.325	0	—		0.343	0	—	
6000	20	0.310	0	0.345	**	0.326	0	0.360	**
10000	6.6	0.570	0	—		0.620	0	—	
10000	20	0.510	0	0.550	**	0.530	0	0.570	**
15000	20	0.750	0	0.798	**	—	—	—	
25000	20	1.275	0	1.34	**	—	—	—	

*Add the Kw loss in the cable from the insulating current transformer to the lamp to the Kw loss in the insulating current transformer to obtain the total Kw loss for the lamp and transformer.

**For insulating current transformer Kvar, use 19 per cent of the total Kw as explained above. To this value add the Kvar of the cable from the transformer to the lamp to obtain the total Kvar for the lamp and transformer.

Table 14 gives the kw losses in the circuit conductors. The kvar losses in the circuit are given in Table 15.

Table 14—Kilowatt Losses per 1000 Feet of Non-Magnetic Sheathed Copper Cable Buried Directly in Earth

Conductor Size A.W.G.	Ampere Rating of Series Circuit			
	6.6	7.5	15	20
4	0.012	0.016	0.063	0.110
6	0.019	0.025	0.100	0.177
8	0.031	0.040	0.158	0.281
10	0.051	0.066	0.263	0.470

Table 15—Approximate Kilovar Losses per 1000 Feet of #4, #6, and #8 Non-Magnetic Sheathed Copper Cable Buried Directly in Earth

Spacing between Conductors	Ampere Rating of Series Circuit			
	6.6	7.5	15	20
80 Feet	0.01	0.013	0.05	0.09
3 Feet*	0.006	0.008	0.03	0.06

*Use these values for conductors in pole and mast arm.

The use of insulating current transformers on a series circuit results in a load power factor which may be considerably less than 99.5 percent. In determining the required constant-current transformer capacity when insulating current transformers are used, it is necessary to consider the kvars as well as the kw of the load circuits. Table 13 also gives the kvars to be included in the determination of constant-current transformer rating required. The values given in this table assume the normal condition of the lamp in service. Allowances for lamp depreciation and transformer losses are included.

The values in Table 13 are based on the assumption that film cutouts are used on the secondary of the insulating current transformers. If no film cutout were used, and the lamp failed, the secondary of the insulating current transformer would be open circuited. Under the open-circuited condition, the kw losses in the insulating current transformer are negligible but the kvar losses may be in the order of five times the normal maximum kw rating of the transformer. When film-cutout protection is provided, a lamp failure produces a kw load on the series circuit equal to the internal losses of the insulating current transformer. Therefore, only the kw and kvar values for normal operation need be considered for constant-current transformer loading.

In some cases, series-to-multiple transformers will be used and their effect on the series-circuit load should be determined. Where the single-lamp type is used, the following kw and kvar values should be used:

Lamp Watts	kw	kvar
500	0.560	0.080
1000	1.098	0.160

Using these values, the method for calculating loading is identical to that for insulating current transformers. Film cutout protection is recommended.

Series-to-multiple transformers designed to serve two or more multiple lamps have an internal air gap to limit the secondary voltage. A film cutout is not recommended for use with this type of transformer since it would have no purpose in the circuit. The kw and kvar values for series-to-multiple transformer designed to serve two or more multiple lamps are as follows:

Lamp Watts	kw	kvar
0–350	0.380	0.64
350–750	0.790	1.30

It is recommended that not more than one of the series-to-multiple transformers, for lamps up to 350 watts, be used for each 2.5 kw of constant-current transformer capacity. At least 5 kw of constant-current transformer capacity should be available for each of the transformers designed for 350 to 700-watt lamps. The reason for these limitations is the reactance reflected into the series circuit by the internal air gap in the series-to-multiple transformer.

Electric-Discharge Lamp Load—In determining the load placed on a constant-current transformer by mercury and fluorescent lamps, three considerations are necessary:

1. The constant-current transformer capacity required for normal operation of the lamps.
2. The constant-current transformer capacity required to start the lamps at the lowest ambient temperature anticipated.
3. The constant-current transformer capacity required to prevent operation of the protective relay during the starting and warm-up period of the lamps.

It is possible for all three requirements to be different. The conditions of application will determine which requirement is the greatest, and thus will determine the constant-current transformer capacity necessary.

Electric-discharge lamps have negative temperature-resistance characteristics. It is therefore necessary to limit the flow of current through the lamps. The constant-current transformer controls the circuit current to a fixed value. An additional transformer is used with each electric-discharge lamp to match the lamp characteristics to the series circuit by providing the proper starting voltage for the lamps and by transforming the constant current in the series circuit to the proper operating current required by the lamp. Since this matching transformer limits the starting voltage at the lamp, the use of a film cutout can serve no purpose.

Under normal operating conditions, the load on the constant-current transformer is made up of the kw and kvars required by the various lamps and series transformers and the losses in the circuit conductors. Table 16 gives load values for both electric-discharge lamps and series transformers. The circuit losses may be obtained from Tables 14 and 15. When the total kw and kvars have been determined, the values should be

Table 16—Constant-Current Transformer Capacity Required for Operation of Mercury and Fluorescent Lamps

		A-H22 175W. Merc.	C-H5 250W. Merc.	E-H1, 400W, Merc.		A-H18 700W. Merc.	A-H15 1000W. Merc.	Two F72T12/ HO 1.0 amp. Fluor.	Two F72T12/ SHO 1.5 amp. Fluor.	Two F48T12/ SHO 1.5 amp. Fluor.
				Std. Trans.	U.A.T. Trans.					
Normal Operation	Kw	0.190	0.280	0.428	0.435	0.737	1.050	0.220	0.340	0.231
	Kvar	0.127	0.185	0.278	0.194	0.483	0.700	0.165	0.274	0.175
Open-Circuit	Kw	0.018	0.040	0.028	0.044	0.075	0.100	0.050	0.050	0.050
Secondary	Kvar	0.550	0.700	1.190	1.135	1.940	2.770	0.850	0.850	0.850

NOTE: 1. These values do not contain any allowance for line losses and are based on nominal lamp and transformer values.

2. The two sets of values for the E-H1, 400-watt, mercury lamp are for the former ("standard") series-mercury transformer and the new universal aluminum tank series-mercury transformer.

3. If the circuit is to serve as a parent circuit to cascade control the operation of a second circuit, 0.53 Kvar must be allowed for the Type AN-2-6.6 (or equal) series-operated oil switch.

plotted on either Fig. 26 or Fig. 27 to find the constant-current transformer capacity required for normal operation.

It should be noted that an open-circuit condition exists on the secondary of a series transformer when the lamp fails. This places a high reactive load on the series circuit and can seriously affect the number of lamps that can be operated on the circuit. This stresses the need for a good maintenance program.

At the moment a series circuit is energized, all of the series transformers on the circuit have an open-circuited secondary. A high impedance is reflected into the series circuit. If adequate constant-current transformer capacity is not provided, the voltage across the lamps may not be sufficient for proper starting. The voltage required by a mercury or fluorescent lamp for proper starting is a function of the lamp design and the ambient temperature. The available starting voltage per lamp is a function of the series transformer design and the primary voltage applied to the constant-current transformer. These factors have been taken into account in Table 17.

During the starting cycle of mercury and fluorescent lamps, the high impedance caused by the open-circuit condition of the series transformers can cause a lower than normal current to flow in the series circuit. If the current is too low, the protective relay will operate and de-energize the circuit. Should this occur, it will be impossible to obtain full normal operation of the lamps. This is most important for a "hot restart" of mercury lamps.

Table 18 gives the recommended maximum number of series-mercury transformers for given constant-current transformer ratings to assure proper "hold-in" operation of the protective relay. There are so many factors involved (including setting, tolerances, and condition of the protective relay) that it is almost impossible to give the absolute maximum number of lamps that can be started without causing the protective relay contacts to "drop-out." Experience indicates the recommended maximums given in the Table are practical values.

Mixed Load—It is possible to use incandescent, mercury, and fluorescent lamps in any combination on a series street-lighting circuit as long as the constant-current transformer capacity is not exceeded. Since the filaments of the incandescent lamps have very little resistance when cold, virtually all of the constant-current transformer capacity is available to start mercury or fluorescent lamps. Under proper conditions, it is possible to install incandescent lamps on a circuit that is loaded to capacity with electric-discharge lamps.

The method for calculating constant-current transformer capacity for mixed incandescent and electric-discharge lamp loads is as follows:

1. The total kw and kvars on the circuit should be determined and plotted on the curve of either Fig. 26 or Fig. 27.
2. The number of mercury or fluorescent lamps on the circuit must not exceed the number of lamps that can be started as given in Table 17.
3. The number of mercury or fluorescent lamps must be checked against Table 18 to make sure that the protective relay will not prevent starting.

The following procedure can be used to determine the constant-current transformer capacity required in a circuit, regardless of the type or types of lamps to be served.

1. Calculate the total circuit kw requirements with all lamps operating. (Tables 13, 14, 16 and 17)
2. Calculate the total circuit kvar requirements with all lamps operating. (Tables 13, 15 and 16)
3. Determine the maximum number of lamps that can be expected to be inoperative at any given time. This will depend upon the maintenance of the system. If only incandescent lamps are used, omit steps 4 and 5.
4. Subtract the normal operating kw and kvar for the number of inoperative lamps (as determined

Table 17—Constant-Current Transformer Capacity in KW Required for Reliable Starting of Mercury and Fluorescent Lamps

Ambient Temp. in Degrees Fahrenheit	Percent of Rated Primary Voltage	A-H22 175W. Merc.	C-H5 250W. Merc.	E-H1, 400 W., Merc.				A-H18 700W. Merc.	A-H15 1000W. Merc.	Two F72T12/ HO 1.0 amp. Fluor.	Two F72T12/ SHO 1.5 amp. Fluor.	Two F48T12/ SHO 1.5 amp. Fluor.
				Std. Trans.		U.A.T. trans.						
				Std. lamp	Lifeguard	Std. lamp	Lifeguard					
−20	100	0.415	0.465	0.760	.710	0.620	0.535	1.15	1.55	0.545	0.715	0.620
	95	0.435	0.490	0.800	.750	0.650	0.560	1.20	1.60	0.575	0.835	0.650
0	100	0.320	0.420	0.620	.580	0.530	0.495	1.15	1.55	0.450	0.630	0.550
	95	0.335	0.440	0.650	.610	0.560	0.510	1.20	1.60	0.470	0.770	0.580
+20 or above	100	0.320	0.420	0.580	.580	0.485	0.485	1.15	1.55			
	95	0.335	0.440	0.610	.610	0.510	0.510	1.20	1.60			
+50 or above	100									0.425	0.525	0.420
	95									0.445	0.650	0.440

NOTE: 1. All values based on nominal lamp and series-mercury or fluorescent transformers.
2. These values do not consider the use of a protective relay in the circuit which may operate to de-energize the circuit due to low current at the instant of starting.
3. Four values are shown for the E-H1, 400 watt, mercury lamp: the former (standard) transformer, the new (universal aluminum tank) transformer, the standard mercury lamp, and the new "Lifeguard" mercury lamp.

Table 18—Recommended Maximum Number of Series-Mercury Transformers per Constant-Current Transformer for Proper Operation of the Protective Relay

Constant-Current Transformer: Rating in Kw	Constant-Current Transformer: Percent of Rated Primary Voltage	A-H22 175W. Merc.	C-H5 250W. Merc.	E-H1, 400W., Merc.: Std. trans.	E-H1, 400W., Merc.: U.A.T. trans.	A-H18 700W. Merc.	A-H15 1000W. Merc.	Two 6′ HO 1.0 amp. Fluor.	Two 6′ SHO 1.5 amp. Fluor.	Two 4′ SHO 1.5 amp. Fluor.
WITH STANDARD PC-120-3.8/6.6 (OR EQUAL) PROTECTIVE RELAY										
10	100	26	19	11	14	8	5	18	16	16
	95	24	18	10	14	7	5	17	15	15
15	100	40	28	17	22	12	8	27	25	25
	95	38	27	16	21	11	8	25	23	23
20	100	53	38	23	29	16	10	36	33	33
	95	50	36	22	28	15	10	34	31	31
25	100	66	47	29	37	19	13	45	41	41
	95	62	45	27	35	20	13	42	39	39
30	100	80	57	35	44	24	16	55	50	50
	95	76	54	33	42	23	16	52	47	47
WITH NEW PC-120-2.5/6.6 (OR EQUAL) PROTECTIVE RELAY*										
10	100	33	25	15	18	10	7	28	26	26
	95	35	24	14	17	10	7	27	24	24
15	100	50	38	22	26	15	10	42	38	38
	95	52	36	21	25	14	10	40	36	36
20	100	67	52	29	36	20	14	56	51	51
	95	70	49	28	34	19	13	53	49	49
25	100	83	64	37	44	25	17	70	64	64
	95	87	61	35	42	24	17	67	61	61
30	100	105	77	44	53	30	21	84	77	77
	95	100	73	42	51	29	20	80	73	73

NOTE: 1. All values based on nominal lamp and series-mercury or fluorescent transformers.
2. The two sets of values for the E-H1, 400 watt, mercury lamp are for the former ("standard") series-mercury transformer or the new ("U.A.T.") series-mercury transformer.
* This protective relay is now standard production.

in step 3) from the total circuit kw and kvar. (Table 16)

5. To the kw and kvar determined in step 4, add the kw and kvar for the number of series-mercury or fluorescent transformers operating with open-circuited secondaries (as determined in step 3). (Table 16)
6. Determine whether the voltage at the primary of the constant-current transformer will be 95 per cent or 100 per cent of rated voltage.
7. Using the appropriate curves of either Fig. 26 or Fig. 27, locate the total circuit kw on the ordinate and the total circuit kvar on the abscissa. Plot the point representing the intersection of these two valves. The constant-current transformer rating curve immediately above the plotted point is the required rating for operating the circuit once the lamps have started. In the case where only incandescent lamps are used, the indicated constant-current transformer capacity is all that is required. In the case of mercury or fluorescent lamps, additional constant-current transformer capacity may be required.
8. Determine the lowest ambient temperature at which the circuit will be energized. From Table 17, determine the constant-current transformer capacity required to start one lamp. The number of lamps multiplied by this value will give the minimum constant-current transformer rating for starting the lamps.
9. If a protective relay is used, check Table 18 to see what constant-current transformer capacity is required to start the lamps without causing the protective relay to drop-out and de-energize the circuit. The larger of the two constant-current transformer ratings determined in steps 8 and 9 is required for starting purposes.
10. Compare the constant-current transformer ratings determined in steps 7, 8 and 9. The largest rating determined is that required for reliable starting and operation.

The following example is given to illustrate the manner in which the required rating of a constant-current transformer is determined. Assume a 6.6-ampere series circuit serving fourteen type E-H1 mercury lamps and fifteen 10,000-lumen, 2000-hour life incandescent lamps. Standard mercury lamps are used with series-mercury transformers and the incandescent lamps are operated from the 20-ampere secondary of 6.6/20-ampere insulating current transformers. A standard 3.8/6.6-ampere protective relay is used. Assume that a maximum of two mercury lamps are inoperative before circuit maintenance is performed. The 3700-foot primary circuit is underground and consists of direct-buried #6 copper cable. The circuit is run on opposite sides of the street and the separation between conductors is approximately 80 feet. Assume approximately 72 feet of #10 cable are used per lamp from the pole base to the lamp. The lowest ambient temperature to consider is −20 C. The voltage at the primary terminals of the constant-current transformer is 95 per cent of rated voltage at time of lamp turn-on.

From Table 14:

kw loss in 72 feet of #10 cable $= \frac{(72)}{(1000)}\ (0.470) =$ 0.034 kw per lamp

From Table 15:

kvar loss in 72 feet of #10 cable $= \frac{(72)}{(1000)}\ (0.06) =$ 0.004 kvar per lamp

From Table 13:

kw loss in one insulating current transformer = 0.550 kw
kw loss of one insulating current transformer plus secondary leads $= 0.550 + 0.034 = 0.584$ kw
kvar loss per insulating current transformer = $(0.19)\ (0.584) = 0.111$ kvar

From Table 14:

kw loss in #6 primary cable $= \frac{(3700)}{(1000)}\ (0.019) = 0.07$ kw

From Table 15:

kvar loss in #6 primary cable $= \frac{(3700)}{(1000)}\ (0.01) =$ 0.04 kvar

Since two mercury lamps can be expected to be inoperative at any time, open-circuited secondary conditions are assumed for two series-mercury transformers.

From Table 16:

kw loss in one series-mercury transformer (normal operation) = 0.428 kw
kvar loss in one series-mercury transformer (normal operation) = 0.278 kvar
kw loss in one series-mercury transformer (open circuited secondary) = 0.028 kw
kvar loss in one series-mercury transformer (open-circuited secondary) = 1.190 kvar

Total kw:

Insulating current transformers plus secondary leads $= (15)(0.584) = 8.75$ kw
Series-mercury transformers $= (12)(0.428) + (2)(0.028) = 5.19$ kw
Primary cable $= 0.07$ kw
14.01 kw

Total kvar:

Insulating current transformer $= (15)(0.111) = 1.67$ kvar
Secondary leads $= (15)(0.004) = 0.06$ kvar
Series-mercury transformers $= (12)(0.278) + (2)(1.190) = 5.72$ kvar
Primary cable $= 0.04$ kvar
7.49 kvar

Plotting the Total kw and Total kvar values on the coordinates of Fig. 26 gives a point that falls just below the curve for a 20-kw constant-current transformer. This, then, is the rating necessary to satisfy operating conditions.

Table 17 shows that 0.80 kw of rated constant-current transformer capacity must be provided to start each E-H1 mercury lamp under the stated conditions. Thus, (14) (0.80) = 11.2 kw of constant-current transformer capacity is required to start the mercury lamps.

Table 18 should be checked to make sure the protective relay will not operate to de-energize the circuit when attempting to start the mercury lamps. The information in this table indicates that a 15-kw constant-current transformer is required.

The highest requirement for constant-current transformer capacity is determined by operating conditions in this case. Therefore, a 20-kw constant-current transformer should be used.

In some cases, a given constant-current transformer is available and it is desired to find how many lamps can be served from that transformer. The following example illustrates this type of a calculation.

Assume a 6.6-ampere series circuit to be served from a 30-kw constant-current transformer. There is to be 100 feet of #6 cable per lamp in the underground primary circuit. The circuit is run on opposite sides of the street and the separation between conductors is approximately 80 feet. The lowest anticipated ambient temperature at time of lamp turn-on is 20 F. The voltage at the primary terminals of the constant-current transformer is 100 per cent of rated voltage at time of lamp turn-on. A standard 3.8/6.6-ampere protective relay is used.

The problem is to determine the maximum number of E-H1 mercury lamps that can be operated on the circuit using standard lamps and series-mercury transformers. Assume no lamp outages.

From Table 14:

kw loss in 100 feet of #6 primary cable $= \frac{(100)}{(1000)}\ (0.019) = 0.0019$ kw

From Table 15:

kvar loss in 100 feet of #6 primary cable $= \frac{(100)}{(1000)}\ (0.01) = 0.001$ kvar

From Table 16:

kw loss in one series-mercury transformer = 0.428 kw
kvar loss in one series-mercury transformer = 0.278 kvar

Total kw per lamp:

Primary Cable = 0.0019 kw
Series-mercury transformer = 0.428 kw
0.43 kw

Total kvar per lamp:

Primary cable = 0.001 kvar
Series-mercury transformer = 0.278 kvar
0.28 kvar

For ease of plotting these values on the curves of Fig. 27, multiply both the kw and kvars by ten. Using 4.3 kw as the ordinate and 2.8 kvar as the abcissa, plot the one point. Next, draw a straight line through this point and the origin and extend the line so that it interests the load curve for a 30-kw constant-current transformer. This intersection shows that 21.1 kw is available to operate the mercury lamps. At 0.43 kw per lamp, the number of mercury lamps that can be operated is:

$$\frac{(21.1)}{(0.43)} = 49 \text{ lamps}$$

Table 17 shows that 0.58 kw of constant-current transformer capacity is required to start each mercury lamp. Therefore the number of lamps that can be started is:

$$\frac{(30)}{(0.58)} = 51 \text{ lamps.}$$

Table 18 indicates that no more than 35 E-H1 lamps can be started on the circuit without causing the protective relay to drop-out and de-energize the circuit. Thus, the protective relay is the limiting factor in this application. A maximum of 35 lamps is the limit for this circuit under the specified conditions.

More lamps could be installed on the circuit if the new universal aluminum tank series-mercury transformer were used to operate LIFEGUARD E-H1 mercury lamps. Assuming all other conditions to be the same, an analysis similar to that above shows a maximum of 56 lamps can be operated, 62 can be started, and 44 can be started without causing the protective relay to de-energize the circuit. The protective relay is still the limiting factor, but 44 lamps can be installed instead of 35 as in the previous case.

If the protective relay were changed from the 3.8/6.6-ampere relay to the 2.5/6.6-ampere relay, the maximum number of lamps that could be started without causing the relay to drop-out would be 53.

The procedure outlined above for determining constant-current transformer loading is realistic. Using this procedure will result in the most efficient use of constant-current transformer capacity while assuring dependable operation of the lamps for all reasonable anticipated conditions.

There are a number of existing installations in which the number of mercury lamps exceeds the recommendations determined from this procedure. This has been done as an economy measure in most cases to minimize the number of constant-current transformers and associated equipments on the system. Although some savings can be realized by loading a transformer beyond the recommended value, these savings may be made at the expense of more lamp outages, and possible poor lumer maintenance and lower light output.

21. Maintenance

Dirt on lamps, reflectors, and enclosing glassware is the largest contributor to lighting depreciation. In some checks of street lighting installations, depreciation factors as high as 60 per cent have been found. The lighting becomes completely inadequate if allowed to depreciate to such an extent. Luminaires should be cleaned regularly according to a definite prearranged schedule.

The cleaning schedule should be set up on an annual basis in such a way that under normal operating conditions the lighting depreciation due to the accumulation of dirt will not exceed 15 per cent. Cleaning every two or three months will accomplish this result under average dirt conditions, but in very dirty locations, cleaning may be necessary every few weeks.

Lamp replacements should always be made as promptly as possible, since adequate lighting at a given location is largely dependent on the light output of a single luminaire. If one lamp is out, a serious traffic hazard may exist. Lamps may be replaced individually, as they burn out, or on a group replacement plan.

Individual Lamp Replacement—A plan is particularly desirable where lamp breakage is high or where lamps are near maintenance headquarters. Patrol crews handle outages and answer outage complaints.

Group Lamp Replacement—Group replacement, the periodic replacement of all lamps on the system, is preferred by some street lighting maintenance organizations for several reasons:

1. There is always a time lag between a lamp failure and its replacement; so a reduction in the total number of outages, by periodic replacement, results in fewer hours of darkness and danger caused by the dead lamps.
2. Group replacement automatically eliminates the dim lamps on series circuits.
3. Fewer replacements are required while the circuits are energized and during hours of darkness. Both factors contribute to the safety of the crews.
4. Complaints of outages are minimized. The basis for this group replacement lies in the uniformity of lamp life achieved through close control of manufacture. Premature outages can be held to approximately 10 per cent if group replacement is made before the lamp has burned a sufficient time to be approaching the accelerated point on the mortality curve. Of course, the few lamp outages which do occur should be replaced promptly.

Regulation of Voltage or Current—The nominal life of an incandescent lamp has been chosen with the intent of maintaining a reasonable balance between operating efficiency and cost of lamp replacement for the average installation.

Voltage changes are quite common on multiple circuits, and it is recommended that the voltage throughout the system be checked at least once a year to obtain a true picture of operating conditions.

The constant-current transformer maintains close control over the secondary current; as a result, series circuits are relatively free from trouble due to variations in current. Constant-current transformers require very little maintenance. However, at least once a year the following checks should be made:

1. Secondary current value. Weight or position of counterweight should be adjusted to correct any deviation from correct value.
2. Sensitivity should be checked by checking movement of mechanism. Poor sensitivity can be caused by misalignment of parts or foreign materials in the bearings.
3. Oil should be tested for moisture or contamination by a dielectric test.

The oil switches should be given standard switch tests and inspections.

Relays and Switches—The air-insulated relays used in street-lighting service are of rugged construction to assure long life without frequent inspection. However, inspection once each year will often disclose conditions which can be easily corrected to assure longer life without rebuilding. Factory adjustments of the mechanism should not be changed unless faulty operation clearly indicates that adjustments are necessary.

Time switches should be given the same care as any other high-grade time-keeping mechanism.

Corrective Measures—The difference in the maintenance on series and multiple circuits, other than the checks given above, can best be given by a brief review of some of the troubles and causes of these troubles on each type of system.

On a multiple system, the following troubles and causes may be expected when incandescent lamps are used:

Indication of Trouble	Probable Cause or Causes
1. Lamp out, but apparently O.K.	Lamp loose in socket Loose or broken connections Failure of individual control
2. Lamp burns dimly	Low voltage
3. Short lamp life	High voltage Incorrect lamp Mechanical damage Excessive vibration
4. Lamp breakage	Water contacting lamp bulb Lamp touches luminaire
5. All lamps out	Transformer primary fuse open CSP transformer secondary breaker open Failure in multiple relay Failure in primary switch Failure of control

On series circuits, the following might be expected:

Indication of Trouble	Probable Cause or Causes
1. Lamp out, but apparently O.K.	Lamp loose in socket Loose or broken connections Film cutout punctured
2. One lamp burns dimly	Partial failure of film cutout Incorrect lamp Filament broken and rewelded
3. All lamps burn dimly	Low current—constant current transformer jammed. Low current—constant current transformer out of adjustment Low current—low primary voltage Low current—constant current transformer overloaded.
4. Portion of circuit out	Film cutouts punctured—incorrect cutouts Film cutouts punctured—lightning Film cutouts punctured—power surges Circuit grounded at two or more points
5. All lamps out	Feeder power off Control power off Series circuit open Primary switch failure
6. Short lamp life	High current—constant current transformer jammed High current—constant current transformer out of adjustment Mechanical damage Incorrect lamp Excessive vibration
7. Lamp breakage	Water contacting lamp bulb Lamp touches luminaire
8. Burned sockets and receptacles	Improper film cutout

continued on next page

Indication of Trouble	Probable Cause or Causes
9. Radio and telephone interference	Overhead circuit contacts trees Inadequate insulation on high voltage circuits Open-circuited isolating transformers

22. Cost Comparisons

In order to provide a true picture of the relative costs of different systems, a cost analysis should include not only labor and material costs for the original installation, but also all maintenance, operation, and amortizing costs. Taxes, interest, and insurance should be included when amortizing the cost of the installation.

As labor costs and local practices vary throughout the country, it is impossible to make a cost comparison that is exact for all cases. However, for purpose of illustration, a cost study is presented which uses an average of costs for various parts of the country. While the study is not exact for any one locality or installation, it will provide an indication as to the relative costs of the various systems compared. In the cost studies, the actual mounting height is used rather than the "nominal" mounting height of 25 feet or 30 feet. As there is a difference in luminaire mounting height for transformer-base or anchor-base poles, this then results in a different coefficient of utilization for any particular unit when using different types of standards.

Table 19 presents a cost comparison of various types of luminaires and distribution systems that may be employed to provide illumination levels used in downtown business districts today. The systems utilizing color-corrected mercury lamps are included to show the relative cost between the 400-watt clear, and 400-watt color-corrected mercury lamps, and also to provide an indication of relative cost of higher wattage lamps. As the 400-watt clear mercury lamp is a more familiar lamp than the color-corrected or higher wattage lamps, this lamp was chosen as the mercury lamp to be used in all of the cost studies, even though the trend is toward the use of color-corrected lamps for new installations. The 425-watt A-H17 high-voltage lamp using a reactor ballast becomes unstable at approximately 90 per cent of rated lamp open-circuit voltage. Consequently, this lamp was not used as the 100 per cent base, as this characteristic would eliminate it from consideration for many installations. The least expensive system (excluding the high-voltage mercury lamp) is the E-H1 mercury lamp with the high-reactance ballast when served from a 480-volt distribution system. This system was used as the 100 per cent base.

Table 20 presents a cost comparison of various luminaires that might be used to provide illumination levels used on many high density traffic roadways and secondary business streets.

Table 21 is a cost study of installations for expressway type roads. This study also shows a comparison between the cost of mounting the luminaires along the sides of the road or mounting them in the medial strip.

The form used for the cost studies is the one officially recognized by the Illuminating Engineering Society. Most items are self-explanatory, but Line 14, "Net luminaire cost (each)," Line 15, "Net additional accessory costs per luminaire," and Line 16, "Estimated wiring and installation cost per luminaire," should be explained.

Line 14 includes the cost of the luminaire, standard, and ballast or series transformer. Using System I of Table 19 as an example, the cost is as follows:

Luminaire	=$ 73.76
Standard	= 135.74
6.6–20 amp. series transformer	= 65.45
Total	=$274.95

Line 15 includes the cost of the wire, transformer, and control equipment. Although the cost study is for a one-mile section of roadway, this figure was obtained on the basis of the total installation being much longer. A 30-kw constant-current transformer was loaded as indicated in the cost study, and the cost for this complete circuit was pro-rated among the number of units on the circuit to obtain the cost per luminaire. Again using system I of Table 19, the cost is obtained as follows:

30-Kw "package type," self-protecting constant-current transformer	=$1782.55
Hanger iron	= 12.65
Photo-control	= 39.00
2700 ft #8 1/c 6000-volt direct-buried cable	= 569.70
2400 ft #10 R WRH wire	= 94.56
Total cost for the one circuit	$2498.46

$$\text{Cost per luminaire} = \frac{\$2498.46}{34} = \$73$$

Line 16 includes the labor costs for installing and connecting all equipment. Again, this cost per luminaire was figured on the total cost of one circuit, and then this cost was pro-rated among the number of luminaires on the circuit to obtain the cost per luminaire. Continuing using System I of Table 19, the cost is obtained as follows:

Install transformer base standard complete—$50.00 (each)	=$1700.00
Install and connect luminaire—$7.00 (each)	= 238.00
Install and connect 6.6–20 ampere series transformer $6.00 (each)	= 204.00
Install and connect package type self protecting constant-current transformer	= 110.00
Install and connect photo control	= 7.00
Install cable in pole and bracket—1/c—$10.00 (each)	= 340.00
Install 100 ft. underground cable—2 cables $42.00/100 ft. (each)	= 42.00
Install 2200 ft. underground cable—1 cable $40.00/100 ft. (each)	= 880.00
Total Cost for the one circuit	=$3521.00

$$\text{Cost per luminaire} = \frac{\$3521.00}{34} = \$104$$

Table 19—Cost Comparison* of Eighteen Systems

		6.6 AMPERES SERIES[1]					6.6 AMP. ST. SERIES[2]		120/240 V[3]		240/480 VOLT[3]			480 VOLT[3]			480 VOLT[3]		
LIGHTING SYSTEM NUMBER		I 34 Units/Cir	II 50 Units/Cir	III 32 Units/Cir	IV[4] 44 Units/Cir	V 32 Units/Cir	VI 52 Units/Cir	VII[5] 36 Units/Cir	VIII	IX	X High React	XI Reg. Output	XII	XIII High React	XIV Reg. Output	XV Reactor	XVI High React	XVII Reactor	XVIII Reactor
DESCRIPTION OF LIGHTING SYSTEMS	1. Type of lamp (Fil., merc., fluor., etc.)	Filament	Filament	Mercury	Mercury	Fluorescent	Filament	Mercury	Filament	Filament	Mercury	Mercury	Fluorescent	Mercury	Mercury	Mercury	Color Corrected Mercury		
	2. Lamp description (Type) (Watts per lamp only)	15,000 L PS-52 715	10,000 L PS-40 485	E-H1 400	E-H1 400	F72T12/RS 95	10,000 L PS-40 540	A-H24 435	15,000 L PS-52 800	10,000 L PS-40 575	E-H1 400	E-H1 400	F72T12/RS 95	E-H1 400	E-H1 400	A-H17 425	J-H1 400	B-H18 700	B-H15 1000
	3. Type of luminaire	Pendant	Pendant	Horizontal Mercury	Horizontal Mercury	Tilted Fluorescent	Pendant	Horizontal Mercury	Pendant	Pendant	Horizontal Mercury	Horizontal Mercury	Tilted Fluorescent	Horizontal Mercury	Horizontal Mercury	Horizontal Mercury	Horizontal Mercury	Horizontal Mercury	Horizontal Mercury
	4. Number of lamps per luminaire	1	1	1	1	4	1	1	1	1	1	1	4	1	1	1	1	1	1
BASIC DATA	5. Rated initial lamp lumens per luminaire	15,000	10,000	21,000	21,000	23,400	10,000	20,000	15,000	10,000	21,000	21,000	23,400	21,000	21,000	21,000	20,000	34,000	52,000
	6. Lamp life	1,700	1,700	7,000	7,000	7,500	1,700	6,000	1,350	1,350	7,000	7,000	7,500	7,000	7,000	7,000	7,000	7,000	7,000
	7. Watts per luminaire (including auxiliary) + 10 per cent line loss	825	583	484	484	484	594	473	880	632	505	512	504	505	510	495	505	809	1,144
	8. Coefficient of utilization	.398	.464	.516	.516	.281	.440	.499	.374	.440	.516	.516	.290	.516	.516	.516	.463	.404	.368
	9. Maintenance factor	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	10. Number of luminaires	160	206	88	88	144	216	96	170	216	88	88	140	88	88	88	102	69	50
	Spacing	66 Opp	51 Opp	120 Opp	120 Opp	73 Opp	49 Opp	111 Opp	62 Opp	49 Opp	120 Opp	120 Opp	75 Opp	120 Opp	120 Opp	120 Opp	103 Opp	77 Stag	106 Stag
	11. Average footcandles Initial	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	12. Energy rate ($ per KWH)	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01	$.01
	13. Estimated burning hours per year	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
INITIAL COST	14. Net luminaire cost (each)[6]	$ 275.—	231.—	243.—	243.—	439.—	167.—	173.—	186.—	160.—	245.—	245.—	361.—	250.—	250.—	232.—	263.—	260.—	324.—
	15. Net additional accessory cost per luminaire[7]	$ 73.—	53.—	88.—	71.—	79.—	63.—	95.—	77.—	62.—	56.—	56.—	41.—	43.—	43.—	43.—	53.—	57.—	77.—
	16. Estimated wiring and installation cost per luminaire	$ 104.—	97.—	124.—	124.—	110.—	85.—	110.—	93.—	86.—	126.—	126.—	100.—	125.—	125.—	125.—	118.—	139.—	162.—
	17. Net initial lamp cost each (list less 30 per cent)	$ 2.10	1.75	14.00	14.00	2.63	1.74	19.25	2.70	1.02	14.00	14.00	2.63	14.00	14.00	14.18	16.10	34.65	38.15
	18. Net initial lamp cost per luminaire (4 × 17)	$ 2.10	1.75	14.00	14.00	10.52	1.74	19.25	2.70	1.02	14.00	14.00	10.52	14.00	14.00	14.18	16.10	34.65	38.15
	19. Total initial cost per luminaire (14 + 15 + 16 + 18)	$ 454.—	383.—	469.—	452.—	638.—	317.—	397.—	359.—	309.—	441.—	441.—	512.—	432.—	432.—	414.—	450.—	491.—	601.—
	20. TOTAL INITIAL COST (10 × 19)	$72,640.—	78,898.—	41,272.—	39,776.—	91,872.—	68,472.—	38,112.—	61,030.—	66,744.—	38,808.—	38,808.—	71,680.—	38,016.—	38,016.—	36,432.—	45,900.—	33,879.—	30,050.—
ANNUAL FIXED CHGS.	21. Initial cost per luminaire less lamps (14 + 15 + 16)	$ 452.—	381.—	455.—	438.—	628.—	315.—	378.—	356.—	308.—	427.—	427.—	502.—	418.—	418.—	400.—	434.—	456.—	563.—
	22. Total initial cost less lamps (10 × 21)	$72,320.—	78,486.—	40,040.—	38,544.—	90,432.—	68,040.—	36,288.—	60,520.—	66,528.—	37,576.—	37,576.—	70,280.—	36,784.—	36,784.—	35,200.—	44,268.—	31,464.—	28,150.—
	23. ANNUAL FIXED CHARGES (15 per cent of 22)	$10,848.—	11,773.—	6,006.—	5,782.—	13,565.—	10,206.—	5,443.—	9,078.—	9,979.—	5,636.—	5,636.—	10,542.—	5,518.—	5,518.—	5,280.—	6,640.—	4,720.—	4,222.—
ANNUAL OPERATING COSTS	24. Annual no. lamp replacements (4 × 10 × 13 ÷ 6)	376	485	50	50	307	508	64	504	508	50	50	299	50	50	50	58	39	29
	25. Annual cost of replacement lamps (17 × 24)	$ 790.—	849.—	700.—	700.—	807.—	884.—	1,232.—	1,361.—	518.—	700.—	700.—	786.—	700.—	700.—	709.—	934.—	1,351.—	1,106.—
	26. Annual cost of replacement parts[8]	$ 723.—	785.—	400.—	385.—	904.—	680.—	363.—	605.—	665.—	376.—	376.—	703.—	368.—	368.—	352.—	443.—	315.—	282.—
	27. Total annual maintenance material cost (25 + 26)	$ 1,513.—	1,634.—	1,100.—	1,085.—	1,711.—	1,564.—	1,595.—	1,866.—	1,183.—	1,076.—	1,076.—	1,489.—	1,068.—	1,068.—	1,061.—	1,377.—	1,666.—	1,388.—
	28. Estimated labor cost to replace one lamp	$ 1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—	1.—
	29. Total labor costs to replace lamps (24 × 28)	$ 376.—	485.—	50.—	50.—	307.—	508.—	64.—	504.—	508.—	50.—	50.—	299.—	50.—	50.—	50.—	58.—	39.—	29.—
	30. Estimated cleaning cost per luminaire	$ 1.—	1.—	1.—	1.—	2.—	1.—	1.—	1.—	1.—	1.—	1.—	2.—	1.—	1.—	1.—	1.—	1.—	1.—
	31. Number of cleanings per year	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	32. Annual cleaning cost (10 × 30 × 31)	$ 320.—	412.—	176.—	176.—	576.—	432.—	192.—	340.—	432.—	176.—	176.—	560.—	176.—	176.—	176.—	204.—	138.—	100.—
	33. Total annual maintenance labor cost (29 + 32)	$ 696.—	897.—	226.—	226.—	883.—	940.—	256.—	844.—	940.—	226.—	226.—	859.—	226.—	226.—	226.—	262.—	177.—	129.—
	34. Total Annual Maintenance Cost (27 + 33)	$ 2,209.—	2,531.—	1,326.—	1,311.—	2,594.—	2,504.—	1,851.—	2,710.—	2,123.—	1,302.—	1,302.—	2,348.—	1,294.—	1,294.—	1,287.—	1,639.—	1,843.—	1,517.—
	35. Annual Energy Cost (7 × 10 × 12 × 13 ÷ 1000)	$ 5,280.—	4,804.—	1,704.—	1,704.—	2,788.—	5,132.—	1,816.—	5,976.—	5,460.—	1,778.—	1,802.—	2,822.—	1,778.—	1,795.—	1,742.—	2,060.—	2,233.—	2,288.—
	36. TOTAL ANNUAL OPERATING COST (34 + 35)	$ 7,489.—	7,335.—	3,030.—	3,015.—	5,382.—	7,636.—	3,667.—	8,686.—	7,583.—	3,080.—	3,104.—	5,170.—	3,072.—	3,089.—	3,029.—	3,699.—	4,076.—	3,805.—
TOTAL & REL. COSTS	37. TOTAL ANNUAL COST (23 + 36)	$18,337.—	19,108.—	9,036.—	8,797.—	18,947.—	17,842.—	9,110.—	17,764.—	17,562.—	8,716.—	8,740.—	15,712.—	8,590.—	8,607.—	8,309.—	10,339.—	8,796.—	8,027.—
	38. Relative Annual Cost	213%	222%	105%	102%	220%	208%	106%	207%	204%	101%	102%	183%	100%	100%	97%	120%	102%	93%
	39. Annual Cost per Footcandle (37 ÷ 11)	$ 6,112.—	6,369.—	3,012.—	2,932.—	6,316.—	5,947.—	3,037.—	5,921.—	5,854.—	2,905.—	2,913.—	5,237.—	2,863.—	2,869.—	2,770.—	3,446.—	2,932.—	2,676.—
	40. Relative Annual Cost per Footcandle	213%	222%	105%	102%	220%	208%	106%	207%	204%	101%	102%	183%	100%	100%	97%	120%	102%	93%

* Comparison assumes one mile section of roadway, 60 feet, curb to curb, underground circuits, steel poles, approx. 30-foot mounting height, average of 3.0 footcandles provided initially. Distribution system is independent of existing systems. Minimum temperature at turn-on time assumed to be 60°F.

[1] Using 30-kw constant-current transformers, #8 wire, and individual insulating transformers or ballasts.
[2] Using 30-kw constant-current transformers, #8 wire, no insulating transformers or ballasts.
[3] Loading based on the use of a completely self-protecting Class A transformer with taps, loaded up to 125 per cent of rated capacity.
[4] Experimental loading—not generally recommended—no protective relay.
[5] This value for non-magnetic sheathed cable buried directly in earth.
[6] Luminaire + pole + ballast or insulating transformer.
[7] Wire + transformer or regulator + control equipment.
[8] One per cent of Total Initial Cost Less Lamps (Line 22).

Table 20—Cost Comparison* of Six Systems

		120/240[1]		480 Volt[1]			240/480[1]
	LIGHTING SYSTEM NUMBER	I	II	III High Reactance	IV Reactor	V High Reactance	VI
DESCRIPTION OF LIGHTING SYSTEMS	1. Type of lamp (Fil., merc., fluor., etc.)	Filament	Filament	Mercury	Mercury	Color Corr. Mercury	Fluorescent
	2. Lamp description (Type)	15,000 L PS-52	10,000 L PS-40	E-H1 400	A-H17 425	J-H1 400	F72T12/RS 95
	(Watts per lamp only)	800	575				
	3. Type of luminaire	Pendant	Pendant	Horizontal Mercury	Horizontal Mercury	Horizontal Mercury	Tilted Fluorescent
	4. Number of lamps per luminaire	One	One	One	One	One	Four
BASIC DATA	5. Rated initial lamp lumens per luminaire	15,000	10,000	21,000	21,000	20,000	23,400
	6. Lamp life	1,350	1,350	7,000	7,000	7,000	7,500
	7. Watts per luminaire (including auxiliary) + 10 per cent line loss	880	632	505	495	505	504
	8. Coefficient of utilization	.378	.466	.503	.503	.453	.294
	9. Maintenance factor	—	—	—	—	—	—
	10. Number of luminaires	112	136	60	60	70	92
	Spacing	95 Opp	78 Opp	88 Stag	88 Stag	76 Stag	115 Opp
	11. Average footcandles initial	2.0	2.0	2.0	2.0	2.0	2.0
	12. Energy rate ($ per KWH)	$.01	.01	.01	.01	.01	.01
	13. Estimated burning hours per year	4,000	4,000	4,000	4,000	4,000	4,000
INITIAL COST	14. Net luminaire cost (each)[2]	$ 142.00	116.00	185.00	166.00	198.00	293.00
	15. Net additional accessory cost per luminaire[3]	$ 70.00	58.00	26.00	26.00	25.00	25.00
	16. Estimated wiring and installation cost per luminaire	$ 67.00	64.00	76.00	76.00	75.00	71.00
	17. Net initial lamp cost each (list less 30 per cent)	$ 2.70	1.02	14.00	14.18	16.10	2.63
	18. Net initial lamp cost per luminaire (4 × 17)	$ 2.70	1.02	14.00	14.18	16.10	10.52
	19. Total initial cost per luminaire (14 + 15 + 16 + 18)	$ 282.00	239.00	301.00	282.00	314.00	400.00
	20. TOTAL INITIAL COST (10 × 19)	$31,584.00	32,504.00	18,060.00	16,920.00	21,980.00	36,800.00
ANNUAL FIXED CHGS.	21. Initial cost per luminaire less lamps (14 + 15 + 16)	$ 279.00	238.00	278.00	268.00	298.00	389.00
	22. Total initial cost less lamps (10 × 21)	$31,248.00	32,368.00	17,220.00	16,080.00	20,860.00	35,788.00
	23. ANNUAL FIXED CHARGES (15 per cent of 22)	$ 4,687.00	4,855.00	2,583.00	2,412.00	3,129.00	5,368.00
ANNUAL OPERATING COSTS	24. Annual no. lamp replacements (4 × 10 × 13 ÷ 6)	332	403	34	34	40	196
	25. Annual cost of replacement lamps (17 × 24)	$ 896.00	411.00	476.00	482.00	644.00	515.00
	26. Annual cost of replacement parts[4]	$ 312.00	324.00	172.00	161.00	209.00	358.00
	27. Total annual maintenance material cost (25 + 26)	$ 1,208.00	735.00	648.00	643.00	853.00	873.00
	28. Estimated labor cost to replace one lamp	$ 1.00	1.00	1.00	1.00	1.00	1.00
	29. Total labor costs to replace lamps (24 × 28)	$ 332.00	403.00	34.00	34.00	40.00	196.00
	30. Estimated cleaning cost per luminaire	$ 1.00	1.00	1.00	1.00	1.00	2.00
	31. Number of cleanings per year	2	2	2	2	2	2
	32. Annual cleaning cost (10 × 30 × 31)	$ 224.00	272.00	120.00	120.00	140.00	368.00
	33. Total annual maintenance labor cost (29 + 32)	$ 556.00	675.00	154.00	154.00	180.00	564.00
	34. Total Annual Maintenance Cost (27 + 33)	$ 1,764.00	1,410.00	802.00	797.00	1,033.00	1,437.00
	35. Annual Energy Cost (7 × 10 × 12 × 13 ÷ 1000)	$ 3,942.00	3,438.00	1,212.00	1,188.00	1,414.00	1,855.00
	36. TOTAL ANNUAL OPERATING COST (34 + 35)	$ 5,706.00	4,848.00	2,014.00	1,985.00	2,447.00	3,292.00
TOTAL & REL. COSTS	37. TOTAL ANNUAL COST (23 + 36)	$10,393.00	9,703.00	4,597.00	4,397.00	5,576.00	8,660.00
	38. Relative Annual Cost	226%	211%	100%	96%	121%	188%
	39. Annual Cost per Footcandle (37 ÷ 11)	$ 5,196.00	4,852.00	2,298.00	2,198.00	2,788.00	4,330.00
	40. Relative Annual Cost per Footcandle	226%	211%	100%	96%	121%	188%

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*Comparison assumes one mile section of roadway, 60 feet curb to curb, overhead circuits, wood poles, approx. 30-foot mounting height, average of 2.0 footcandles provided initially. Distribution system is independent of existing systems. Minimum temperature at turn-on time assumed to be O F.

[1] Loading based on the use of a completely self-protecting Class A transformer with taps, loaded up to 125 per cent of rated capacity.

[2] Luminaire+pole+ballast.

[3] Wire+transformer+control equipment.

[4] One per cent of total initial cost less lamps (Line 22).

Table 21—Cost Comparison* of Six Systems

		Poles Mounted on Outside of Roadway			Poles Mounted in Medial Strip		
	LIGHTING SYSTEM NUMBER	I 120/240V[1]	II 480V[1]	III 240/480V[1]	IV 120/240V[1]	V 480V[1]	VI 240/480V[1]
DESCRIPTION OF LIGHTING SYSTEMS	1. Type of lamp (Fil., merc., fluor., etc.)	Filament	Mercury	Fluorescent	Filament	Mercury	Fluorescent
	2. Lamp description (Type)	10,000 L PS-40	E-H1	F72T12/RS	10,000 L PS-40	E-H1	F72T12/RS
	(Watts per lamp only)	575	400	95	575	400	95
	3. Type of luminaire	Pendant	Horizontal Mercury	Tilted Fluorescent	Pendant	Horizontal Mercury	Tilted Fluorescent
	4. Number of lamps per luminaire	One	One	Four	One	One	Four
BASIC DATA	5. Rated initial lamp lumens per luminaire	10,000	21,000	23,400	10,000	21,000	23,400
	6. Lamp life	1,350	7,000	7,500	1,350	7,000	7,500
	7. Watts per luminaire (including auxiliary) + 10 per cent line loss	632	505	504	632	505	504
	8. Coefficient of utilization	.358	.413	.22	.304	.399	.22
	9. Maintenance factor	—	—	—	—	—	—
	10. Number of luminaires	176	72	124	208	76	124
	Spacing	60 Opp	72 Stag	85 Opp	51	139	85
	11. Average footcandles initial	2.0	2.0	2.0	2.0	2.0	2.0
	12. Energy rate ($ per KWH)	.01	.01	.01	.01	.01	.01
	13. Estimated burning hours per year	4,000	4,000	4,000	4,000	4,000	4,000
INITIAL COST	14. Net luminaire cost (each)[2]	$ 189.—	268.—	372.—	133.—	203.—	314.—
	15. Net additional accessory cost per luminaire[3]	$ 34.—	22.—	20.—	29.—	19.—	18.—
	16. Estimated wiring and installation cost per luminaire	$ 70.—	81.—	76.—	45.—	53.—	47.—
	17. Net initial lamp cost each (list less 30 per cent)	$ 1.02	14.00	2.63	1.02	14.00	2.63
	18. Net initial lamp cost per luminaire (4 × 17)	$ 1.02	14.00	10.52	1.02	14.00	10.52
	19. Total initial cost per luminaire (14 + 15 + 16 + 18)	$ 294.—	385.—	478.—	208.—	289.—	390.—
	20. TOTAL INITIAL COST (10 × 19)	$51,744.—	27,720.—	59,272.—	43,264.—	21,964.—	48,360.—
ANNUAL FIXED CHGS.	21. Initial cost per luminaire less lamps (14 + 15 + 16)	$ 293.—	371.—	468.—	207.—	275.—	379.—
	22. Total initial cost less lamps (10 × 21)	$51,568.—	26,712.—	58,032.—	43,056.—	20,900.—	46,996.—
	23. ANNUAL FIXED CHARGES (15 per cent of 22)	$ 7,735.—	4,007.—	8,705.—	6,458.—	3,135.—	7,049.—
ANNUAL OPERATING COSTS	24. Annual no. lamp replacements (4 × 10 × 13 ÷ 6)	521	41	264	616	43	264
	25. Annual cost of replacement lamps (17 × 24)	$ 531.—	574.—	692.—	628.—	602.—	694.—
	26. Annual cost of replacement parts[4]	$ 516.—	267.—	580.—	430.—	209.—	470.—
	27. Total annual maintenance material cost (25 + 26)	$ 1,047.—	841.—	1,272.—	1,058.—	811.—	1,164.—
	28. Estimated labor cost to replace one lamp	$ 1.—	1.—	1.—	1.—	1.—	1.—
	29. Total labor costs to replace lamps (24 × 28)	$ 521.—	41.—	264.—	616.—	43.—	264.—
	30. Estimated cleaning cost per luminaire	$ 1.—	1.—	2.—	1.—	1.—	2.—
	31. Number of cleanings per year	2	2	2	2	2	2
	32. Annual cleaning cost (10 × 30 × 31)	$ 352.—	144.—	496.—	416.—	152.—	496.—
	33. Total annual maintenance labor cost (29 + 32)	$ 873.—	185.—	760.—	1,032.—	195.—	760.—
	34. Total Annual Maintenance Cost (27 + 33)	$ 1,910.—	1,026.—	2,032.—	2,090.—	1,006.—	1,924.—
	35. Annual Energy Cost (7 × 10 × 12 × 13 ÷ 1000)	$ 4,449.—	1,454.—	2,500.—	5,258.—	1,535.—	2,500.—
	36. TOTAL ANNUAL OPERATING COST (34 + 35)	$ 6,359.—	2,480.—	4,532.—	7,348.—	2,541.—	4,424.—
TOTAL & REL. COSTS	37. TOTAL ANNUAL COST (23 + 36)	$14,094.—	6,487.—	13,237.—	13,806.—	5,676.—	11,473.—
	38. Relative Annual Cost	248%	114%	233%	243%	100%	202%
	39. Annual Cost per Footcandle (37 ÷ 11)	$ 7,047.—	3,244.—	6,618.—	6,903.—	2,838.—	5,736.—
	40. Relative Annual Cost per Footcandle	248%	114%	233%	243%	100%	202%

*Comparison assumes one mile section of divided roadway, 30-20-30 feet, overhead circuits, steel poles, approx. 30-foot mounting height, average of 2.0 footcandles provided initially. Distribution system is independent of existing systems. Minimum temperature at turn-on time assumed to be O F.

[1] Loading based on the use of a completely self-protecting Class A transformer with taps, loaded up to 125 per cent of rated capacity.

[2] Luminaire+pole+ballast.

[3] Wire+transformer+control equipment.

[4] One per cent of total initial cost less lamps (Line 22).

It is not practical to include a complete list of all material and labor costs used in these comparisons. However, the above costs are typical of those used throughout the cost studies. It is not expected that the costs shown above agree exactly with the costs for any particular installation, as explained previously. Although these costs may be judged to be high or low in regard to a specific installation, the importance of these cost studies does not lie in the actual costs (although this should not be a large difference when compared to a specific case), but in the relative costs. As long as the same costs are used in all cases, the relative cost will be unaffected.

The cost study comparing incandescent, fluorescent, and mercury luminaires served by series or multiple circuits (Table 19) shows that the type of distribution system will make little if any difference in either the initial or annual operating cost. This can be expected for all cases except where very long runs are to be made, such as along residential or secondary traffic streets. In this case, the series distribution system will tend to be more economical.

The use of wood poles and overhead wiring (Table 20) results in a considerable savings in the cost per luminaire. When the total annual cost is considered, however, the savings are not as great as might be expected. The savings show a range of only 20 per cent to 30 per cent, depending upon the system being considered.

Although some economy can be realized by using twin-bracket poles mounted in a medial strip, the savings are not as great as might at first be expected. (See Table 21.) This is due almost entirely to the fact that more units are required, because the coefficient of utilization is lower. This, then, means more equipment to purchase, install, operate, and maintain. Also, the additional bracket tends to off-set some of the difference. This is especially true in view of the fact that more luminaires are required. Hence, the number of twin-bracket poles for medial strip mounting is more than half the number of single-bracket poles for mounting at the side of the road. While the Total Initial Cost is approximately 20 per cent to 25 per cent less for the medial strip mounting systems, the annual cost is approximately the same for incandescent and only about 15 per cent less for the mercury and fluorescent systems. It is felt by some authorities that mounting poles in the medial strip presents a much more dangerous traffic hazard than mounting them at the sides of the road. In view of this, the small savings made possible by the method may not be justified.

The cost of any particular installation will depend upon many factors, and will vary greatly depending upon the specific conditions encountered for each installation. For the particular set of conditions for these cost studies, the approximate cost for a system using underground wiring and steel poles is $400 per unit for incandescent, $550 per unit for fluorescent, and $450 per unit for mercury. If wood poles and overhead wiring are used, the cost per unit is approximately $250 for incandescent, $400 for fluorescent, and $300 for mercury. To obtain more accurate costs for any given installation, the cost studies presented here should be followed through in detail, and the exact costs for the conditions involved substituted for the values shown. However, for most cases the figures given above will provide a fair approximation.

Although the incandescent systems have the lowest cost per unit, more units are required, to provide a given illumination level than are required with mercury because of the lower lumen output and utilization. The systems with the fluorescent lamp, which is the most efficient light source today, also require more units than are required with mercury, because of the low coefficient of utilization. When all factors are taken into consideration, a given illumination level can be obtained more economically by using mercury than by using incandescent or fluorescent units. As pointed out previously, the least expensive method of obtaining a given illumination level is not always the most desirable method. Mercury, while being the least expensive method, detracts from the brilliance of colors predominantly in the red end of the spectrum. In many cases, a more expensive installation will be justified from the standpoint of color rendition alone. Depending upon the color rendition desired, the new Silver-White colored mercury or the fluorescent-mercury lamps can be used to obtain better color rendition and still retain the inherent economy of the mercury source. Such factors as this, and many others from an appearance or aesthetic viewpoint, may have such a strong influence as to relegate cost to a position of secondary importance. These factors must be taken into account for each installation and, although they do not show up in a cost study, they may very definitely have a monetary value, even though the exact amount cannot be determined.

REFERENCES

1. Street Lighting—Then and Now, *Illuminating Engineering*, Vol. 51, January, 1956, pp. 86–96.
2. Westinghouse Lighting Handbook, April, 1958 revision. Westinghouse Electric Corporation, Lamp Division, Bloomfield, New Jersey.
3. American Standard Practice for Street and Highway Lighting, A.S.A. Standard D12.1—1953, UDC 628.971.

APPENDIX

THIS APPENDIX includes a number of tables of application data collected from numerous sources. These tables are included as an aid to the user of this book in solving distribution system problems.

Tables 1 through 11 are tables of conductor impedance and physical characteristics. Included are data for overhead, open-wire lines; overhead self-supporting cable; and cables for underground circuits.

Table 12 is included to facilitate derivation of equivalent circuits for power and distribution transformers from the impedance data usually furnished by the manufacturer.

Table 14 on residential underground distribution system design practices is included because of the many different practices by the various companies and because of the increasing application of underground systems in residential areas. This table has been abstracted from the article "Residential Distribution Adaptable" by Mr. F. E. Andrews which appeared in the December 12, 1955 issue of *Electrical World*.

The subject of lightning protection is to be included in Volume II. However, for quick reference on lightning arrester selection Table 15 is included.

Table 1—Characteristics of **COPPER** Conductors, Hard Drawn, 97.3 Per cent Conductivity

Size of Conductor		Number of Strands	Diameter of Individual Strands Inches	Outside Diameter Inches	Breaking Strength Pounds	Weight Pounds per Mile	Approx. Current Carrying Capacity* Amps	Geometric Mean Radius at 60 Cycles Feet	r_a Resistance Ohms per Conductor per Mile								x_a Inductive Reactance Ohms per Conductor Per Mile At 1 Ft. Spacing			x_a' Shunt Capacitive Reactance Megohms per Conductor Per Mile At 1 Ft. Spacing		
									25°C. (77°F.)				50°C. (122°F.)									
Circular Mils	A.W.G. or B. & S.								d-c	25 cycles	50 cycles	60 cycles	d-c	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles
1 000 000	...	37	0.1644	1.151	43 830	16 300	1 300	0.0368	0.0585	0.0594	0.0620	0.0634	0.0640	0.0648	0.0672	0.0685	0.1666	0.333	0.400	0.216	0.1081	0.0901
900 000	...	37	0.1560	1.092	39 510	14 670	1 220	0.0349	0.0650	0.0658	0.0682	0.0695	0.0711	0.0718	0.0740	0.0752	0.1693	0.339	0.406	0.220	0.1100	0.0916
800 000	...	37	0.1470	1.029	35 120	13 040	1 130	0.0329	0.0731	0.0739	0.0760	0.0772	0.0800	0.0806	0.0826	0.0837	0.1722	0.344	0.413	0.224	0.1121	0.0934
750 000	...	37	0.1424	0.997	33 400	12 230	1 090	0.0319	0.0780	0.0787	0.0807	0.0818	0.0853	0.0859	0.0878	0.0888	0.1739	0.348	0.417	0.226	0.1132	0.0943
700 000	...	37	0.1375	0.963	31 170	11 410	1 040	0.0308	0.0836	0.0842	0.0861	0.0871	0.0914	0.0920	0.0937	0.0947	0.1759	0.352	0.422	0.229	0.1145	0.0954
600 000	...	37	0.1273	0.891	27 020	9 781	940	0.0285	0.0975	0.0981	0.0997	0.1006	0.1066	0.1071	0.1086	0.1095	0.1799	0.360	0.432	0.235	0.1173	0.0977
500 000	...	37	0.1162	0.814	22 510	8 151	840	0.0260	0.1170	0.1175	0.1188	0.1196	0.1280	0.1283	0.1296	0.1303	0.1845	0.369	0.443	0.241	0.1205	0.1004
500 000	...	19	0.1622	0.811	21 590	8 151	840	0.0256	0.1170	0.1175	0.1188	0.1196	0.1280	0.1283	0.1296	0.1303	0.1853	0.371	0.445	.241	0.1206	0.1005
450 000	...	19	0.1539	0.770	19 750	7 336	780	0.0243	0.1300	0.1304	0.1316	0.1323	0.1422	0.1426	0.1437	0.1443	0.1879	0.376	0.451	0.245	0.1224	0.1020
400 000	...	19	0.1451	0.726	17 560	6 521	730	0.0229	0.1462	0.1466	0.1477	0.1484	0.1600	0.1603	0.1613	0.1619	0.1909	0.382	0.458	0.249	0.1245	0.1038
350 000	...	19	0.1357	0.679	15 590	5 706	670	0.0214	0.1671	0.1675	0.1684	0.1690	0.1828	0.1831	0.1840	0.1845	0.1943	0.389	0.466	0.254	0.1269	0.1058
350 000	...	12	0.1708	0.710	15 140	5 706	670	0.0225	0.1671	0.1675	0.1684	0.1690	0.1828	0.1831	0.1840	0.1845	0.1918	0.384	0.460	0.251	0.1253	0.1044
300 000	...	19	0.1257	0.629	13 510	4 891	610	0.01987	0.1950	0.1953	0.1961	0.1966	0.213	0.214	0.214	0.215	0.1982	0.396	0.476	0.259	0.1296	0.1080
300 000	...	12	0.1581	0.657	13 170	4 891	610	0.0208	0.1950	0.1953	0.1961	0.1966	0.213	0.214	0.214	0.215	0.1957	0.392	0.470	0.256	0.1281	0.1068
250 000	...	19	0.1147	0.574	11 360	4 076	540	0.01813	0.234	0.234	0.235	0.235	0.256	0.256	0.257	0.257	0.203	0.406	0.487	0.266	0.1329	0.1108
250 000	...	12	0.1443	0.600	11 130	4 076	540	0.01902	0.234	0.234	0.235	0.235	0.256	0.256	0.257	0.257	0.200	0.401	0.481	0.263	0.1313	0.1094
211 600	4/0	19	0.1055	0.528	9 617	3 450	480	0.01668	0.276	0.277	0.277	0.278	0.302	0.303	0.303	0.303	0.207	0.414	0.497	0.272	0.1359	0.1132
211 600	4/0	12	0.1328	0.552	9 483	3 450	490	0.01750	0.276	0.277	0.277	0.278	0.302	0.303	0.303	0.303	0.205	0.409	0.491	0.269	0.1343	0.1119
211 600	4/0	7	0.1739	0.522	9 154	3 450	480	0.01579	0.276	0.277	0.277	0.278	0.302	0.303	0.303	0.303	0.210	0.420	0.503	0.273	0.1363	0.1136
167 800	3/0	12	0.1183	0.492	7 556	2 736	420	0.01559	0.349	0.349	0.349	0.350	0.381	0.381	0.382	0.382	0.210	0.421	0.505	0.277	0.1384	0.1153
167 800	3/0	7	0.1548	0.464	7 366	2 736	420	0.01404	0.349	0.349	0.349	0.350	0.381	0.381	0.382	0.382	0.216	0.431	0.518	0.281	0.1405	0.1171
133 100	2/0	7	0.1379	0.414	5 926	2 170	360	0.01252	0.440	0.440	0.440	0.440	0.481	0.481	0.481	0.481	0.222	0.443	0.532	0.289	0.1445	0.1205
105 500	1/0	7	0.1228	0.368	4 752	1 720	310	0.01113	0.555	0.555	0.555	0.555	0.606	0.607	0.607	0.607	0.227	0.455	0.546	0.298	0.1488	0.1240
83 690	1	7	0.1093	0.328	3 804	1 364	270	0.00992	0.699	0.699	0.699	0.699	0.765				0.233	0.467	0.560	0.306	0.1528	0.1274
83 690	1	3	0.1670	0.360	3 620	1 351	270	0.01016	0.692	0.692	0.692	0.692	0.757				0.232	0.464	0.557	0.299	0.1495	0.1246
66 370	2	7	0.0974	0.292	3 045	1 082	230	0.00883	0.881	0.882	0.882	0.882	0.964				0.239	0.478	0.574	0.314	0.1570	0.1308
66 370	2	3	0.1487	0.320	2 913	1 071	240	0.00903	0.873				0.955				0.238	0.476	0.571	0.307	0.1537	0.1281
66 370	2	1	.....	0.258	3 003	1 061	220	0.00836	0.864				0.945				0.242	0.484	0.581	0.323	0.1614	0.1345
52 630	3	7	0.0867	0.260	2 433	858	200	0.00787	1.112				1.216				0.245	0.490	0.588	0.322	0.1611	0.1343
52 630	3	3	0.1325	0.285	2 359	850	200	0.00805	1.101				1.204				0.244	0.488	0.585	0.316	0.1578	0.1315
52 630	3	1	.....	0.229	2 439	841	190	0.00745	1.090		Same as d-c		1.192		Same as d-c		0.248	0.496	0.595	0.331	0.1656	0.1380
41 740	4	3	0.1180	0.254	1 879	674	180	0.00717	1.388				1.518				0.250	0.499	0.599	0.324	0.1619	0.1349
41 740	4	1	.....	0.204	1 970	667	170	0.00663	1.374				1.503				0.254	0.507	0.609	0.339	0.1697	0.1415
33 100	5	3	0.1050	0.226	1 505	534	150	0.00638	1.750				1.914				0.256	0.511	0.613	0.332	0.1661	0.1384
33 100	5	1	.....	0.1819	1 591	529	140	0.00590	1.733				1.895				0.260	0.519	0.623	0.348	0.1738	0.1449
26 250	6	3	0.0935	0.201	1 205	424	130	0.00568	2.21				2.41				0.262	0.523	0.628	0.341	0.1703	0.1419
26 250	6	1	.....	0.1620	1 280	420	120	0.00526	2.18				2.39				0.265	0.531	0.637	0.356	0.1779	0.1483
20 820	7	1	.....	0.1443	1 030	333	110	0.00468	2.75				3.01				0.271	0.542	0.651	0.364	0.1821	0.1517
16 510	8	1	.....	0.1285	826	264	90	0.00417	3.47				3.80				0.277	0.554	0.665	0.372	0.1862	0.1552

*For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft/sec), frequency—60 cycles.

Table 2—Characteristics of **Aluminum** Conductors, Hard Drawn, 61 Per Cent Conductivity

(Aluminum Company of America.)

Size of Conductor Circular Mils or A.W.G.	No. of Strands	Diameter of Individual Strands Inches	Outside Diameter Inches	Ultimate Strength Pounds	Weight Pounds Per Mile	Geometric Mean Radius at 60 Cycles Feet	Approx. Current Carrying Capacity* Amps	r_a Resistance Ohms Per Conductor Per Mile								x_a Inductive Reactance Ohms per Conductor Per Mile At 1 Ft. Spacing			x_a Shunt Capacitive Reactance Megohms Per Conductor Per Mile At 1 Ft. Spacing		
								25°C. (77°F.)				50°C. (122°F.)									
								d-c	25 cycles	50 cycles	60 cycles	d-c	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles
6	7	0.0612	0.184	528	130	0.00556	100	3.56	3.56	3.56	3.56	3.91	3.91	3.91	3.91	0.2626	0.5251	0.6301	0.3468	0.1734	0.1445
4	7	0.0772	0.232	826	207	0.00700	134	2.24	2.24	2.24	2.24	2.46	2.46	2.46	2.46	0.2509	0.5017	0.6201	0.3302	0.1651	0.1376
3	7	0.0867	0.260	1022	261	0.00787	155	1.77	1.77	1.77	1.77	1.95	1.95	1.95	1.95	0.2450	0.4899	0.5879	0.3221	0.1610	0.1342
2	7	0.0974	0.292	1266	329	0.00883	180	1.41	1.41	1.41	1.41	1.55	1.55	1.55	1.55	0.2391	0.4782	0.5739	0.3139	0.1570	0.1308
1	7	0.1094	0.328	1537	414	0.00992	209	1.12	1.12	1.12	1.12	1.23	1.23	1.23	1.23	0.2333	0.4665	0.5598	0.3055	0.1528	0.1273
1/0	7	0.1228	0.368	1865	523	0.01113	242	0.885	0.8851	0.8853	0.885	0.973	0.9731	0.9732	0.973	0.2264	0.4528	0.5434	0.2976	0.1488	0.1240
1/0	19	0.0745	0.373	2090	523	0.01177	244	0.885	0.8851	0.8853	0.885	0.973	0.9731	0.9732	0.973	0.2246	0.4492	0.5391	0.2964	0.1482	0.1235
2/0	7	0.1379	0.414	2350	659	0.01251	282	0.702	0.7021	0.7024	0.702	0.771	0.7711	0.7713	0.771	0.2216	0.4431	0.5317	0.2890	0.1445	0.1204
2/0	19	0.0837	0.419	2586	659	0.01321	283	0.702	0.7021	0.7024	0.702	0.771	0.7711	0.7713	0.771	0.2188	0.4376	0.5251	0.2882	0.1441	0.1201
3/0	7	0.1548	0.464	2845	832	0.01404	327	0.557	0.5571	0.5574	0.558	0.612	0.6121	0.6124	0.613	0.2157	0.4314	0.5177	0.2810	0.1405	0.1171
3/0	19	0.0940	0.470	3200	832	0.01483	328	0.557	0.5571	0.5574	0.558	0.612	0.6121	0.6124	0.613	0.2129	0.4258	0.5110	0.2801	0.1400	0.1167
4/0	7	0.1739	0.522	3590	1049	0.01577	380	0.441	0.4411	0.4415	0.442	0.485	0.4851	0.4855	0.486	0.2099	0.4196	0.5036	0.2726	0.1363	0.1136
4/0	19	0.1055	0.528	3890	1049	0.01666	381	0.441	0.4411	0.4415	0.442	0.485	0.4851	0.4855	0.486	0.2071	0.4141	0.4969	0.2717	0.1358	0.1132
250 000	37	0.0822	0.575	4860	1239	0.01841	425	0.374	0.3741	0.3746	0.375	0.411	0.4111	0.4115	0.412	0.2020	0.4040	0.4848	0.2657	0.1328	0.1107
266 800	7	0.1953	0.586	4525	1322	0.01771	441	0.350	0.3502	0.3506	0.351	0.385	0.3852	0.3855	0.386	0.2040	0.4079	0.4895	0.2642	0.1321	0.1101
266 800	37	0.0849	0.594	5180	1322	0.01902	443	0.350	0.3502	0.3506	0.351	0.385	0.3852	0.3855	0.386	0.2004	0.4007	0.4809	0.2633	0.1316	0.1097
300 000	19	0.1257	0.629	5300	1487	0.01983	478	0.311	0.3112	0.3117	0.312	0.342	0.3422	0.3426	0.343	0.1983	0.3965	0.4758	0.2592	0.1296	0.1080
300 000	37	0.0900	0.630	5830	1487	0.02017	478	0.311	0.3112	0.3117	0.312	0.342	0.3422	0.3426	0.343	0.1974	0.3947	0.4737	0.2592	0.1296	0.1080
336 400	19	0.1331	0.666	5940	1667	0.02100	514	0.278	0.2782	0.2788	0.279	0.306	0.3062	0.3067	0.307	0.1953	0.3907	0.4688	0.2551	0.1276	0.1063
336 400	37	0.0954	0.668	6400	1667	0.02135	514	0.278	0.2782	0.2788	0.279	0.306	0.3062	0.3067	0.307	0.1945	0.3890	0.4668	0.2549	0.1274	0.1062
350 000	37	0.0973	0.681	6680	1735	0.02178	528	0.267	0.2672	0.2678	0.268	0.294	0.2942	0.2947	0.295	0.1935	0.3870	0.4644	0.2537	0.1268	0.1057
397 500	19	0.1447	0.724	6880	1967	0.02283	575	0.235	0.2352	0.2359	0.236	0.258	0.2582	0.2589	0.259	0.1911	0.3822	0.4587	0.2491	0.1246	0.1038
477 000	19	0.1585	0.793	8090	2364	0.02501	646	0.196	0.1963	0.1971	0.198	0.215	0.2153	0.2160	0.216	0.1865	0.3730	0.4476	0.2429	0.1214	0.1012
500 000	19	0.1623	0.812	8475	2478	0.02560	664	0.187	0.1873	0.1882	0.189	0.206	0.2062	0.2070	0.208	0.1853	0.3707	0.4448	0.2412	0.1206	0.1005
500 000	37	0.1162	0.813	9010	2478	0.02603	664	0.187	0.1873	0.1882	0.189	0.206	0.2062	0.2070	0.208	0.1845	0.3689	0.4427	0.2410	0.1205	0.1004
556 500	19	0.1711	0.856	9440	2758	0.02701	710	0.168	0.1683	0.1693	0.170	0.185	0.1853	0.1862	0.187	0.1826	0.3652	0.4383	0.2374	0.1187	0.0989
636 000	37	0.1311	0.918	11240	3152	0.02936	776	0.147	0.1474	0.1484	0.149	0.162	0.1623	0.1633	0.164	0.1785	0.3569	0.4283	0.2323	0.1162	0.0968
715 500	37	0.1391	0.974	12640	3546	0.03114	817	0.137	0.1314	0.1326	0.133	0.144	0.1444	0.1455	0.146	0.1754	0.3508	0.4210	0.2282	0.1141	0.0951
750 000	37	0.1424	0.997	12980	3717	0.03188	864	0.125	0.1254	0.1267	0.127	0.137	0.1374	0.1385	0.139	0.1743	0.3485	0.4182	0.2266	0.1133	0.0944
750 000	61	0.1109	0.998	13510	3717	0.03211	864	0.125	0.1254	0.1267	0.127	0.137	0.1374	0.1385	0.139	0.1739	0.3477	0.4173	0.2263	0.1132	0.0943
795 000	37	0.1466	1.026	13770	3940	0.03283	897	0.117	0.1175	0.1188	0.120	0.129	0.1294	0.1306	0.131	0.1728	0.3455	0.4146	0.2244	0.1122	0.0935
874 500	37	0.1538	1.077	14830	4334	0.03443	949	0.107	0.1075	0.1089	0.110	0.118	0.1185	0.1198	0.121	0.1703	0.3407	0.4088	0.2210	0.1105	0.0921
954 000	37	0.1606	1.024	16180	4728	0.03596	1000	0.0979	0.0985	0.1002	0.100	0.108	0.1085	0.1100	0.111	0.1682	0.3363	0.4036	0.2179	0.1090	0.0908
1 000 000	61	0.1280	1.152	17670	4956	0.03707	1030	0.0934	0.0940	0.0956	0.0966	0.103	0.1035	0.1050	0.106	0.1666	0.3332	0.3998	0.2162	0.1081	0.0901
1 000 000	91	0.1048	1.153	18380	4956	0.03720	1030	0.0934	0.0940	0.0956	0.0966	0.103	0.1035	0.1050	0.106	0.1664	0.3328	0.3994	0.2160	0.1080	0.0900
1 033 500	37	0.1672	1.170	18260	5122	0.03743	1050	0.0904	0.0910	0.0927	0.0936	0.0994	0.0999	0.1015	0.102	0.1661	0.3322	0.3987	0.2150	0.1075	0.0896
1 113 000	61	0.1351	1.216	19660	5517	0.03910	1110	0.0839	0.0845	0.0864	0.0874	0.0922	0.0928	0.0945	0.0954	0.1639	0.3278	0.3934	0.2124	0.1062	0.0885
1 192 500	61	0.1398	1.258	21000	5908	0.04048	1160	0.0783	0.0790	0.0810	0.0821	0.0860	0.0866	0.0884	0.0895	0.1622	0.3243	0.3892	0.2100	0.1050	0.0875
1 192 500	91	0.1145	1.259	21400	5908	0.04062	1160	0.0783	0.0790	0.0810	0.0821	0.0860	0.0866	0.0884	0.0895	0.1620	0.3240	0.3888	0.2098	0.1049	0.0874
1 272 000	61	0.1444	1.300	22000	6299	0.04180	1210	0.0734	0.0741	0.0762	0.0774	0.0806	0.0813	0.0832	0.0843	0.1606	0.3211	0.3853	0.2076	0.1038	0.0865
1 351 500	61	0.1489	1.340	23400	6700	0.04309	1250	0.0691	0.0699	0.0721	0.0733	0.0760	0.0767	0.0787	0.0798	0.1590	0.3180	0.3816	0.2054	0.1027	0.0856
1 431 000	61	0.1532	1.379	24300	7091	0.04434	1300	0.0653	0.0661	0.0685	0.0697	0.0718	0.0725	0.0747	0.0759	0.1576	0.3152	0.3782	0.2033	0.1016	0.0847
1 510 500	61	0.1574	1.417	25600	7487	0.04556	1320	0.0618	0.0627	0.0651	0.0665	0.0679	0.0687	0.0710	0.0722	0.1562	0.3123	0.3748	0.2014	0.1007	0.0839
1 590 000	61	0.1615	1.454	27000	7883	0.04674	1380	0.0587	0.0596	0.0622	0.0636	0.0645	0.0653	0.0677	0.0690	0.1549	0.3098	0.3718	0.1997	0.0998	0.0832
1 590 000	91	0.1322	1.454	28100	7883	0.04691	1380	0.0587	0.0596	0.0622	0.0636	0.0645	0.0653	0.0677	0.0690	0.1547	0.3094	0.3713	0.1997	0.0998	0.0832

*For conductor at 75°C, wind 1.4 miles per hour (2 ft/sec), frequency = 60 cycles.

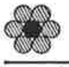


Table 3—Characteristics of **Aluminum Cable Steel Reinforced**

(Aluminum Company of America)

<table>
<tr><th rowspan="3">Circular Mils or A.W.G. Aluminum</th><th colspan="3">Aluminum</th><th colspan="2">Steel</th><th rowspan="3">Outside Diameter Inches</th><th rowspan="3">Copper Equivalent* Circular Mils or A.W.G.</th><th rowspan="3">Ultimate Strength Pounds</th><th rowspan="3">Wt. Lbs. per Mile</th><th rowspan="3">Geometric Mean Radius at 60 Cycles Feet</th><th rowspan="3">Approx. Current Carrying Capacity† Amps</th><th colspan="8">r_a
Resistance
Ohms per Conductor per Mile</th><th colspan="6" rowspan="2">x_a
Inductive Reactance
Ohms per Conductor per Mile at 1 Ft. Spacing
All Currents</th><th colspan="3" rowspan="2">x_a'
Shunt Capacitive Reactance
Megohms per Conductor per Mile at 1 Ft. Spacing</th></tr>
<tr><th rowspan="2">Strands</th><th rowspan="2">Layers</th><th rowspan="2">Strand Dia. Inches</th><th rowspan="2">Strands</th><th rowspan="2">Strand Dia. Inches</th><th colspan="4">25°C. (77°F.)
Small Currents</th><th colspan="4">50°C. (122°F.)
Current Approx.
75% Capacity‡</th></tr>
<tr><th>d-c</th><th>25 cycles</th><th>50 cycles</th><th>60 cycles</th><th>d-c</th><th>25 cycles</th><th>50 cycles</th><th>60 cycles</th><th colspan="2">25 cycles</th><th colspan="2">50 cycles</th><th colspan="2">60 cycles</th><th>25 cycles</th><th>50 cycles</th><th>60 cycles</th></tr>
<tr><td>1 590 000</td><td>54</td><td>3</td><td>0.1716</td><td>19</td><td>0.1030</td><td>1.545</td><td>1 000 000</td><td>56 000</td><td>10 777</td><td>0.0520</td><td>1 380</td><td>0.0587</td><td>0.0588</td><td>0.0590</td><td>0.0591</td><td>0.0646</td><td>0.0656</td><td>0.0675</td><td>0.0684</td><td colspan="2">0.1495</td><td colspan="2">0.299</td><td colspan="2">0.359</td><td>0.1953</td><td>0.0977</td><td>0.0814</td></tr>
<tr><td>1 510 500</td><td>54</td><td>3</td><td>0.1673</td><td>19</td><td>0.1004</td><td>1.506</td><td>950 000</td><td>53 200</td><td>10 237</td><td>0.0507</td><td>1 340</td><td>0.0618</td><td>0.0619</td><td>0.0621</td><td>0.0622</td><td>0.0680</td><td>0.0690</td><td>0.0710</td><td>0.0720</td><td colspan="2">0.1508</td><td colspan="2">0.302</td><td colspan="2">0.362</td><td>0.1971</td><td>0.0986</td><td>0.0821</td></tr>
<tr><td>1 431 000</td><td>54</td><td>3</td><td>0.1628</td><td>19</td><td>0.0977</td><td>1.465</td><td>900 000</td><td>50 400</td><td>9 699</td><td>0.0493</td><td>1 300</td><td>0.0652</td><td>0.0653</td><td>0.0655</td><td>0.0656</td><td>0.0718</td><td>0.0729</td><td>0.0749</td><td>0.0760</td><td colspan="2">0.1522</td><td colspan="2">0.304</td><td colspan="2">0.365</td><td>0.1991</td><td>0.0996</td><td>0.0830</td></tr>
<tr><td>1 351 000</td><td>54</td><td>3</td><td>0.1582</td><td>19</td><td>0.0949</td><td>1.424</td><td>850 000</td><td>47 600</td><td>9 160</td><td>0.0479</td><td>1 250</td><td>0.0691</td><td>0.0692</td><td>0.0694</td><td>0.0695</td><td>0.0761</td><td>0.0771</td><td>0.0792</td><td>0.0803</td><td colspan="2">0.1536</td><td colspan="2">0.307</td><td colspan="2">0.369</td><td>0.201</td><td>0.1006</td><td>0.0838</td></tr>
<tr><td>1 272 000</td><td>54</td><td>3</td><td>0.1535</td><td>19</td><td>0.0921</td><td>1.382</td><td>800 000</td><td>44 800</td><td>8 621</td><td>0.0465</td><td>1 200</td><td>0.0734</td><td>0.0735</td><td>0.0737</td><td>0.0738</td><td>0.0808</td><td>0.0819</td><td>0.0840</td><td>0.0851</td><td colspan="2">0.1551</td><td colspan="2">0.310</td><td colspan="2">0.372</td><td>0.203</td><td>0.1016</td><td>0.0847</td></tr>
<tr><td>1 192 500</td><td>54</td><td>3</td><td>0.1486</td><td>19</td><td>0.0892</td><td>1.338</td><td>750 000</td><td>43 100</td><td>8 082</td><td>0.0450</td><td>1 160</td><td>0.0783</td><td>0.0784</td><td>0.0786</td><td>0.0788</td><td>0.0862</td><td>0.0872</td><td>0.0894</td><td>0.0906</td><td colspan="2">0.1568</td><td colspan="2">0.314</td><td colspan="2">0.376</td><td>0.206</td><td>0.1028</td><td>0.0857</td></tr>
<tr><td>1 113 000</td><td>54</td><td>3</td><td>0.1436</td><td>19</td><td>0.0862</td><td>1.293</td><td>700 000</td><td>40 200</td><td>7 544</td><td>0.0435</td><td>1 110</td><td>0.0839</td><td>0.0840</td><td>0.0842</td><td>0.0844</td><td>0.0924</td><td>0.0935</td><td>0.0957</td><td>0.0969</td><td colspan="2">0.1585</td><td colspan="2">0.317</td><td colspan="2">0.380</td><td>0.208</td><td>0.1040</td><td>0.0867</td></tr>
<tr><td>1 033 500</td><td>54</td><td>3</td><td>0.1384</td><td>7</td><td>0.1384</td><td>1.246</td><td>650 000</td><td>37 100</td><td>7 019</td><td>0.0420</td><td>1 060</td><td>0.0903</td><td>0.0905</td><td>0.0907</td><td>0.0909</td><td>0.0994</td><td>0.1005</td><td>0.1025</td><td>0.1035</td><td colspan="2">0.1603</td><td colspan="2">0.321</td><td colspan="2">0.385</td><td>0.211</td><td>0.1053</td><td>0.0878</td></tr>
<tr><td>954 000</td><td>54</td><td>3</td><td>0.1329</td><td>7</td><td>0.1329</td><td>1.196</td><td>600 000</td><td>34 200</td><td>6 479</td><td>0.0403</td><td>1 010</td><td>0.0979</td><td>0.0980</td><td>0.0981</td><td>0.0982</td><td>0.1078</td><td>0.1088</td><td>0.1118</td><td>0.1128</td><td colspan="2">0.1624</td><td colspan="2">0.325</td><td colspan="2">0.390</td><td>0.214</td><td>0.1068</td><td>0.0890</td></tr>
<tr><td>900 000</td><td>54</td><td>3</td><td>0.1291</td><td>7</td><td>0.1291</td><td>1.162</td><td>566 000</td><td>32 300</td><td>6 112</td><td>0.0391</td><td>970</td><td>0.104</td><td>0.104</td><td>0.104</td><td>0.104</td><td>0.1145</td><td>0.1155</td><td>0.1175</td><td>0.1185</td><td colspan="2">0.1639</td><td colspan="2">0.328</td><td colspan="2">0.393</td><td>0.216</td><td>0.1078</td><td>0.0898</td></tr>
<tr><td>874 500</td><td>54</td><td>3</td><td>0.1273</td><td>7</td><td>0.1273</td><td>1.146</td><td>550 000</td><td>31 400</td><td>5 940</td><td>0.0386</td><td>950</td><td>0.107</td><td>0.107</td><td>0.107</td><td>0.108</td><td>0.1178</td><td>0.1188</td><td>0.1218</td><td>0.1228</td><td colspan="2">0.1646</td><td colspan="2">0.329</td><td colspan="2">0.395</td><td>0.217</td><td>0.1083</td><td>0.0903</td></tr>
<tr><td>795 000</td><td>54</td><td>3</td><td>0.1214</td><td>7</td><td>0.1214</td><td>1.093</td><td>500 000</td><td>28 500</td><td>5 399</td><td>0.0368</td><td>900</td><td>0.117</td><td>0.118</td><td>0.118</td><td>0.119</td><td>0.1288</td><td>0.1308</td><td>0.1358</td><td>0.1378</td><td colspan="2">0.1670</td><td colspan="2">0.334</td><td colspan="2">0.401</td><td>0.220</td><td>0.1100</td><td>0.0917</td></tr>
<tr><td>795 000</td><td>26</td><td>2</td><td>0.1749</td><td>7</td><td>0.1360</td><td>1.108</td><td>500 000</td><td>31 200</td><td>5 770</td><td>0.0375</td><td>900</td><td>0.117</td><td>0.117</td><td>0.117</td><td>0.117</td><td>0.1288</td><td>0.1288</td><td>0.1288</td><td>0.1288</td><td colspan="2">0.1660</td><td colspan="2">0.332</td><td colspan="2">0.399</td><td>0.219</td><td>0.1095</td><td>0.0912</td></tr>
<tr><td>795 000</td><td>30</td><td>2</td><td>0.1628</td><td>19</td><td>0.0977</td><td>1.140</td><td>500 000</td><td>38 400</td><td>6 517</td><td>0.0393</td><td>910</td><td>0.117</td><td>0.117</td><td>0.117</td><td>0.117</td><td>0.1288</td><td>0.1288</td><td>0.1288</td><td>0.1288</td><td colspan="2">0.1637</td><td colspan="2">0.327</td><td colspan="2">0.393</td><td>0.217</td><td>0.1085</td><td>0.0904</td></tr>
<tr><td>715 500</td><td>54</td><td>3</td><td>0.1151</td><td>7</td><td>0.1151</td><td>1.036</td><td>450 000</td><td>26 300</td><td>4 859</td><td>0.0349</td><td>830</td><td>0.131</td><td>0.131</td><td>0.131</td><td>0.132</td><td>0.1442</td><td>0.1452</td><td>0.1472</td><td>0.1482</td><td colspan="2">0.1697</td><td colspan="2">0.339</td><td colspan="2">0.407</td><td>0.224</td><td>0.1119</td><td>0.0932</td></tr>
<tr><td>715 500</td><td>26</td><td>2</td><td>0.1659</td><td>7</td><td>0.1290</td><td>1.051</td><td>450 000</td><td>28 100</td><td>5 193</td><td>0.0355</td><td>840</td><td>0.131</td><td>0.131</td><td>0.131</td><td>0.131</td><td>0.1442</td><td>0.1442</td><td>0.1442</td><td>0.1442</td><td colspan="2">0.1687</td><td colspan="2">0.337</td><td colspan="2">0.405</td><td>0.223</td><td>0.1114</td><td>0.0928</td></tr>
<tr><td>715 500</td><td>30</td><td>2</td><td>0.1544</td><td>19</td><td>0.0926</td><td>1.081</td><td>450 000</td><td>34 600</td><td>5 865</td><td>0.0372</td><td>840</td><td>0.131</td><td>0.131</td><td>0.131</td><td>0.131</td><td>0.1442</td><td>0.1442</td><td>0.1442</td><td>0.1442</td><td colspan="2">0.1664</td><td colspan="2">0.333</td><td colspan="2">0.399</td><td>0.221</td><td>0.1104</td><td>0.0920</td></tr>
<tr><td>666 600</td><td>54</td><td>3</td><td>0.1111</td><td>7</td><td>0.1111</td><td>1.000</td><td>419 000</td><td>24 500</td><td>4 527</td><td>0.0337</td><td>800</td><td>0.140</td><td>0.140</td><td>0.141</td><td>0.141</td><td>0.1541</td><td>0.1571</td><td>0.1591</td><td>0.1601</td><td colspan="2">0.1715</td><td colspan="2">0.343</td><td colspan="2">0.412</td><td>0.226</td><td>0.1132</td><td>0.0943</td></tr>
<tr><td>636 000</td><td>54</td><td>3</td><td>0.1085</td><td>7</td><td>0.1085</td><td>0.977</td><td>400 000</td><td>23 600</td><td>4 319</td><td>0.0329</td><td>770</td><td>0.147</td><td>0.147</td><td>0.148</td><td>0.148</td><td>0.1618</td><td>0.1638</td><td>0.1678</td><td>0.1688</td><td colspan="2">0.1726</td><td colspan="2">0.345</td><td colspan="2">0.414</td><td>0.228</td><td>0.1140</td><td>0.0950</td></tr>
<tr><td>636 000</td><td>26</td><td>2</td><td>0.1564</td><td>7</td><td>0.1216</td><td>0.990</td><td>400 000</td><td>25 000</td><td>4 616</td><td>0.0335</td><td>780</td><td>0.147</td><td>0.147</td><td>0.147</td><td>0.147</td><td>0.1618</td><td>0.1618</td><td>0.1618</td><td>0.1618</td><td colspan="2">0.1718</td><td colspan="2">0.344</td><td colspan="2">0.412</td><td>0.227</td><td>0.1135</td><td>0.0946</td></tr>
<tr><td>636 000</td><td>30</td><td>2</td><td>0.1456</td><td>19</td><td>0.0874</td><td>1.019</td><td>400 000</td><td>31 500</td><td>5 213</td><td>0.0351</td><td>780</td><td>0.147</td><td>0.147</td><td>0.147</td><td>0.147</td><td>0.1618</td><td>0.1618</td><td>0.1618</td><td>0.1618</td><td colspan="2">0.1693</td><td colspan="2">0.339</td><td colspan="2">0.406</td><td>0.225</td><td>0.1125</td><td>0.0937</td></tr>
<tr><td>605 000</td><td>54</td><td>3</td><td>0.1059</td><td>7</td><td>0.1059</td><td>0.953</td><td>380 500</td><td>22 500</td><td>4 109</td><td>0.0321</td><td>750</td><td>0.154</td><td>0.155</td><td>0.155</td><td>0.155</td><td>0.1695</td><td>0.1715</td><td>0.1755</td><td>0.1775</td><td colspan="2">0.1739</td><td colspan="2">0.348</td><td colspan="2">0.417</td><td>0.230</td><td>0.1149</td><td>0.0957</td></tr>
<tr><td>605 000</td><td>26</td><td>2</td><td>0.1525</td><td>7</td><td>0.1186</td><td>0.966</td><td>380 500</td><td>24 100</td><td>4 391</td><td>0.0327</td><td>760</td><td>0.154</td><td>0.154</td><td>0.154</td><td>0.154</td><td>0.1700</td><td>0.1720</td><td>0.1720</td><td>0.1720</td><td colspan="2">0.1730</td><td colspan="2">0.346</td><td colspan="2">0.415</td><td>0.229</td><td>0.1144</td><td>0.0953</td></tr>
<tr><td>556 500</td><td>26</td><td>2</td><td>0.1463</td><td>7</td><td>0.1138</td><td>0.927</td><td>350 000</td><td>22 400</td><td>4 039</td><td>0.0313</td><td>730</td><td>0.168</td><td>0.168</td><td>0.168</td><td>0.168</td><td>0.1849</td><td>0.1859</td><td>0.1859</td><td>0.1859</td><td colspan="2">0.1751</td><td colspan="2">0.350</td><td colspan="2">0.420</td><td>0.232</td><td>0.1159</td><td>0.0965</td></tr>
<tr><td>556 500</td><td>30</td><td>2</td><td>0.1362</td><td>7</td><td>0.1362</td><td>0.953</td><td>350 000</td><td>27 200</td><td>4 588</td><td>0.0328</td><td>730</td><td>0.168</td><td>0.168</td><td>0.168</td><td>0.168</td><td>0.1849</td><td>0.1859</td><td>0.1859</td><td>0.1859</td><td colspan="2">0.1728</td><td colspan="2">0.346</td><td colspan="2">0.415</td><td>0.230</td><td>0.1149</td><td>0.0957</td></tr>
<tr><td>500 000</td><td>30</td><td>2</td><td>0.1291</td><td>7</td><td>0.1291</td><td>0.904</td><td>314 500</td><td>24 400</td><td>4 122</td><td>0.0311</td><td>690</td><td>0.187</td><td>0.187</td><td>0.187</td><td>0.187</td><td>0.206</td><td></td><td></td><td></td><td colspan="2">0.1754</td><td colspan="2">0.351</td><td colspan="2">0.421</td><td>0.234</td><td>0.1167</td><td>0.0973</td></tr>
<tr><td>477 000</td><td>26</td><td>2</td><td>0.1355</td><td>7</td><td>0.1054</td><td>0.858</td><td>300 000</td><td>19 430</td><td>3 462</td><td>0.0290</td><td>670</td><td>0.196</td><td>0.196</td><td>0.196</td><td>0.196</td><td>0.216</td><td></td><td></td><td></td><td colspan="2">0.1790</td><td colspan="2">0.358</td><td colspan="2">0.430</td><td>0.237</td><td>0.1186</td><td>0.0988</td></tr>
<tr><td>477 000</td><td>30</td><td>2</td><td>0.1261</td><td>7</td><td>0.1261</td><td>0.883</td><td>300 000</td><td>23 300</td><td>3 933</td><td>0.0304</td><td>670</td><td>0.196</td><td>0.196</td><td>0.196</td><td>0.196</td><td>0.216</td><td></td><td></td><td></td><td colspan="2">0.1766</td><td colspan="2">0.353</td><td colspan="2">0.424</td><td>0.235</td><td>0.1176</td><td>0.0980</td></tr>
<tr><td>397 500</td><td>26</td><td>2</td><td>0.1236</td><td>7</td><td>0.0961</td><td>0.783</td><td>250 000</td><td>16 190</td><td>2 885</td><td>0.0265</td><td>590</td><td>0.235</td><td></td><td></td><td></td><td>0.259</td><td></td><td></td><td></td><td colspan="2">0.1836</td><td colspan="2">0.367</td><td colspan="2">0.441</td><td>0.244</td><td>0.1219</td><td>0.1015</td></tr>
<tr><td>397 500</td><td>30</td><td>2</td><td>0.1151</td><td>7</td><td>0.1151</td><td>0.806</td><td>250 000</td><td>19 980</td><td>3 277</td><td>0.0278</td><td>600</td><td>0.235</td><td colspan="3">Same as d-c</td><td>0.259</td><td colspan="3">Same as d-c</td><td colspan="2">0.1812</td><td colspan="2">0.362</td><td colspan="2">0.435</td><td>0.242</td><td>0.1208</td><td>0.1006</td></tr>
<tr><td>336 400</td><td>26</td><td>2</td><td>0.1138</td><td>7</td><td>0.0885</td><td>0.721</td><td>4/0</td><td>14 050</td><td>2 442</td><td>0.0244</td><td>530</td><td>0.278</td><td></td><td></td><td></td><td>0.306</td><td></td><td></td><td></td><td colspan="2">0.1872</td><td colspan="2">0.376</td><td colspan="2">0.451</td><td>0.250</td><td>0.1248</td><td>0.1039</td></tr>
<tr><td>336 400</td><td>30</td><td>2</td><td>0.1059</td><td>7</td><td>0.1059</td><td>0.741</td><td>4/0</td><td>17 040</td><td>2 774</td><td>0.0255</td><td>530</td><td>0.278</td><td></td><td></td><td></td><td>0.306</td><td></td><td></td><td></td><td colspan="2">0.1855</td><td colspan="2">0.371</td><td colspan="2">0.445</td><td>0.248</td><td>0.1238</td><td>0.1032</td></tr>
<tr><td>300 000</td><td>26</td><td>2</td><td>0.1074</td><td>7</td><td>0.0835</td><td>0.680</td><td>188 700</td><td>12 650</td><td>2 178</td><td>0.0230</td><td>490</td><td>0.311</td><td></td><td></td><td></td><td>0.342</td><td></td><td></td><td></td><td colspan="2">0.1908</td><td colspan="2">0.382</td><td colspan="2">0.458</td><td>0.254</td><td>0.1269</td><td>0.1057</td></tr>
<tr><td>300 000</td><td>30</td><td>2</td><td>0.1000</td><td>7</td><td>0.1000</td><td>0.700</td><td>188 700</td><td>15 430</td><td>2 473</td><td>0.0241</td><td>500</td><td>0.311</td><td></td><td></td><td></td><td>0.342</td><td></td><td></td><td></td><td colspan="2">0.1883</td><td colspan="2">0.377</td><td colspan="2">0.452</td><td>0.252</td><td>0.1258</td><td>0.1049</td></tr>
<tr><td>266 800</td><td>26</td><td>2</td><td>0.1013</td><td>7</td><td>0.0788</td><td>0.642</td><td>3/0</td><td>11 250</td><td>1 936</td><td>0.0217</td><td>460</td><td>0.350</td><td></td><td></td><td></td><td>0.385</td><td></td><td></td><td></td><td colspan="2">0.1936</td><td colspan="2">0.387</td><td colspan="2">0.465</td><td>0.258</td><td>0.1289</td><td>0.1074</td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3">For Current Approx. 75% Capacity ‡</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td colspan="6">Single Layer Conductors</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td colspan="3">Small Currents</td><td colspan="3">Current Approx. 75% Capacity‡</td></tr>
<tr><td>25 cycles</td><td>50 cycles</td><td>60 cycles</td><td>25 cycles</td><td>50 cycles</td><td>60 cycles</td></tr>
<tr><td>266 800</td><td>6</td><td>1</td><td>0.2109</td><td>7</td><td>0.0703</td><td>0.633</td><td>3/0</td><td>9 645</td><td>1 802</td><td>0.00684</td><td>460</td><td>0.351</td><td>0.351</td><td>0.351</td><td>0.352</td><td>0.386</td><td>0.430</td><td>0.510</td><td>0.552</td><td>0.194</td><td>0.388</td><td>0.466</td><td>0.252</td><td>0.504</td><td>0.605</td><td>0.259</td><td>0.1294</td><td>0.1079</td></tr>
<tr><td>4/0</td><td>6</td><td>1</td><td>0.1878</td><td>1</td><td>0.1878</td><td>0.563</td><td>2/0</td><td>8 420</td><td>1 542</td><td>0.00814</td><td>340</td><td>0.441</td><td>0.442</td><td>0.444</td><td>0.445</td><td>0.485</td><td>0.514</td><td>0.567</td><td>0.592</td><td>0.218</td><td>0.437</td><td>0.524</td><td>0.242</td><td>0.484</td><td>0.581</td><td>0.267</td><td>0.1336</td><td>0.1113</td></tr>
<tr><td>3/0</td><td>6</td><td>1</td><td>0.1672</td><td>1</td><td>0.1672</td><td>0.502</td><td>1/0</td><td>6 675</td><td>1 223</td><td>0.00600</td><td>300</td><td>0.556</td><td>0.557</td><td>0.559</td><td>0.560</td><td>0.612</td><td>0.642</td><td>0.697</td><td>0.723</td><td>0.225</td><td>0.450</td><td>0.540</td><td>0.259</td><td>0.517</td><td>0.621</td><td>0.275</td><td>0.1377</td><td>0.1147</td></tr>
<tr><td>2/0</td><td>6</td><td>1</td><td>0.1490</td><td>1</td><td>0.1490</td><td>0.447</td><td>1</td><td>5 345</td><td>970</td><td>0.00510</td><td>270</td><td>0.702</td><td>0.702</td><td>0.704</td><td>0.706</td><td>0.773</td><td>0.806</td><td>0.866</td><td>0.895</td><td>0.231</td><td>0.462</td><td>0.554</td><td>0.267</td><td>0.534</td><td>0.641</td><td>0.284</td><td>0.1418</td><td>0.1182</td></tr>
<tr><td>1/0</td><td>6</td><td>1</td><td>0.1327</td><td>1</td><td>0.1327</td><td>0.398</td><td>2</td><td>4 280</td><td>769</td><td>0.00446</td><td>230</td><td>0.885</td><td>0.885</td><td>0.887</td><td>0.888</td><td>0.974</td><td>1.01</td><td>1.08</td><td>1.12</td><td>0.237</td><td>0.473</td><td>0.568</td><td>0.273</td><td>0.547</td><td>0.656</td><td>0.292</td><td>0.1460</td><td>0.1216</td></tr>
<tr><td>1</td><td>6</td><td>1</td><td>0.1182</td><td>1</td><td>0.1182</td><td>0.355</td><td>3</td><td>3 480</td><td>610</td><td>0.00418</td><td>200</td><td>1.12</td><td>1.12</td><td>1.12</td><td>1.12</td><td>1.23</td><td>1.27</td><td>1.34</td><td>1.38</td><td>0.242</td><td>0.483</td><td>0.580</td><td>0.277</td><td>0.554</td><td>0.665</td><td>0.300</td><td>0.1500</td><td>0.1250</td></tr>
<tr><td>2</td><td>6</td><td>1</td><td>0.1052</td><td>1</td><td>0.1052</td><td>0.316</td><td>4</td><td>2 790</td><td>484</td><td>0.00418</td><td>180</td><td>1.41</td><td>1.41</td><td>1.41</td><td>1.41</td><td>1.55</td><td>1.59</td><td>1.66</td><td>1.69</td><td>0.247</td><td>0.493</td><td>0.592</td><td>0.277</td><td>0.554</td><td>0.665</td><td>0.308</td><td>0.1542</td><td>0.1285</td></tr>
<tr><td>2</td><td>7</td><td>1</td><td>0.0974</td><td>1</td><td>0.1299</td><td>0.325</td><td>4</td><td>3 525</td><td>566</td><td>0.00504</td><td>180</td><td>1.41</td><td>1.41</td><td>1.41</td><td>1.41</td><td>1.55</td><td>1.59</td><td>1.62</td><td>1.65</td><td>0.247</td><td>0.493</td><td>0.592</td><td>0.267</td><td>0.535</td><td>0.642</td><td>0.306</td><td>0.1532</td><td>0.1276</td></tr>
<tr><td>3</td><td>6</td><td>1</td><td>0.0937</td><td>1</td><td>0.0937</td><td>0.281</td><td>5</td><td>2 250</td><td>384</td><td>0.00430</td><td>160</td><td>1.78</td><td>1.78</td><td>1.78</td><td>1.78</td><td>1.95</td><td>1.98</td><td>2.04</td><td>2.07</td><td>0.252</td><td>0.503</td><td>0.604</td><td>0.275</td><td>0.551</td><td>0.661</td><td>0.317</td><td>0.1583</td><td>0.1320</td></tr>
<tr><td>4</td><td>6</td><td>1</td><td>0.0834</td><td>1</td><td>0.0834</td><td>0.250</td><td>6</td><td>1 830</td><td>304</td><td>0.00437</td><td>140</td><td>2.24</td><td>2.24</td><td>2.24</td><td>2.24</td><td>2.47</td><td>2.50</td><td>2.54</td><td>2.57</td><td>0.257</td><td>0.514</td><td>0.611</td><td>0.274</td><td>0.549</td><td>0.659</td><td>0.325</td><td>0.1627</td><td>0.1355</td></tr>
<tr><td>4</td><td>7</td><td>1</td><td>0.0772</td><td>1</td><td>0.1029</td><td>0.257</td><td>6</td><td>2 288</td><td>356</td><td>0.00452</td><td>140</td><td>2.24</td><td>2.24</td><td>2.24</td><td>2.24</td><td>2.47</td><td>2.50</td><td>2.53</td><td>2.55</td><td>0.257</td><td>0.515</td><td>0.618</td><td>0.273</td><td>0.545</td><td>0.655</td><td>0.323</td><td>0.1615</td><td>0.1346</td></tr>
<tr><td>5</td><td>6</td><td>1</td><td>0.0743</td><td>1</td><td>0.0743</td><td>0.223</td><td>7</td><td>1 460</td><td>241</td><td>0.00416</td><td>120</td><td>2.82</td><td>2.82</td><td>2.82</td><td>2.82</td><td>3.10</td><td>3.12</td><td>3.16</td><td>3.18</td><td>0.262</td><td>0.525</td><td>0.630</td><td>0.279</td><td>0.557</td><td>0.665</td><td>0.333</td><td>0.1666</td><td>0.1388</td></tr>
<tr><td>6</td><td>6</td><td>1</td><td>0.0661</td><td>1</td><td>0.0661</td><td>0.198</td><td>8</td><td>1 170</td><td>191</td><td>0.00394</td><td>100</td><td>3.56</td><td>3.56</td><td>3.56</td><td>3.56</td><td>3.92</td><td>3.94</td><td>3.97</td><td>3.98</td><td>0.268</td><td>0.536</td><td>0.643</td><td>0.281</td><td>0.561</td><td>0.673</td><td>0.342</td><td>0.1708</td><td>0.1423</td></tr>
</table>

*Based on copper 97 per cent, aluminum 61 per cent conductivity.

†For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft/sec), frequency = 60 cycles.

‡"Current Approx. 75% Capacity" is 75% of the "Approx. Current Carrying Capacity in Amps." and is approximately the current which will produce 50°C. conductor temp. (25°C. rise) with 25°C. air temp., wind 1.4 miles per hour.

Table 4-A—Characteristics of **Copperweld-Copper** Conductors

(Copperweld Steel Company)

Size of Conductor				Copper Equivalent Circular Mils or A.W.G.	Rated Breaking Load Lbs.	Weight Lbs. per Mile	Geometric Mean Radius at 60 Cycles Feet	Approx. Current Carrying Capacity at 60 Cycles Amps*	r_a Resistance Ohms per Conductor per Mile at 25°C.(77°F.) Small Currents				r_a Resistance Ohms per Conductor per Mile at 50°C. (122°F.) Current Approx. 75% of Capacity**				x_a Inductive Reactance Ohms per Conductor per Mile One ft. Spacing Average Currents			x_a' Capacitive Reactance Megohms per Conductor per Mile One ft. Spacing		
Nominal Designation	Number and Diameter of Wires		Outside Diameter Inches																			
	Copperweld	Copper							d-c	25 cycles	50 cycles	60 cycles	d-c	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles
350 E	7x.1576"	12x.1576"	0.788	350 000	32 420	7 409	0.0220	660	0.1658	0.1728	0.1789	0.1812	0.1812	0.1915	0.201	0.204	0.1929	0.386	0.463	0.243	0.1216	0.1014
350 EK	4x.1470"	15x.1470"	0.735	350 000	23 850	6 536	0.0245	680	0.1658	0.1682	0.1700	0.1705	0.1812	0.1845	0.1873	0.1882	0.1875	0.375	0.450	0.248	0.1241	0.1034
350 V	3x.1751"	9x.1893"	0.754	350 000	23 480	6 578	0.0226	650	0.1655	0.1725	0.1800	0.1828	0.1809	0.1910	0.202	0.206	0.1915	0.383	0.460	0.246	0.1232	0.1027
300 E	7x.1459"	12x.1459"	0.729	300 000	27 770	6 351	0.0204	600	0.1934	0.200	0.207	0.209	0.211	0.222	0.232	0.235	0.1969	0.394	0.473	0.249	0.1244	0.1037
300 EK	4x.1361"	15x.1361"	0.680	300 000	20 960	5 602	0.0227	610	0.1934	0.1958	0.1976	0.198	0.211	0.215	0.218	0.219	0.1914	0.383	0.460	0.254	0.1269	0.1057
300 V	3x.1621"	9x.1752"	0.698	300 000	20 730	5 639	0.0209	590	0.1930	0.200	0.208	0.210	0.211	0.222	0.233	0.237	0.1954	0.391	0.469	0.252	0.1259	0.1050
250 E	7x.1332"	12x.1332"	0.666	250 000	23 920	5 292	0.01859	540	0.232	0.239	0.245	0.248	0.254	0.265	0.275	0.279	0.202	0.403	0.484	0.255	0.1276	0.1604
250 EK	4x.1242"	15x.1242"	0.621	250 000	17 840	4 669	0.0207	540	0.232	0.235	0.236	0.237	0.254	0.258	0.261	0.261	0.1960	0.392	0.471	0.260	0.1301	0.1084
250 V	3x.1480"	9x.1600"	0.637	250 000	17 420	4 699	0.01911	530	0.232	0.239	0.246	0.249	0.253	0.264	0.276	0.281	0.200	0.400	0.480	0.258	0.1292	0.1077
4/0 E	7x.1225"	12x.1225"	0.613	4/0	20 730	4 479	0.01711	480	0.274	0.281	0.287	0.290	0.300	0.312	0.323	0.326	0.206	0.411	0.493	0.261	0.1306	0.1088
4/0 G	2x.1944"	5x.1944"	0.583	4/0	15 640	4 168	0.01409	460	0.273	0.284	0.294	0.298	0.299	0.318	0.336	0.342	0.215	0.431	0.517	0.265	0.1324	0.1103
4/0 EK	4x.1143"	15x.1143"	0.571	4/0	15 370	3 951	0.01903	490	0.274	0.277	0.278	0.279	0.300	0.304	0.307	0.308	0.200	0.401	0.481	0.266	0.1331	0.1109
4/0 V	3x.1361"	9x.1472"	0.586	4/0	15 000	3 977	0.01758	470	0.274	0.281	0.288	0.291	0.299	0.311	0.323	0.328	0.204	0.409	0.490	0.264	0.1322	0.1101
4/0 F	1x.1833"	6x.1833"	0.550	4/0	12 290	3 750	0.01558	470	0.273	0.280	0.285	0.287	0.299	0.309	0.318	0.322	0.210	0.421	0.505	0.269	0.1344	0.1220
3/0 E	7x.1091"	12x.1091"	0.545	3/0	16 800	3 552	0.01521	420	0.346	0.353	0.359	0.361	0.378	0.391	0.402	0.407	0.212	0.423	0.508	0.270	0.1348	0.1123
3/0 J	3x.1851"	4x.1851"	0.555	3/0	16 170	3 732	0.01156	410	0.344	0.356	0.367	0.372	0.377	0.398	0.419	0.428	0.225	0.451	0.541	0.268	0.1341	0.1118
3/0 G	2x.1731"	2x.1731"	0.519	3/0	12 860	3 305	0.01254	400	0.344	0.355	0.365	0.369	0.377	0.397	0.416	0.423	0.221	0.443	0.531	0.273	0.1365	0.1137
3/0 EK	4x.1018"	4x.1018"	0.509	3/0	12 370	3 134	0.01697	420	0.346	0.348	0.350	0.351	0.378	0.382	0.386	0.386	0.206	0.412	0.495	0.274	0.1372	0.1143
3/0 V	3x.1311"	9x.1311"	0.522	3/0	12 220	3 154	0.01566	410	0.345	0.352	0.360	0.362	0.377	0.390	0.403	0.408	0.210	0.420	0.504	0.273	0.1363	0.1136
3/0 F	1x.1632"	6x.1632"	0.490	3/0	9 980	2 974	0.01388	410	0.344	0.351	0.356	0.358	0.377	0.388	0.397	0.401	0.216	0.432	0.519	0.277	0.1385	0.1155
2/0 K	4x.1780"	3x.1780"	0.534	2/0	17 600	3 411	0.00912	360	0.434	0.447	0.459	0.466	0.475	0.499	0.524	0.535	0.237	0.475	0.570	0.271	0.1355	0.1129
2/0 J	3x.1648"	4x.1648"	0.494	2/0	13 430	2 960	0.01029	350	0.434	0.446	0.457	0.462	0.475	0.498	0.520	0.530	0.231	0.463	0.555	0.277	0.1383	0.1152
2/0 G	2x.1542"	5x.1542"	0.463	2/0	10 510	2 622	0.01119	350	0.434	0.445	0.456	0.459	0.475	0.497	0.518	0.525	0.227	0.454	0.545	0.281	0.1406	0.1171
2/0 V	3x.1080"	9x.1167"	0.465	2/0	9 846	2 502	0.01395	360	0.435	0.442	0.450	0.452	0.476	0.489	0.504	0.509	0.216	0.432	0.518	0.281	0.1404	0.1170
2/0 F	1x.1454"	6x.1454"	0.436	2/0	8 094	2 359	0.01235	350	0.434	0.441	0.446	0.448	0.475	0.487	0.497	0.501	0.222	0.444	0.533	0.285	0.1427	0.1189
1/0 K	4x.1585"	3x.1585"	0.475	1/0	14 490	2 703	0.00812	310	0.548	0.560	0.573	0.579	0.599	0.625	0.652	0.664	0.243	0.487	0.584	0.279	0.1397	0.1164
1/0 J	3x.1467"	4x.1467"	0.440	1/0	10 970	2 346	0.00917	310	0.548	0.559	0.570	0.576	0.599	0.624	0.648	0.659	0.237	0.474	0.569	0.285	0.1423	0.1186
1/0 G	2x.1373"	5x.1373"	0.412	1/0	8 563	2 078	0.00996	310	0.548	0.559	0.568	0.573	0.599	0.623	0.645	0.654	0.233	0.466	0.559	0.289	0.1447	0.1206
1/0 F	1x.1294"	6x.1294"	0.388	1/0	6 536	1 870	0.01099	310	0.548	0.554	0.559	0.562	0.599	0.612	0.622	0.627	0.228	0.456	0.547	0.294	0.1469	0.1224
1 N	5x.1546"	2x.1546"	0.464	1	15 410	2 541	0.00638	280	0.691	0.705	0.719	0.726	0.755	0.787	0.818	0.832	0.256	0.512	0.614	0.281	0.1405	0.1171
1 K	4x.1412"	3x.1412"	0.423	1	11 900	2 144	0.00723	270	0.691	0.704	0.716	0.722	0.755	0.784	0.813	0.825	0.249	0.498	0.598	0.288	0.1438	0.1198
1 J	3x.1307"	4x.1307"	0.392	1	9 000	1 861	0.00817	270	0.691	0.703	0.714	0.719	0.755	0.783	0.808	0.820	0.243	0.486	0.583	0.293	0.1465	0.1221
1 G	2x.1222"	5x.1222"	0.367	1	6 956	1 649	0.00887	260	0.691	0.702	0.712	0.716	0.755	0.781	0.805	0.815	0.239	0.478	0.573	0.298	0.1488	0.1240
1 F	1x.1153"	6x.1153"	0.346	1	5 266	1 483	0.00980	270	0.691	0.698	0.704	0.705	0.755	0.769	0.781	0.786	0.234	0.468	0.561	0.302	0.1509	0.1258
2 P	6x.1540"	1x.1540"	0.462	2	16 870	2 487	0.00501	250	0.871	0.886	0.901	0.909	0.952	0.988	1.024	1.040	0.268	0.536	0.643	0.281	0.1406	0.1172
2 N	5x.1377"	2x.1377"	0.413	2	12 680	2 015	0.00568	240	0.871	0.885	0.899	0.906	0.952	0.986	1.020	1.035	0.261	0.523	0.627	0.289	0.1446	0.1205
2 K	4x.1257"	3x.1257"	0.377	2	9 730	1 701	0.00644	240	0.871	0.884	0.896	0.902	0.952	0.983	1.014	1.028	0.255	0.510	0.612	0.296	0.1479	0.1232
2 J	3x.1164"	4x.1164"	0.349	2	7 322	1 476	0.00727	230	0.871	0.883	0.894	0.899	0.952	0.982	1.010	1.022	0.249	0.498	0.598	0.301	0.1506	0.1255
2 A	1x.1699"	2x.1699"	0.366	2	5 876	1 356	0.00763	240	0.869	0.875	0.880	0.882	0.950	0.962	0.973	0.979	0.247	0.493	0.592	0.298	0.1489	0.1241
2 G	2x.1089"	5x.1089"	0.327	2	5 626	1 307	0.00790	230	0.871	0.882	0.892	0.896	0.952	0.980	1.006	1.016	0.245	0.489	0.587	0.306	0.1529	0.1275
2 F	1x.1026"	6x.1026"	0.308	2	4 233	1 176	0.00873	230	0.871	0.878	0.884	0.885	0.952	0.967	0.979	0.985	0.230	0.479	0.575	0.310	0.1551	0.1292
3 P	6x.1371"	1x.1371"	0.411	3	13 910	1 973	0.00445	220	1.098	1.113	1.127	1.136	1.200	1.239	1.273	1.296	0.274	0.547	0.657	0.290	0.1448	0.1207
3 N	5x.1226"	2x.1226"	0.368	3	10 390	1 598	0.00506	210	1.098	1.112	1.126	1.133	1.200	1.237	1.273	1.289	0.267	0.534	0.641	0.298	0.1487	0.1239
3 K	4x.1120"	3x.1120"	0.336	3	7 910	1 349	0.00574	210	1.098	1.111	1.123	1.129	1.200	1.233	1.267	1.281	0.261	0.522	0.626	0.304	0.1520	0.1266
3 J	3x.1036"	4x.1036"	0.311	3	5 955	1 171	0.00648	200	1.098	1.110	1.121	1.126	1.200	1.232	1.262	1.275	0.255	0.509	0.611	0.309	0.1547	0.1289
3 A	1x.1513"	2x.1513"	0.326	3	4 810	1 075	0.00679	210	1.096	1.102	1.107	1.109	1.198	1.211	1.225	1.229	0.252	0.505	0.606	0.306	0.1531	0.1275
4 P	6x.1221"	1x.1221"	0.366	4	11 420	1 564	0.00397	190	1.385	1.400	1.414	1.423	1.514	1.555	1.598	1.616	0.280	0.559	0.671	0.298	0.1489	0.1241
4 N	5x.1092"	2x.1092"	0.328	4	8 460	1 267	0.00451	180	1.385	1.399	1.413	1.420	1.514	1.554	1.593	1.610	0.273	0.546	0.655	0.306	0.1528	0.1274
4 D	2x.1615"	1x.1615"	0.348	4	7 340	1 191	0.00566	190	1.382	1.389	1.396	1.399	1.511	1.529	1.544	1.542	0.262	0.523	0.628	0.301	0.1507	0.1256
4 A	1x.1347"	2x.1347"	0.290	4	3 938	853	0.00604	180	1.382	1.388	1.393	1.395	1.511	1.525	1.540	1.545	0.258	0.517	0.620	0.314	0.1572	0.1310
5 P	6x.1087"	1x.1087"	0.326	5	9 311	1 240	0.00353	160	1.747	1.762	1.776	1.785	1.909	1.954	2.00	2.02	0.285	0.571	0.685	0.306	0.1531	0.1275
5 D	2x.1438"	1x.1438"	0.310	5	6 035	944	0.00504	160	1.742	1.749	1.756	1.759	1.905	1.924	1.941	1.939	0.268	0.535	0.642	0.310	0.1548	0.1290
5 A	1x.1200"	2x.1200"	0.258	5	3 193	676	0.00538	160	1.742	1.748	1.753	1.755	1.905	1.920	1.936	1.941	0.264	0.528	0.634	0.323	0.1614	0.1345
6 D	2x.1281"	1x.1281"	0.276	6	4 942	749	0.00449	140	2.20	2.21	2.21	2.22	2.40	2.42	2.44	2.44	0.273	0.547	0.656	0.318	0.1590	0.1325
6 A	1x.1068"	2x.1068"	0.230	6	2 585	536	0.00479	140	2.20	2.20	2.21	2.21	2.40	2.42	2.44	2.44	0.270	0.540	0.648	0.331	0.1655	0.1379
6 C	1x.1046"	2x.1046"	0.225	6	2 143	514	0.00469	130	2.20	2.20	2.21	2.21	2.40	2.42	2.44	2.44	0.271	0.542	0.651	0.333	0.1663	0.1386
7 D	2x.1141"	1x.1141"	0.246	7	4 022	594	0.00400	120	2.77	2.78	2.79	2.79	3.03	3.05	3.07	3.07	0.279	0.558	0.670	0.326	0.1631	0.1359
7 A	1x.1266"	2x.0895"	0.223	7	2 754	495	0.00441	120	2.77	2.78	2.78	2.78	3.03	3.05	3.07	3.07	0.274	0.548	0.658	0.333	0.1666	0.1388
8 D	2x.1016"	1x.1016"	0.219	8	3 256	471	0.00356	110	3.49	3.50	3.51	3.51	3.82	3.84	3.86	3.86	0.285	0.570	0.684	0.334	0.1672	0.1393
8 A	1x.1127"	2x.0797"	0.199	8	2 233	392	0.00394	100	3.49	3.50	3.51	3.51	3.82	3.84	3.86	3.87	0.280	0.560	0.672	0.341	0.1706	0.1422
8 C	1x.0808"	2x.0834"	0.179	8	1 362	320	0.00373	100	3.49	3.50	3.51	3.51	3.82	3.84	3.86	3.86	0.283	0.565	0.679	0.349	0.1744	0.1453
9½ D	2x.0808"	1x.0808"	0.174	9½	1 743	298	0.00283	85	4.91	4.92	4.92	4.93	5.37	5.39	5.42	5.42	0.297	0.593	0.712	0.351	0.1754	0.1462

*Based on a conductor temperature of 75°C. and an ambient of 25°C., wind 1.4 miles per hour (2 ft/sec.), frequency = 60 cycles, average tarnished surface.

**Resistances at 50°C. total temperature, based on an ambient of 25°C. plus 25°C. rise due to heating effect of current. The approximate magnitude of current necessary to produce the 25°C. rise is 75% of the "Approximate Current Carrying Capacity at 60 cycles."

Table 4-B—Characteristics of **Copperweld** Conductors

(Copperweld Steel Company)

Nominal Conductor Size	Number and Size of Wires	Outside Diameter Inches	Area of Conductor Circular Mils	Rated Breaking Load Pounds Strength		Weight Pounds per Mile	Geometric Mean Radius at 60 cycles and Average Currents Feet	Approx. Current Carrying Capacity* Amps at 60 Cycles	r_a Resistance Ohms per Conductor per Mile at 25°C. (77°F.) Small Currents				r_a Resistance Ohms per Conductor per Mile at 75°C. (167°F.) Current Approx. 75% of Capacity**				x_a Inductive Reactance Ohms per Conductor per Mile One Ft. Spacing Average Currents			x_a' Capacitive Reactance Megohms per Conductor per Mile One Ft. Spacing		
				High	Extra High				d-c	25 cycles	50 cycles	60 cycles	d-c	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles
30% Conductivity																						
7/8″	19 No. 5	0.910	628 900	55 570	66 910	9 344	0.00758	620	0.306	0.316	0.326	0.331	0.363	0.419	0.476	0.499	0.261	0.493	0.592	0.233	0.1165	0.0971
13/16″	19 No. 6	0.810	498 800	45 830	55 530	7 410	0.00675	540	0.386	0.396	0.406	0.411	0.458	0.518	0.580	0.605	0.267	0.505	0.606	0.241	0.1206	0.1005
23/32″	19 No. 7	0.721	395 500	37 740	45 850	5 877	0.00601	470	0.486	0.496	0.506	0.511	0.577	0.643	0.710	0.737	0.273	0.517	0.621	0.250	0.1248	0.1040
21/32″	19 No. 8	0.642	313 700	31 040	37 690	4 660	0.00535	410	0.613	0.623	0.633	0.638	0.728	0.799	0.872	0.902	0.279	0.529	0.635	0.258	0.1289	0.1074
9/16″	19 No. 9	0.572	248 800	25 500	30 610	3 696	0.00477	360	0.773	0.783	0.793	0.798	0.917	0.995	1.075	1.106	0.285	0.541	0.649	0.266	0.1330	0.1109
5/8″	7 No. 4	0.613	292 200	24 780	29 430	4 324	0.00511	410	0.656	0.664	0.672	0.676	0.778	0.824	0.870	0.887	0.281	0.533	0.640	0.261	0.1306	0.1088
9/16″	7 No. 5	0.546	231 700	20 470	24 650	3 429	0.00455	360	0.827	0.835	0.843	0.847	0.981	1.030	1.080	1.099	0.287	0.545	0.654	0.269	0.1347	0.1122
1/2″	7 No. 6	0.486	183 800	16 890	20 460	2 719	0.00405	310	1.042	1.050	1.058	1.062	1.237	1.290	1.343	1.364	0.293	0.557	0.668	0.278	0.1388	0.1157
7/16″	7 No. 7	0.433	145 700	13 910	16 890	2 157	0.00361	270	1.315	1.323	1.331	1.335	1.560	1.617	1.675	1.697	0.299	0.569	0.683	0.286	0.1429	0.1191
3/8″	7 No. 8	0.385	115 600	11 440	13 890	1 710	0.00321	230	1.658	1.666	1.674	1.678	1.967	2.03	2.09	2.12	0.305	0.581	0.697	0.294	0.1471	0.1226
11/32″	7 No. 9	0.343	91 650	9 393	11 280	1 356	0.00286	200	2.09	2.10	2.11	2.11	2.48	2.55	2.61	2.64	0.311	0.592	0.711	0.303	0.1512	0.1260
5/16″	7 No. 10	0.306	72 680	7 758	9 196	1 076	0.00255	170	2.64	2.64	2.65	2.66	3.13	3.20	3.27	3.30	0.316	0.604	0.725	0.311	0.1553	0.1294
3 No. 5	3 No. 5	0.392	99 310	9 262	11 860	1 467	0.00457	220	1.926	1.931	1.936	1.938	2.29	2.31	2.34	2.35	0.289	0.545	0.654	0.293	0.1465	0.1221
3 No. 6	3 No. 6	0.349	78 750	7 639	9 754	1 163	0.00407	190	2.43	2.43	2.44	2.44	2.88	2.91	2.94	2.95	0.295	0.556	0.668	0.301	0.1506	0.1255
3 No. 7	3 No. 7	0.311	62 450	6 291	7 922	922.4	0.00363	160	3.06	3.07	3.07	3.07	3.63	3.66	3.70	3.71	0.301	0.568	0.682	0.310	0.1547	0.1289
3 No. 8	3 No. 8	0.277	49 530	5 174	6 282	731.5	0.00323	140	3.86	3.87	3.87	3.87	4.58	4.61	4.65	4.66	0.307	0.580	0.696	0.318	0.1589	0.1324
3 No. 9	3 No. 9	0.247	39 280	4 250	5 129	580.1	0.00288	120	4.87	4.87	4.88	4.88	5.78	5.81	5.85	5.86	0.313	0.591	0.710	0.326	0.1629	0.1358
3 No. 10	3 No. 10	0.220	31 150	3 509	4 160	460.0	0.00257	110	6.14	6.14	6.15	6.15	7.28	7.32	7.36	7.38	0.319	0.603	0.724	0.334	0.1671	0.1392
40% Conductivity																						
7/8″	19 No. 5	0.910	628 900	50 240	....	9 344	0.01175	690	0.229	0.239	0.249	0.254	0.272	0.321	0.371	0.391	0.236	0.449	0.539	0.233	0.1165	0.0971
13/16″	19 No. 6	0.810	498 800	41 600	....	7 410	0.01046	610	0.289	0.299	0.309	0.314	0.343	0.396	0.450	0.472	0.241	0.461	0.553	0.241	0.1206	0.1005
23/32″	19 No. 7	0.721	395 500	34 390	....	5 877	0.00931	530	0.365	0.375	0.385	0.390	0.433	0.490	0.549	0.573	0.247	0.473	0.567	0.250	0.1248	0.1040
21/32″	19 No. 8	0.642	313 700	28 380	....	4 660	0.00829	470	0.460	0.470	0.480	0.485	0.546	0.608	0.672	0.698	0.253	0.485	0.582	0.258	0.1289	0.1074
9/16″	19 No. 9	0.572	248 800	23 390	....	3 696	0.00739	410	0.580	0.590	0.600	0.605	0.688	0.756	0.826	0.753	0.259	0.496	0.595	0.266	0.1330	0.1109
5/8″	7 No. 4	0.613	292 200	22 310	....	4 324	0.00792	470	0.492	0.500	0.508	0.512	0.584	0.624	0.664	0.680	0.255	0.489	0.587	0.261	0.1306	0.1088
9/16″	7 No. 5	0.546	231 700	18 510	....	3 429	0.00705	410	0.620	0.628	0.636	0.640	0.736	0.780	0.843	0.840	0.261	0.501	0.601	0.269	0.1347	0.1122
1/2″	7 No. 6	0.486	183 800	15 330	....	2 719	0.00628	350	0.782	0.790	0.798	0.802	0.928	0.975	1.021	1.040	0.267	0.513	0.615	0.278	0.1388	0.1157
7/16″	7 No. 7	0.433	145 700	12 670	....	2 157	0.00559	310	0.986	0.994	1.002	1.006	1.170	1.220	1.271	1.291	0.273	0.524	0.629	0.286	0.1429	0.1191
3/8″	7 No. 8	0.385	115 600	10 460	....	1 710	0.00497	270	1.244	1.252	1.260	1.264	1.476	1.530	1.584	1.606	0.279	0.536	0.644	0.294	0.1471	0.1226
11/32″	7 No. 9	0.343	91 650	8 616	....	1 356	0.00443	230	1.568	1.576	1.584	1.588	1.861	1.919	1.978	2.00	0.285	0.548	0.658	0.303	0.1512	0.1260
5/16″	7 No. 10	0.306	72 680	7 121	....	1 076	0.00395	200	1.978	1.986	1.994	1.998	2.35	2.41	2.47	2.50	0.291	0.559	0.671	0.311	0.1553	0.1294
3 No. 5	3 No. 5	0.392	99 310	8 373	....	1 467	0.00621	250	1.445	1.450	1.455	1.457	1.714	1.738	1.762	1.772	0.269	0.514	0.617	0.293	0.1465	0.1221
3 No. 6	3 No. 6	0.349	78 750	6 934	....	1 163	0.00553	220	1.821	1.826	1.831	1.833	2.16	2.19	2.21	2.22	0.275	0.526	0.631	0.301	0.1506	0.1255
3 No. 7	3 No. 7	0.311	62 450	5 732	....	922.4	0.00492	190	2.30	2.30	2.31	2.31	2.73	2.75	2.78	2.79	0.281	0.537	0.645	0.310	0.1547	0.1289
3 No. 8	3 No. 8	0.277	49 530	4 730	....	731.5	0.00439	160	2.90	2.90	2.91	2.91	3.44	3.47	3.50	3.51	0.286	0.549	0.659	0.318	0.1589	0.1324
3 No. 9	3 No. 9	0.247	39 280	3 898	....	580.1	0.00391	140	3.65	3.66	3.66	3.66	4.33	4.37	4.40	4.41	0.292	0.561	0.673	0.326	0.1629	0.1358
3 No. 10	3 No. 10	1.220	31 150	3 221	....	460.0	0.00348	120	4.61	4.61	4.62	4.62	5.46	5.50	5.53	5.55	0.297	0.572	0.687	0.334	0.1671	0.1392
3 No. 12	3 No. 12	0.174	19 590	2 236	....	289.3	0.00276	90	7.32	7.33	7.33	7.34	8.69	8.73	8.77	8.78	0.310	0.596	0.715	0.351	0.1754	0.1462

*Based on conductor temperature of 125°C. and an ambient of 25°C.

**Resistance at 75°C. total temperature, based on an ambient of 25°C. plus 50°C. rise due to heating effect of current.
The approximate magnitude of current necessary to produce the 50°C. rise is 75% of the "Approximate Current Carrying Capacity at 60 Cycles."

Table 5—60-Cycle Characteristics of Three-Conductor Belted Paper-Insulated Cables

Voltage Class	Insulation Thickness		AWG (B&S) or MCM	Type of Conductor (5)	Weight per 1000 Ft. Aluminum	Weight per 1000 Ft. Copper	Diameter or Sector Depth	Resistance (1) Ohms/Mi. Aluminum	Resistance (1) Ohms/Mi. Copper	GMR of one Conductor (2) Inches	POSITIVE & NEGATIVE SEQUENCE		GMR Three Conductors	ZERO SEQUENCE				LEAD SHEATH	
	Conductor	Belt									Series Reactance Ohms/Mile	Shunt Capacitive Reactance (3) Ohms for 1 Mi.		Series Resistance (4) Ohm/Mile		Series Reactance (4) Ohms/Mile	Shunt Capacitive Reactance (3) Ohms for 1 Mi.	Thickness Mils	Resistance Ohms/Mi. at 50°C.
														Alu-minum	Copper				
1,000 Volts Grounded or Ungrounded	55	35	6	CR	1290	1460	.184	4.13	2.52	0.067	0.181	6000	0.180	12.47	10.86	.311	11,300	85	2.78
	55	35	4	CR	1490	1760	.232	2.58	1.58	0.084	0.170	5200	0.212	9.54	8.54	.298	10,000	90	2.32
	55	35	2	CR	1880	2310	.292	1.64	1.01	0.106	0.162	4500	0.258	7.76	7.13	.274	8,700	90	2.04
	55	35	1	CR	2180	2720	.332	1.29	0.800	0.126	0.152	4200	0.291	6.66	6.17	.256	8,000	95	1.79
	55	35	0	CR	2400	3090	.373	1.03	0.638	0.142	0.146	3900	0.322	6.01	5.62	.246	7,700	95	1.66
	55	35	00	CS	2260	3120	.323	0.816	0.511	0.151	0.132	2400	0.270	6.41	6.09	.271	4,700	95	1.86
	55	35	000	CS	2520	3610	.364	0.650	0.410	0.171	0.132	2100	0.296	5.81	5.57	.265	4,300	95	1.72
	55	35	0000	CS	2960	4330	.417	0.518	0.328	0.191	0.130	1900	0.331	5.02	4.83	.255	3,900	100	1.50
	55	35	250	CS	3220	4840	.455	0.443	0.280	0.210	0.127	1700	0.356	4.70	4.54	.248	3,500	100	1.42
	55	35	300	CS	3650	5600	.497	0.368	0.236	0.230	0.126	1500	0.383	4.18	4.04	.246	3,200	105	1.27
	55	35	350	CS	3970	6240	.539	0.318	0.204	0.249	0.125	1400	0.410	3.89	3.77	.242	2,900	105	1.19
	55	35	400	CS	4240	6830	.572	0.282	0.182	0.265	0.123	1300	0.432	3.73	3.63	.236	2,700	105	1.15
	55	35	500	CS	4970	8220	.642	0.230	0.150	0.297	0.121	1200	0.477	3.23	3.15	.233	2,400	110	1.00
	65	40	600	CS	5850	9750	.700	0.195	0.128	0.327	0.123	1200	0.526	2.82	2.753	.231	2,500	115	0.875
	65	40	700	CS	6550	11100	.754	0.172	0.112	0.353	0.121	1100	0.561	2.55	2.49	.229	2,200	120	0.794
	65	40	750	CS	6900	11750	.780	0.162	0.107	0.366	0.120	1100	0.578	2.47	2.42	.228	1,900	120	0.770
3,000 Volts Grounded or Ungrounded	70	40	6	CR	1500	1670	.184	4.13	2.52	0.067	0.192	6700	0.192	11.30	9.69	0.322	12,500	90	2.39
	70	40	4	CR	1740	2010	.232	2.58	1.58	0.084	0.181	5800	0.227	9.06	8.06	0.298	11,200	90	2.16
	70	40	2	CR	2130	2560	.292	1.64	1.01	0.106	0.171	5100	0.271	7.04	6.41	0.280	9,800	95	1.80
	70	40	1	CR	2340	2880	.332	1.29	0.800	0.126	0.161	4700	0.304	6.33	5.84	0.263	9,200	95	1.68
	70	40	0	CR	2670	3360	.373	1.03	0.638	0.142	0.156	4400	0.335	5.47	5.08	0.256	8,600	100	1.48
	70	40	00	CS	2440	3300	.323	0.816	0.511	0.151	0.142	3500	0.285	6.02	5.70	0.275	6,700	95	1.73
	70	40	000	CS	2690	3780	.364	0.650	0.410	0.171	0.138	2700	0.312	5.54	5.30	0.266	5,100	95	1.63
	70	40	0000	CS	3050	4420	.417	0.518	0.328	0.191	0.135	2400	0.347	4.78	4.59	0.258	4,600	100	1.42
	70	40	250	CS	3530	5150	.455	0.443	0.280	0.210	0.132	2100	0.372	4.25	4.09	0.254	4,200	105	1.27
	70	40	300	CS	3860	5810	.497	0.368	0.236	0.230	0.130	1900	0.398	3.97	3.84	0.252	3,800	105	1.20
	70	40	350	CS	4180	6450	.539	0.318	0.204	0.249	0.129	1800	0.425	3.74	3.62	0.244	3,700	105	1.14
	70	40	400	CS	4640	7230	.572	0.282	0.182	0.265	0.128	1700	0.448	3.43	3.33	0.242	3,400	110	1.05
	70	40	500	CS	5350	8600	.642	0.230	0.150	0.297	0.126	1500	0.493	2.98	2.90	0.238	3,000	115	0.918
	75	40	600	CS	5990	9890	.700	0.195	0.128	0.327	0.125	1400	0.537	2.76	2.69	0.232	2,800	115	0.855
	75	40	700	CS	6750	11300	.754	0.170	0.112	0.353	0.123	1300	0.572	2.49	2.43	0.230	2,600	120	0.775
	75	40	750	CS	7050	11900	.780	0.162	0.107	0.366	0.123	1300	0.588	2.44	2.38	0.229	2,500	120	0.758
5,000 Volts Grounded or Ungrounded	85	45	6	CR	1630	1800	.184	4.13	2.52	0.067	0.203	7500	0.196	10.79	9.18	0.342	13,400	90	2.22
	85	45	4	CR	2130	2400	.232	2.58	1.58	0.084	0.190	6600	0.238	8.58	7.58	0.308	12,100	90	2.00
	85	45	2	CR	2380	2810	.292	1.64	1.01	0.106	0.178	5800	0.283	6.71	6.08	0.287	10,700	95	1.69
	85	45	1	CR	2580	3120	.332	1.29	0.800	0.126	0.168	5300	0.317	5.79	5.30	0.270	10,000	100	1.50
	85	45	0	CR	2860	3550	.373	1.03	0.638	0.142	0.160	5000	0.347	5.26	4.87	0.260	9,300	100	1.41
	85	45	00	CS	2590	3450	.323	0.816	0.511	0.151	0.148	3600	0.299	5.75	5.43	0.279	6,900	95	1.64
	85	45	000	CS	2950	4040	.364	0.650	0.410	0.171	0.143	3200	0.326	5.00	4.76	0.273	6,100	100	1.45
	85	45	0000	CS	3300	4670	.417	0.518	0.328	0.191	0.141	2800	0.362	4.54	4.35	0.260	5,600	100	1.34
	85	45	250	CS	3700	5320	.455	0.443	0.280	0.210	0.138	2600	0.388	4.07	3.91	0.258	5,200	105	1.21
	85	45	300	CS	4010	5960	.497	0.368	0.236	0.230	0.135	2400	0.414	3.82	3.69	0.252	4,600	105	1.15
	85	45	350	CS	4490	6760	.539	0.318	0.204	0.249	0.133	2200	0.442	3.44	3.32	0.248	4,200	110	1.04
	85	45	400	CS	4820	7410	.572	0.282	0.182	0.265	0.131	2000	0.465	3.28	3.18	0.244	4,000	110	1.00
	85	45	500	CS	5530	8780	.642	0.230	0.150	0.297	0.129	1800	0.510	2.88	2.80	0.238	3,500	115	0.885
	85	45	600	CS	6300	10200	.700	0.195	0.128	0.327	0.128	1600	0.548	2.59	2.52	0.236	3,200	120	0.798
	85	45	700	CS	6850	11400	.754	0.170	0.112	0.353	0.126	1500	0.583	2.42	2.36	0.234	2,900	120	0.750
	85	45	750	CS	7300	12150	.780	0.162	0.107	0.366	0.125	1500	0.600	2.28	2.22	0.232	2,700	125	0.707
8,000 Volts Grounded	105	55	6	CR	1930	2100	.184	4.13	2.52	0.067	0.216	8500	0.211	9.80	8.19	0.354	14,900	95	1.89
	105	55	4	CR	2200	2470	.232	2.58	1.58	0.084	0.201	7400	0.254	7.77	6.77	0.318	13,400	95	1.73
	105	55	2	CR	2690	3120	.292	1.64	1.01	0.106	0.189	6500	0.299	6.08	5.45	0.296	12,000	100	1.48
	105	55	1	CR	2840	3380	.332	1.29	0.800	0.126	0.177	6000	0.333	5.46	4.97	0.282	11,200	100	1.39
	105	55	0	CR	3200	3890	.373	1.03	0.638	0.142	0.169	5600	0.364	4.75	4.36	0.272	10,500	105	1.24
	105	55	00	CS	2930	3790	.323	0.816	0.511	0.151	0.156	4300	0.320	5.12	4.80	0.285	8,300	100	1.43
	105	55	000	CS	3220	4310	.364	0.650	0.410	0.171	0.151	3800	0.348	4.67	4.43	0.277	7,400	100	1.34
	105	55	0000	CS	3680	5050	.417	0.518	0.328	0.191	0.147	3500	0.383	4.07	3.90	0.270	6,600	105	1.19
	105	55	250	CS	4000	5620	.455	0.443	0.280	0.210	0.144	3200	0.407	3.83	3.67	0.265	6,100	105	1.13
	105	55	300	CS	4460	6410	.497	0.368	0.236	0.230	0.141	2900	0.434	3.46	3.33	0.260	5,600	110	1.03
	105	55	350	CS	4780	7050	.539	0.318	0.204	0.249	0.139	2700	0.463	3.25	3.14	0.254	5,200	110	0.978
	105	55	400	CS	5270	7860	.572	0.282	0.182	0.265	0.137	2500	0.486	2.98	2.88	0.250	4,900	115	0.899
	105	55	500	CS	6040	9290	.642	0.230	0.150	0.297	0.135	2200	0.529	2.63	2.55	0.246	4,300	120	0.800
	105	55	600	CS	6600	10500	.700	0.195	0.128	0.327	0.132	2000	0.569	2.47	2.40	0.240	3,900	120	0.758
	105	55	700	CS	7400	11950	.754	0.170	0.112	0.353	0.130	1900	0.605	2.24	2.18	0.237	3,600	125	0.691
	105	55	750	CS	7700	12550	.780	0.162	0.107	0.366	0.129	1800	0.621	2.18	2.13	0.235	3,500	125	0.673

Footnotes on next page.

Table 5 concluded on next page

Table 5—60-Cycle Characteristics of Three-Conductor Belted Paper-Insulated Cables (Concluded)

	Insulation Thickness										POSITIVE & NEGATIVE SEQUENCE			ZERO SEQUENCE				LEAD SHEATH	
														Series Resistance (4) Ohm/Mile					
Voltage Class	Conductor	Belt	AWG (B&S) or MCM	Type of Conductor (5)	Weight per 1000 Ft. Aluminum	Weight per 1000 Ft. Copper	Diameter or Sector Depth	Resistance (1) Ohms/Mi. Aluminum	Resistance (1) Ohms/Mi. Copper	GMR of one Conductor (2) Inches	Series Reactance Ohms/Mile	Shunt Capacitive Reactance (3) Ohms for 1 Mi.	GMR Three Conductors	Alu-minum	Copper	Series Reactance (4) Ohms/Mile	Shunt Capacitive Reactance (3) Ohms for 1 Mi.	Thickness Mils	Resistance Ohms/Mi. at 50°C.
8,000 Volts Ungrounded	105	105	6	CR	2170	2340	.184	4.13	2.52	0.067	0.216	9000	0.211	9.32	7.71	0.384	17,600	95	1.73
	105	105	4	CR	2690	2960	.232	2.58	1.58	0.084	0.201	7900	0.254	7.14	6.14	0.348	15,900	100	1.52
	105	105	2	CR	2720	3150	.292	1.64	1.01	0.106	0.189	6900	0.299	5.78	5.15	0.322	14,100	100	1.38
	105	105	1	CR	3340	3880	.332	1.29	0.800	0.126	0.177	6400	0.333	4.98	4.49	0.308	13,200	105	1.23
	105	105	0	CR	3590	4280	.373	1.03	0.638	0.142	0.169	6000	0.364	4.36	3.97	0.294	12,500	105	1.11
	105	105	00	CS	3330	4190	.323	0.816	0.511	0.151	0.156	5000	0.320	4.61	4.29	0.312	10,300	105	1.26
	105	105	000	CS	3620	4710	.364	0.650	0.410	0.171	0.151	4500	0.348	4.22	3.98	0.302	9,500	105	1.19
	105	105	0000	CS	4120	5490	.417	0.518	0.328	0.191	0.147	4100	0.383	3.70	3.51	0.292	8,700	110	1.06
	105	105	250	CS	4410	6030	.455	0.443	0.280	0.210	0.144	3800	0.407	3.47	3.31	0.286	8,000	110	1.01
	105	105	300	CS	4920	6870	.497	0.368	0.236	0.230	0.141	3500	0.434	3.15	3.02	0.280	7,400	115	0.928
	105	105	350	CS	5270	7540	.539	0.318	0.204	0.249	0.139	3300	0.463	2.97	2.86	0.274	7,000	115	0.884
	105	105	400	CS	5610	8200	.572	0.282	0.182	0.265	0.137	3100	0.486	2.85	2.75	0.268	6,600	115	0.856
	105	105	500	CS	6390	9640	.642	0.230	0.150	0.297	0.135	2800	0.529	2.52	2.44	0.264	6,000	120	0.764
	105	105	600	CS	7150	11050	.700	0.195	0.128	0.327	0.132	2600	0.569	2.28	2.21	0.258	5,400	125	0.694
	105	105	700	CS	7750	12300	.754	0.170	0.112	0.353	0.130	2300	0.605	2.15	2.09	0.254	5,000	125	0.660
	105	105	750	CS	8280	13150	.780	0.162	0.107	0.366	0.129	2200	0.621	2.02	1.97	0.252	4,600	130	0.620
15,000 Volts Grounded	170	75	4	CR	3010	3280	.232	2.58	1.58	0.084	0.232	9600	0.302	6.27	5.27	0.348	16,400	105	1.23
	170	75	2	CR	3270	3700	.292	1.64	1.01	0.106	0.216	8400	0.349	5.06	4.43	0.318	14,700	105	1.14
	170	75	1	CR	3920	4460	.332	1.29	0.800	0.126	0.202	7700	0.384	4.38	3.89	0.304	13,900	110	1.03
	155	75	0	CR	4200	4890	.373	1.03	0.638	0.142	0.188	6900	0.405	4.09	3.70	0.289	12,700	110	1.02
	155	75	00	CR	4630	5490	.419	0.816	0.511	0.159	0.185	6500	0.439	3.57	3.26	0.280	12,000	115	0.918
	155	75	000	CR	4830	5920	.470	0.650	0.410	0.178	0.180	6100	0.476	3.25	3.01	0.272	11,300	115	0.867
	155	75	0000	CS	4580	5950	.417	0.518	0.328	0.191	0.161	4800	0.430	3.44	3.25	0.283	9,000	110	0.973
	155	75	250	CS	5040	6660	.455	0.443	0.280	0.210	0.155	4500	0.457	3.11	2.95	0.276	8,200	115	0.890
	155	75	300	CS	5400	7350	.497	0.368	0.236	0.230	0.153	4200	0.484	2.93	2.80	0.271	7,900	115	0.855
	155	75	350	CS	5900	8170	.539	0.318	0.204	0.249	0.150	4000	0.512	2.67	2.56	0.267	7,200	120	0.784
	155	75	400	CS	6260	8850	.572	0.282	0.182	0.265	0.146	3700	0.536	2.56	2.46	0.262	6,900	120	0.758
	155	75	500	CS	7110	10350	.642	0.230	0.150	0.297	0.144	3300	0.580	2.27	2.19	0.258	6,200	125	0.680
	155	75	600	CS	7900	11800	.700	0.195	0.128	0.327	0.141	3000	0.620	2.06	1.99	0.253	5,700	130	0.620
	155	75	700	CS	8500	13050	.754	0.170	0.112	0.353	0.139	2700	0.657	1.94	1.88	0.249	5,400	130	0.591
	155	75	750	CS	9090	13950	.780	0.162	0.107	0.366	0.138	2600	0.681	1.84	1.78	0.243	5,100	135	0.558
15,000 Volts Ungrounded	170	155	4	CR	3610	3880	.232	2.58	1.58	0.084	0.232	10300	0.302	5.76	4.76	0.378	18,900	110	1.06
	170	155	2	CR	4010	4280	.292	1.64	1.01	0.106	0.216	9000	0.349	4.61	3.98	0.353	17,200	110	0.990
	170	155	1	CR	4580	5120	.332	1.29	0.800	0.126	0.202	8400	0.384	3.99	3.50	0.336	16,400	115	0.900
	155	155	0	CR	4730	5420	.373	1.03	0.638	0.142	0.188	7600	0.405	3.70	3.31	0.320	15,300	115	0.890
	155	155	00	CR	4990	5850	.419	0.816	0.511	0.159	0.185	7000	0.439	3.36	3.05	0.310	14,400	115	0.846
	155	155	000	CR	5550	6640	.470	0.650	0.410	0.178	0.180	6600	0.476	2.95	2.71	0.300	13,600	120	0.768
	155	155	0000	CS	5000	6370	.417	0.518	0.328	0.191	0.161	5600	0.430	3.08	2.89	0.314	11,600	115	0.855
	155	155	250	CS	5730	7350	.455	0.443	0.280	0.210	0.155	5200	0.457	2.80	2.64	0.307	10,800	120	0.786
	155	155	300	CS	6120	8070	.497	0.368	0.236	0.230	0.153	4900	0.484	2.63	2.50	0.301	10,200	120	0.755
	155	155	350	CS	6670	8940	.539	0.318	0.204	0.249	0.150	4600	0.512	2.41	2.30	0.294	9,500	125	0.698
	155	155	400	CS	7050	9640	.572	0.282	0.182	0.265	0.146	4300	0.536	2.31	2.21	0.288	9,000	125	0.676
	155	155	500	CS	7910	11150	.642	0.230	0.150	0.297	0.144	3900	0.580	2.06	1.98	0.283	8,200	130	0.611
	155	155	600	CS	8750	12650	.700	0.195	0.128	0.327	0.141	3600	0.620	1.87	1.80	0.277	7,500	135	0.558
	155	155	700	CS	9400	13950	.754	0.170	0.112	0.353	0.139	3400	0.657	1.78	1.71	0.272	7,200	135	0.535
	155	155	750	CS	9760	14600	.780	0.162	0.107	0.366	0.138	3300	0.681	1.74	1.68	0.266	6,800	135	0.525

(1) A-C resistance based on 65°C. with allowance for stranding, skin effect and proximity effect. Copper 0.15328 ohm (meter, gram); aluminum 0.076397 ohm (meter, gram).

(2) GMR of sector shaped conductors is an approximate figure close enough for most practical applications.

(3) Dielectric constant assumed 3.7.

(4) Zero-sequence impedances based on all return current in the sheath; none in the ground.

(5) The following symbols are used to designate the conductor type—CR—concentric round; CS—compact sector.

Table 6—60-Cycle Characteristics of Three-Conductor Shielded Paper-Insulated Cables

Voltage Class Phase to Phase	Insulation Thickness Mils	M-Circular Mils or AWG (B & S)	Type of Conductor (5)	Weight Per 1000 Ft.—Copper	Weight Per 1000 Ft.—Aluminum	Diameter or Sector Depth Inches	Copper Resistance (1) Ohms Per Mile—65°C	Aluminum Resistance (1) Ohms Per Mile—65°C	GMR of One Conductor (2) Inches	POSITIVE AND NEGATIVE SEQUENCE		GMR—Three Conductors	ZERO SEQUENCE				SHEATH		Approximate Overall Diameter—Inches
										Series Reactance Ohms Per Mile	Shunt Capacitive (3) Reactance—Ohms Per Mile		Cu Series Resistance (4) Ohms Per Mile $r_c + 3r_s$	Aluminum Series Resistance (4) Ohms Per Mile	Series Reactance $(x_s - 2x_d - 3x_s)$ Ohms Per Mile	Shunt Capacitive (3) Reactance—Ohms Per Mile	Thickness Mils	Resistance—Ohms Per Mile—50°C	
15000 (grounded)	190	4	CR	3480	3210	0.232	1.572	2.582	0.084	0.240	7810	0.316	5.29	6.30	0.322	7810	105	1.24	1.64
	190	2	CR	4130	3700	0.292	1.001	1.630	0.106	0.224	6700	0.364	4.48	5.11	0.296	6700	105	1.160	1.75
	175	1	CR	4320	3780	0.332	0.795	1.290	0.126	0.204	5800	0.389	4.02	4.51	0.282	5800	110	1.075	1.80
	175	1/0	CR	4840	4150	0.373	0.629	1.025	0.141	0.200	5310	0.419	3.69	4.09	0.275	5310	110	1.020	1.89
	175	2/0	CS	4650	3790	0.323	0.510	0.810	0.151	0.177	4200	0.357	3.93	4.23	0.305	4200	105	1.140	1.77
	175	3/0	CS	5350	4260	0.364	0.407	0.648	0.171	0.170	3720	0.384	3.53	3.77	0.300	3720	110	1.040	1.86
	175	4/0	CS	5990	4620	0.417	0.326	0.515	0.191	0.166	3360	0.420	3.26	3.45	0.289	3360	110	0.976	1.97
	175	250	CS	6740	5120	0.455	0.278	0.440	0.210	0.161	3250	0.445	2.96	3.12	0.284	3250	115	0.892	2.06
	175	300	CS	7430	5480	0.497	0.234	0.368	0.230	0.157	3060	0.475	2.79	2.93	0.278	3060	115	0.855	2.15
	175	350	CS	8270	6000	0.539	0.202	0.318	0.249	0.154	2895	0.502	2.54	2.66	0.274	2895	120	0.781	2.25
	175	400	CS	8940	6350	0.572	0.181	0.281	0.265	0.152	2580	0.525	2.46	2.56	0.267	2580	120	0.761	2.31
	175	500	CS	10450	7200	0.642	0.149	0.228	0.297	0.147	2460	0.570	2.19	2.27	0.262	2460	125	0.680	2.47
	175	600	CS	11900	8000	0.700	0.127	0.194	0.327	0.145	2380	0.610	2.00	2.06	0.256	2380	130	0.622	2.60
	175	700	CS	13200	8650	0.754	0.112	0.172	0.353	0.141	2260	0.647	1.90	1.96	0.251	2260	130	0.595	2.72
	175	750	CS	14050	9200	0.780	0.106	0.161	0.366	0.140	2140	0.665	1.79	1.84	0.250	2140	135	0.560	2.78
15000 (ungrounded)	230	4	CR	3980	3710	0.232	1.572	2.582	0.084	0.255	8850	0.344	4.75	5.76	0.334	8850	110	1.060	1.83
	230	2	CR	4620	4190	0.292	1.001	1.630	0.106	0.238	7650	0.392	3.94	4.57	0.314	7650	110	0.981	1.96
	230	1	CR	5170	4630	0.332	0.795	1.290	0.126	0.222	7000	0.430	3.50	3.99	0.295	7000	115	0.900	2.05
	215	1/0	CR	5410	4720	0.373	0.629	1.025	0.141	0.212	6150	0.450	3.29	3.69	0.284	6150	115	0.885	2.08
	215	2/0	CS	5360	4500	0.323	0.510	0.810	0.151	0.188	4680	0.386	3.45	3.75	0.318	4680	110	0.981	1.96
	215	3/0	CS	6040	4590	0.364	0.407	0.648	0.171	0.181	4350	0.415	3.11	3.35	0.308	4350	115	0.900	2.05
	215	4/0	CS	6720	5350	0.410	0.326	0.515	0.191	0.176	4030	0.446	2.89	3.08	0.300	4030	115	0.855	2.15
	215	250	CS	7480	5860	0.447	0.278	0.440	0.210	0.171	3620	0.473	2.62	2.78	0.290	3620	120	0.780	2.23
	215	300	CS	8230	6280	0.490	0.234	0.368	0.230	0.167	3500	0.500	2.51	2.65	0.286	3500	120	0.760	2.32
	215	350	CS	9070	6800	0.532	0.202	0.318	0.249	0.162	3380	0.531	2.29	2.41	0.279	3380	125	0.696	2.42
	215	400	CS	9780	7190	0.566	0.181	0.281	0.265	0.159	3220	0.555	2.26	2.30	0.274	3220	125	0.675	2.49
	215	500	CS	11350	8100	0.635	0.149	0.228	0.297	0.155	2900	0.600	1.98	2.06	0.272	2900	130	0.610	2.65
	215	600	CS	12800	8900	0.690	0.127	0.194	0.327	0.152	2740	0.638	1.81	1.87	0.265	2740	135	0.560	2.78
	215	700	CS	14100	9550	0.742	0.112	0.172	0.353	0.147	2620	0.675	1.72	1.78	0.260	2620	135	0.538	2.89
	215	750	CS	14800	9950	0.767	0.106	0.161	0.366	0.146	2500	0.698	1.69	1.74	0.255	2500	135	0.528	2.94
23000 (grounded)	255	2	CR	5090	4660	0.292	1.001	1.630	0.106	0.246	8250	0.410	3.671	4.300	0.316	8250	115	0.890	2.07
	255	1	CR	5480	4940	0.332	0.795	1.290	0.126	0.230	7550	0.448	3.345	3.840	0.300	7550	115	0.850	2.16
	255	1/0	CR	6310	5620	0.373	0.629	1.025	0.141	0.223	6970	0.480	2.969	3.365	0.292	6970	120	0.779	2.26
	240	2/0	CS	5880	5020	0.323	0.510	0.810	0.151	0.195	5000	0.405	3.170	3.470	0.322	5000	115	0.885	2.08
	240	3/0	CS	6390	5300	0.364	0.407	0.648	0.171	0.187	4845	0.435	2.957	3.198	0.310	4845	115	0.850	2.16
	240	4/0	CS	7260	5890	0.410	0.326	0.515	0.191	0.181	4350	0.465	2.646	2.835	0.305	4350	120	0.775	2.27
	240	250	CS	7870	6250	0.447	0.278	0.440	0.210	0.176	3950	0.493	2.518	2.680	0.298	3950	120	0.746	2.35
	240	300	CS	8770	6820	0.490	0.234	0.368	0.230	0.171	3870	0.517	2.294	2.428	0.293	3870	125	0.687	2.45
	240	350	CS	9480	7210	0.532	0.202	0.318	0.249	0.167	3540	0.556	2.190	2.306	0.284	3540	125	0.662	2.54
	240	400	CS	10400	7810	0.566	0.181	0.281	0.265	0.164	3460	0.572	2.031	2.131	0.282	3460	130	0.617	2.62
	240	500	CS	12000	8750	0.635	0.149	0.228	0.297	0.159	3220	0.620	1.829	1.908	0.275	3220	135	0.560	2.78
	240	600	CS	13250	9350	0.690	0.127	0.194	0.327	0.155	3060	0.656	1.738	1.805	0.271	3060	135	0.538	2.89
	240	700	CS	14800	10250	0.742	0.112	0.172	0.353	0.151	2900	0.695	1.611	1.671	0.265	2900	140	0.499	3.01
	240	750	CS	15450	10600	0.767	0.106	0.161	0.366	0.151	2740	0.710	1.605	1.661	0.265	2740	140	0.500	3.07
23000 (ungrounded)	310	2	CR	5980	5550	0.292	1.001	1.630	0.106	0.262	9440	0.446	3.281	3.910	0.328	9440	120	0.756	2.32
	310	1	CR	6580	6040	0.332	0.795	1.290	0.126	0.244	8450	0.486	2.885	3.380	0.312	8450	125	0.696	2.42
	310	1/0	CR	7470	6780	0.373	0.629	1.025	0.141	0.238	7980	0.518	2.639	3.035	0.304	7980	125	0.670	2.51
	310	2/0	CR	7810	6950	0.419	0.510	0.810	0.151	0.228	7350	0.554	2.360	2.660	0.295	7350	130	0.617	2.62
	310	3/0	CS	7750	6660	0.364	0.407	0.648	0.171	0.202	5490	0.482	2.427	2.668	0.328	5490	125	0.672	2.50
	310	4/0	CS	8790	7420	0.410	0.326	0.515	0.191	0.195	5000	0.516	2.191	2.380	0.318	5000	130	0.621	2.61
	310	250	CS	9390	7770	0.447	0.278	0.440	0.210	0.190	4700	0.544	2.078	2.240	0.312	4700	130	0.600	2.69
	310	300	CS	10350	8400	0.490	0.234	0.368	0.230	0.185	4510	0.575	1.909	2.043	0.305	4510	135	0.561	2.79
	310	350	CS	11100	8830	0.532	0.202	0.318	0.249	0.180	4350	0.604	1.822	1.938	0.298	4350	135	0.540	2.88
	310	400	CS	11850	9260	0.566	0.181	0.281	0.265	0.176	4100	0.629	1.761	1.861	0.293	4100	135	0.526	2.95
	310	500	CS	13450	10200	0.635	0.149	0.228	0.297	0.170	3870	0.675	1.594	1.673	0.286	3870	140	0.481	3.11
	310	600	CS	15050	11150	0.690	0.127	0.194	0.327	0.166	3620	0.713	1.467	1.534	0.280	3620	145	0.446	3.23
	310	700	CS	16450	11900	0.742	0.112	0.172	0.353	0.161	3460	0.750	1.412	1.472	0.275	3460	145	0.423	3.34
	310	750	CS	17350	12500	0.767	0.106	0.161	0.366	0.161	3380	0.779	1.309	1.364	0.269	3380	150	0.409	3.41
35000 (grounded)	345	2/0	CR	8550	7690	0.419	0.510	0.810	0.151	0.236	7900	0.579	2.185	2.485	0.303	7900	135	0.559	2.79
	345	3/0	CR	9220	8130	0.470	0.407	0.648	0.171	0.227	7250	0.621	2.017	2.258	0.290	7250	135	0.535	2.90
	345	4/0	CR	10300	8930	0.528	0.326	0.515	0.191	0.219	6810	0.667	1.806	1.995	0.282	6810	140	0.494	3.04
	345	250	CS	10200	8580	0.447	0.278	0.440	0.210	0.197	5110	0.568	1.908	2.070	0.318	5110	135	0.544	2.86
	345	300	CS	11000	9050	0.490	0.234	0.368	0.230	0.191	4840	0.599	1.814	1.948	0.311	4840	135	0.526	2.95
	345	350	CS	11950	9680	0.532	0.202	0.318	0.249	0.186	4600	0.629	1.677	1.793	0.305	4600	140	0.491	3.05
	345	400	CS	12700	10100	0.566	0.181	0.281	0.265	0.182	4400	0.655	1.521	1.721	0.300	4400	140	0.479	3.12
	345	500	CS	14400	11150	0.635	0.149	0.228	0.297	0.176	4110	0.700	1.469	1.548	0.293	4110	145	0.440	3.28
	345	600	CS	16000	12100	0.690	0.127	0.194	0.327	0.171	3870	0.740	1.357	1.424	0.288	3870	150	0.410	3.40
	345	700	CS	17450	12900	0.742	0.112	0.172	0.353	0.166	3710	0.779	1.302	1.362	0.280	3710	150	0.397	3.51
	345	750	CS	18400	13550	0.767	0.106	0.161	0.366	0.168	3630	0.791	1.236	1.291	0.280	3630	155	0.376	3.58

(1) A-C resistance based on 65°C. with allowance for stranding, skin effect and proximity effect. Copper 0.15328 ohm (meter, gram); aluminum 0.076397 ohm (meter, gram).

(2) GMR of sector shaped conductors is an approximate figure close enough for most practical applications.

(3) Dielectric constant assumed 3.7.

(4) Zero sequence impedances based on all return current in the sheath; none in the ground.

(5) The following symbols are used to designate the conductor type—CR—concentric round; CS—compact sector.

Table 7—60-Cycle Characteristics of Single-Conductor Concentric-Strand Paper-Insulated Cables

Voltage Class	Insulation Thickness Mils	Conductor Size AWG (B & S) or Thousand Circular Mils	Weight Per 1000 Ft. Copper Conductor	Weight Per 1000 Ft. Aluminum Conductor	Diameter of Conductor—Inches	GMR of One Conductor—Inches	x_a Reactance at 12 Inches—Ohms Per Phase Per Mile	x_s Reactance of Sheath Ohms Per Phase Per Mile	r_a CU Resistance of Copper Conductor Ohms Per Phase Per Mile	r_a AL Resistance of Aluminum Conductor Ohms Per Phase Per Mile	r_s Resistance of Sheath Ohms Per Phase Per Mile at 50°C	Shunt Capacitive Reactance—Ohms Per Phase Per Mile	Lead Sheath Thickness—Mils
1000 (grounded or ungrounded)	60	6	570	510	0.184	0.067	0.630	0.487	2.504	4.132	6.130	4048.	75
	60	4	665	575	0.232	0.084	0.602	0.473	1.572	2.599	5.498	3361.	75
	60	2	820	680	0.292	0.106	0.574	0.458	0.993	1.637	4.545	2776.	80
	60	1	930	750	0.332	0.126	0.553	0.450	0.786	1.293	4.237	2488.	80
	60	1/0	1050	820	0.373	0.141	0.539	0.442	0.621	1.030	3.968	2249.	80
	60	2/0	1240	950	0.418	0.159	0.525	0.432	0.494	0.816	3.676	2031.	80
	60	3/0	1440	1080	0.470	0.178	0.511	0.423	0.392	0.644	3.201	1833.	85
	60	4/0	1690	1240	0.528	0.200	0.497	0.413	0.311	0.513	2.960	1651.	85
	60	250	1910	1370	0.575	0.221	0.485	0.406	0.264	0.435	2.785	1528.	85
	60	300	2170	1530	0.630	0.242	0.474	0.399	0.221	0.363	2.629	1406.	85
	60	350	2420	1670	0.681	0.262	0.464	0.392	0.189	0.311	2.339	1309.	90
	60	400	2680	1820	0.728	0.280	0.456	0.386	0.166	0.272	2.222	1230.	90
	60	500	3170	2090	0.814	0.312	0.443	0.376	0.134	0.219	2.058	1110.	90
	60	600	3670	2380	0.893	0.345	0.431	0.367	0.112	0.183	1.807	1017.	95
	60	750	4370	2760	0.998	0.385	0.417	0.356	0.091	0.147	1.651	916.	95
	60	1000	5480	3330	1.152	0.445	0.400	0.342	0.070	0.111	1.399	799.	100
	75	1250	6600	3910	1.289	0.499	0.386	0.328	0.058	0.091	1.187	888.	105
	75	1500	7690	4470	1.412	0.546	0.375	0.319	0.050	0.077	1.051	814.	110
	75	1750	8880	5120	1.526	0.592	0.365	0.311	0.044	0.067	0.983	756.	110
	75	2000	9870	5570	1.632	0.633	0.357	0.304	0.040	0.060	0.890	709.	115
3000 (grounded or ungrounded)	75	6	610	550	0.184	0.067	0.630	0.478	2.504	4.132	5.735	4807.	75
	75	4	700	610	0.232	0.084	0.602	0.466	1.572	2.599	5.178	4021.	75
	75	2	850	710	0.292	0.106	0.574	0.452	0.993	1.637	4.310	3343.	80
	75	1	970	790	0.332	0.126	0.553	0.444	0.786	1.293	4.032	3006.	80
	75	1/0	1120	890	0.373	0.141	0.539	0.436	0.621	1.030	3.788	2725.	80
	75	2/0	1280	990	0.418	0.159	0.525	0.427	0.494	0.816	3.521	2467.	80
	75	3/0	1490	1130	0.470	0.178	0.511	0.418	0.392	0.644	3.076	2233.	85
	75	4/0	1750	1300	0.528	0.200	0.497	0.409	0.311	0.513	2.852	2016.	85
	75	250	1970	1430	0.575	0.221	0.485	0.402	0.264	0.435	2.689	1869.	85
	75	300	2250	1610	0.630	0.242	0.474	0.394	0.221	0.363	2.389	1722.	90
	75	350	2520	1770	0.681	0.262	0.464	0.388	0.189	0.311	2.268	1605.	90
	75	400	2790	1930	0.728	0.280	0.456	0.382	0.166	0.272	2.157	1511.	90
	75	500	3270	2190	0.814	0.312	0.443	0.372	0.134	0.219	1.888	1365.	95
	75	600	3740	2450	0.893	0.345	0.431	0.364	0.112	0.183	1.762	1252.	95
	75	750	4430	2820	0.998	0.385	0.417	0.353	0.091	0.147	1.527	1129.	100
	75	1000	5540	3390	1.152	0.445	0.400	0.340	0.070	0.111	1.370	987.	100
	90	1250	6650	3960	1.289	0.499	0.386	0.326	0.058	0.091	1.165	1054.	105
	90	1500	7810	4590	1.412	0.546	0.375	0.317	0.050	0.077	1.033	967.	110
	90	1750	8940	5180	1.526	0.592	0.365	0.309	0.044	0.067	0.923	899.	115
	90	2000	9970	5670	1.632	0.633	0.357	0.302	0.040	0.060	0.876	844.	115
5000 (grounded or ungrounded)	90	6	650	590	0.184	0.067	0.630	0.471	2.504	4.132	5.387	5501.	75
	90	4	750	660	0.232	0.084	0.602	0.458	1.572	2.599	4.545	4631.	80
	90	2	910	770	0.292	0.106	0.574	0.446	0.993	1.637	4.098	3872.	80
	90	1	1040	860	0.332	0.126	0.553	0.438	0.786	1.293	3.846	3493.	80
	90	1/0	1180	950	0.373	0.141	0.539	0.431	0.621	1.030	3.623	3175.	80
	90	2/0	1360	1070	0.418	0.159	0.525	0.421	0.494	0.816	3.158	2882.	85
	90	3/0	1570	1210	0.470	0.178	0.511	0.413	0.392	0.644	2.960	2614.	85
	90	4/0	1830	1380	0.528	0.200	0.497	0.405	0.311	0.513	2.752	2365.	85
	90	250	2030	1490	0.575	0.221	0.485	0.398	0.264	0.435	2.600	2196.	85
	90	300	2320	1680	0.630	0.242	0.474	0.391	0.221	0.363	2.315	2026.	90
	90	350	2590	1840	0.681	0.262	0.464	0.384	0.189	0.311	2.200	1891.	90
	90	400	2860	2000	0.728	0.280	0.456	0.378	0.166	0.272	2.096	1781.	90
	90	500	3330	2260	0.814	0.312	0.443	0.369	0.134	0.219	1.839	1613.	95
	90	600	3810	2520	0.893	0.345	0.431	0.361	0.112	0.183	1.719	1481.	95
	90	750	4510	2900	0.998	0.385	0.417	0.350	0.091	0.147	1.493	1337.	100
	90	1000	5640	3490	1.152	0.445	0.400	0.337	0.070	0.111	1.274	1171.	105
	100	1250	6830	4140	1.289	0.499	0.386	0.324	0.058	0.091	1.151	1163.	105
	100	1500	7940	4720	1.412	0.546	0.375	0.316	0.050	0.077	1.021	1068.	110
	100	1750	9070	5310	1.526	0.592	0.365	0.307	0.044	0.067	0.913	993.	115
	100	2000	10140	5840	1.632	0.633	0.357	0.301	0.040	0.060	0.867	932.	115

Table 7 continued on next page

Table 7—60-Cycle Characteristics of Single-Conductor Concentric-Strand Paper-Insulated Cables (Continued)

Voltage Class	Insulation Thickness Mils	Conductor Size AWG (B & S) or Thousand Circular Mils	Weight Per 1000 Ft. Copper Conductor	Weight Per 1000 Ft. Aluminum Conductor	Diameter of Conductor-Inches	GMR of One Conductor-Inches	x_a Reactance at 12 Inches—Ohms Per Phase Per Mile	x_s Reactance of Sheath Ohms Per Phase Per Mile	r_a CU Resistance of Copper Conductor Ohms Per Phase Per Mile	r_a AL Resistance of Aluminum Conductor Ohms Per Phase Per Mile	r_s Resistance of Sheath Ohms Per Phase Per Mile at 50°C	Shunt Capacitive Reactance—Ohms Per Phase Per Mile	Lead Sheath Thickness—Mils
8000 (grounded)	130	6	825	770	0.184	0.067	0.630	0.452	2.504	4.132	4.310	7103.	80
	130	4	930	840	0.232	0.084	0.602	0.442	1.572	2.599	3.968	6061.	80
	115	2	1080	940	0.292	0.106	0.574	0.436	0.993	1.637	3.788	4684.	80
	115	1	1220	1040	0.332	0.126	0.553	0.429	0.786	1.293	3.571	4244.	80
	115	1/0	1350	1120	0.373	0.141	0.539	0.421	0.621	1.030	3.158	3873.	85
	115	2/0	1530	1240	0.418	0.159	0.525	0.413	0.494	0.816	2.960	3528.	85
	115	3/0	1730	1370	0.470	0.178	0.511	0.406	0.392	0.644	2.785	3212.	85
	115	4/0	1980	1530	0.528	0.200	0.497	0.398	0.311	0.513	2.600	2915.	85
	115	250	2190	1660	0.575	0.221	0.485	0.391	0.264	0.435	2.315	2713.	90
	115	300	2480	1840	0.630	0.242	0.474	0.384	0.221	0.363	2.200	2509.	90
	115	350	2740	1990	0.681	0.262	0.464	0.378	0.189	0.311	2.096	2346.	90
	115	400	3020	2160	0.728	0.280	0.456	0.373	0.166	0.272	2.002	2214.	90
	115	500	3430	2350	0.814	0.312	0.443	0.364	0.134	0.219	1.762	2008.	95
	115	600	3930	2640	0.893	0.345	0.431	0.356	0.112	0.183	1.651	1848.	95
	115	750	4700	3090	0.998	0.385	0.417	0.346	0.091	0.147	1.439	1672.	100
	115	1000	5860	3710	1.152	0.445	0.400	0.333	0.070	0.111	1.233	1468.	105
	115	1250	7060	4370	1.289	0.499	0.386	0.322	0.058	0.091	1.076	1324.	110
	115	1500	8160	4940	1.412	0.546	0.375	0.314	0.050	0.077	1.005	1217.	110
	115	1750	9250	5490	1.526	0.592	0.365	0.305	0.044	0.067	0.899	1132.	115
	115	2000	10240	5950	1.632	0.633	0.357	0.299	0.040	0.060	0.855	1063.	115
8000 (ungrounded)	155	6	910	850	0.184	0.067	0.630	0.442	2.504	4.132	3.968	7963.	80
	155	4	1010	920	0.232	0.084	0.602	0.432	1.572	2.599	3.676	6842.	80
	140	2	1170	1030	0.292	0.106	0.574	0.427	0.993	1.637	3.521	5421.	80
	140	1	1300	1120	0.332	0.126	0.553	0.420	0.786	1.293	3.116	4931.	85
	140	1/0	1430	1200	0.373	0.141	0.539	0.413	0.621	1.030	2.960	4515.	85
	140	2/0	1620	1330	0.418	0.159	0.525	0.406	0.494	0.816	2.785	4127.	85
	140	3/0	1870	1510	0.470	0.178	0.511	0.399	0.392	0.644	2.629	3768.	85
	140	4/0	2090	1640	0.528	0.200	0.497	0.391	0.311	0.513	2.315	3431.	90
	140	250	2320	1780	0.575	0.221	0.485	0.384	0.264	0.435	2.200	3199.	90
	140	300	2620	1980	0.630	0.242	0.474	0.378	0.221	0.363	2.096	2965.	90
	140	350	2890	2140	0.681	0.262	0.464	0.372	0.189	0.311	1.888	2777.	95
	140	400	3170	2310	0.728	0.280	0.456	0.367	0.166	0.272	1.807	2624.	95
	140	500	3670	2600	0.814	0.312	0.443	0.359	0.134	0.219	1.691	2386.	95
	140	600	4170	2880	0.893	0.345	0.431	0.351	0.112	0.183	1.504	2199.	100
	140	750	4970	3360	0.998	0.385	0.417	0.341	0.091	0.147	1.389	1994.	100
	140	1000	6120	3970	1.152	0.445	0.400	0.329	0.070	0.111	1.194	1754.	105
	140	1250	7210	4530	1.289	0.499	0.386	0.318	0.058	0.091	1.045	1585.	110
	140	1509	8380	5160	1.412	0.546	0.375	0.310	0.050	0.077	.978	1459.	110
	140	1750	9540	5780	1.526	0.592	0.365	0.302	0.044	0.067	.876	1358.	115
	140	2000	10590	6290	1.632	0.633	0.357	0.296	0.040	0.060	.797	1277.	120
15000 (grounded)	190	4	1220	1120	0.232	0.084	0.602	0.420	1.572	2.599	3.116	7821.	85
	190	2	1370	1230	0.292	0.106	0.574	0.410	0.993	1.637	2.887	6721.	85
	175	1	1480	1300	0.332	0.126	0.553	0.409	0.786	1.293	2.852	5805.	85
	175	1/0	1610	1380	0.373	0.141	0.539	0.403	0.621	1.030	2.720	5336.	85
	175	2/0	1770	1480	0.418	0.159	0.525	0.396	0.494	0.816	2.572	4896.	85
	175	3/0	1980	1620	0.470	0.178	0.511	0.389	0.392	0.644	2.291	4488.	90
	175	4/0	2250	1800	0.528	0.200	0.497	0.382	0.311	0.513	2.157	4100.	90
	175	250	2480	1940	0.575	0.221	0.485	0.376	0.264	0.435	2.058	3833.	90
	175	300	2770	2130	0.630	0.242	0.474	0.370	0.221	0.363	1.855	3563.	95
	175	350	3080	2330	0.681	0.262	0.464	0.365	0.189	0.311	1.777	3344.	95
	175	400	3380	2520	0.728	0.280	0.456	0.360	0.166	0.272	1.705	3165.	95
	175	500	3900	2825	0.814	0.312	0.443	0.352	0.134	0.219	1.515	2887.	100
	175	600	4380	3090	0.893	0.345	0.431	0.345	0.112	0.183	1.429	2666.	100
	175	750	5150	3540	0.998	0.385	0.417	0.335	0.091	0.147	1.257	2424.	105
	175	1000	6300	4150	1.152	0.445	0.400	0.324	0.070	0.111	1.144	2139.	105
	175	1250	7490	4800	1.289	0.499	0.386	0.314	0.058	0.091	1.005	1937.	110
	175	1500	8600	5380	1.412	0.546	0.375	0.305	0.050	0.077	0.899	1786.	115
	175	1750	9820	6060	1.526	0.592	0.365	0.298	0.044	0.067	0.846	1665.	115
	175	2000	10900	6630	1.632	0.633	0.357	0.292	0.040	0.060	0.772	1567.	120

Table 7 continued on next page

Table 7—60-Cycle Characteristics of Single-Conductor Concentric-Strand Paper-Insulated Cables (Continued)

							x_a	x_s	r_a CU	r_a AL	r_s		
Voltage Class	Insulation Thickness Mils	Conductor Size AWG (B & S) or Thousand Circular Mils	Weight Per 1000 Ft. Copper Conductor	Weight Per 1000 Ft. Aluminum Conductor	Diameter of Conductor—Inches	GMR of One Conductor—Inches	Reactance at 12 Inches—Ohms Per Phase Per Mile	Reactance of Sheath Ohms Per Phase Per Mile	Resistance of Copper Conductor Ohms Per Phase Per Mile	Resistance of Aluminum Conductor Ohms Per Phase Per Mile	Resistance of Sheath Ohms Per Phase Per Mile at 50°C	Shunt Capacitive Reactance—Ohms Per Phase Per Mile	Lead Sheath Thickness—Mils
15000 (ungrounded)	230	4	1370	1280	0.232	0.084	0.602	0.407	1.572	2.599	2.818	8812.	85
	230	2	1510	1370	0.292	0.106	0.574	0.399	0.993	1.637	2.629	7628.	85
	230	1	1630	1450	0.332	0.126	0.553	0.393	0.786	1.293	2.364	7010.	90
	215	1/0	1770	1540	0.373	0.141	0.539	0.392	0.621	1.030	2.339	6183.	90
	215	2/0	1940	1650	0.418	0.159	0.525	0.386	0.494	0.816	2.222	5694.	90
	215	3/0	2140	1780	0.470	0.178	0.511	0.380	0.392	0.644	2.116	5238.	90
	215	4/0	2420	1970	0.528	0.200	0.497	0.373	0.311	0.513	2.002	4804.	90
	215	250	2650	2110	0.575	0.221	0.485	0.367	0.264	0.435	1.807	4502.	95
	215	300	2960	2320	0.630	0.242	0.474	0.362	0.221	0.363	1.733	4195.	95
	215	350	3250	2500	0.681	0.262	0.464	0.357	0.189	0.311	1.664	3946.	95
	215	400	3550	2690	0.728	0.280	0.456	0.352	0.166	0.272	1.515	3742.	100
	215	500	4070	3000	0.814	0.312	0.443	0.345	0.134	0.219	1.429	3423.	100
	215	600	4590	3300	0.893	0.345	0.431	0.338	0.112	0.183	1.351	3169.	100
	215	750	5400	3790	0.998	0.385	0.417	0.329	0.091	0.147	1.194	2889.	105
	215	1000	6640	4490	1.152	0.445	0.400	0.318	0.070	0.111	1.039	2558.	110
	215	1250	7890	5210	1.289	0.499	0.386	0.308	0.058	0.091	0.918	2321.	115
	215	1500	9050	5830	1.412	0.546	0.375	0.301	0.050	0.077	0.863	2144.	115
	215	1750	10170	6410	1.526	0.592	0.365	0.293	0.044	0.067	0.779	2002.	120
	215	2000	11200	6910	1.632	0.633	0.357	0.288	0.040	0.060	0.744	1886.	120
23000 (grounded)	255	2	1740	1590	0.292	0.106	0.574	0.392	0.993	1.637	2.339	8147.	90
	255	1	1860	1680	0.332	0.126	0.553	0.387	0.786	1.293	2.245	7504.	90
	255	1/0	1990	1760	0.373	0.141	0.539	0.382	0.621	1.030	2.157	6948.	90
	240	2/0	2180	1890	0.418	0.159	0.525	0.380	0.494	0.816	2.116	6155.	90
	240	3/0	2380	2020	0.470	0.178	0.511	0.374	0.392	0.644	2.020	5674.	90
	240	4/0	2660	2210	0.528	0.200	0.497	0.367	0.311	0.513	1.807	5214.	95
	240	250	2870	2330	0.575	0.221	0.485	0.362	0.264	0.435	1.733	4894.	95
	240	300	3190	2530	0.630	0.242	0.474	0.357	0.221	0.363	1.664	4567.	95
	240	350	3480	2730	0.681	0.262	0.464	0.352	0.189	0.311	1.515	4301.	100
	240	400	3790	2930	0.728	0.280	0.456	0.347	0.166	0.272	1.460	4083.	100
	240	500	4320	3250	0.814	0.312	0.443	0.340	0.134	0.219	1.379	3741.	100
	240	600	4850	3560	0.893	0.345	0.431	0.334	0.112	0.183	1.241	3468.	105
	240	750	5620	4010	0.998	0.385	0.417	0.325	0.091	0.147	1.158	3166.	105
	240	1000	6830	4680	1.152	0.445	0.400	0.314	0.070	0.111	1.010	2808.	110
	240	1250	8060	5370	1.289	0.499	0.386	0.305	0.058	0.091	0.894	2552.	115
	240	1500	9220	6000	1.412	0.546	0.375	0.297	0.050	0.077	0.805	2359.	120
	240	1750	10450	6670	1.526	0.592	0.365	0.290	0.044	0.067	0.761	2205.	120
	240	2000	11600	7280	1.632	0.633	0.357	0.284	0.040	0.060	0.694	2079.	125
23000 (ungrounded)	310	2	1970	1830	0.292	0.106	0.574	0.378	0.993	1.637	2.096	9183.	90
	310	1	2120	1940	0.332	0.126	0.553	0.374	0.786	1.293	2.020	8494.	90
	310	1/0	2300	2070	0.373	0.141	0.539	0.369	0.621	1.030	1.839	7895.	95
	310	2/0	2520	2230	0.418	0.159	0.525	0.364	0.494	0.816	1.762	7322.	95
	310	3/0	2760	2400	0.470	0.178	0.511	0.359	0.392	0.644	1.691	6783.	95
	310	4/0	3070	2620	0.528	0.200	0.497	0.353	0.311	0.513	1.527	6262.	100
	310	250	3330	2790	0.575	0.221	0.485	0.348	0.264	0.435	1.471	5898.	100
	310	300	3630	2990	0.630	0.242	0.474	0.344	0.221	0.363	1.418	5525.	100
	310	350	3940	3190	0.681	0.262	0.464	0.340	0.189	0.311	1.370	5219.	100
	310	400	4230	3370	0.728	0.280	0.456	0.335	0.166	0.272	1.257	4967.	105
	310	500	4760	3685	0.814	0.312	0.443	0.329	0.134	0.219	1.194	4570.	105
	310	600	5260	3970	0.893	0.345	0.431	0.323	0.112	0.183	1.137	4251.	105
	310	750	6080	4470	0.998	0.385	0.417	0.315	0.091	0.147	1.016	3896.	110
	310	1000	7360	5210	1.152	0.445	0.400	0.305	0.070	0.111	0.894	3472.	115
	310	1250	8700	6020	1.289	0.499	0.386	0.296	0.058	0.091	0.797	3166.	120
	310	1500	9930	6710	1.412	0.546	0.375	0.289	0.050	0.077	0.754	2935.	120
	310	1750	11200	7440	1.526	0.592	0.365	0.283	0.044	0.067	0.685	2749.	125
	310	2000	12300	8020	1.632	0.633	0.357	0.277	0.040	0.060	0.628	2596.	130

Table 7 concluded on next page

Table 7—60-Cycle Characteristics of Single-Conductor Concentric-Strand Paper-Insulated Cables (Concluded)

Voltage Class	Insulation Thickness Mils	Conductor Size AWG (B & S) or Thousand Circular Mils	Weight Per 1000 Ft. Copper Conductor	Weight Per 1000 Ft. Aluminum Conductor	Diameter of Conductor—Inches	GMR of One Conductor—Inches	x_a Reactance at 12 Inches—Ohms Per Phase Per Mile	x_s Reactance of Sheath Ohms Per Phase Per Mile	r_a CU Resistance of Copper Conductor Ohms Per Phase Per Mile	r_a AL Resistance of Aluminum Conductor Ohms Per Phase Per Mile	r_s Resistance of Sheath Ohms Per Phase Per Mile at 50°C	Shunt Capacitive Reactance—Ohms Per Phase Per Mile	Lead Sheath Thickness—Mils
35000 (grounded)	345	2/0	2690	2400	0.418	0.159	0.525	0.357	0.494	0.816	1.664	7848.	95
	345	3/0	2910	2550	0.470	0.178	0.511	0.352	0.392	0.644	1.515	7285.	100
	345	4/0	3190	2740	0.528	0.200	0.497	0.346	0.311	0.513	1.449	6740.	100
	345	250	3430	2890	0.575	0.221	0.485	0.342	0.264	0.435	1.399	6357.	100
	345	300	3770	3130	0.630	0.242	0.474	0.338	0.221	0.363	1.351	5964.	100
	345	350	4100	3350	0.681	0.262	0.464	0.334	0.189	0.311	1.241	5642.	105
	345	400	4430	3570	0.728	0.280	0.456	0.330	0.166	0.272	1.202	5376.	105
	345	500	5020	3950	0.814	0.312	0.443	0.324	0.134	0.219	1.144	4955.	105
	345	600	5610	4320	0.893	0.345	0.431	0.318	0.112	0.183	1.039	4616.	110
	345	750	6460	4850	0.998	0.385	0.417	0.310	0.091	0.147	0.978	4238.	110
	345	1000	7700	5550	1.152	0.445	0.400	0.301	0.070	0.111	0.863	3784.	115
	345	1250	8950	6260	1.289	0.499	0.386	0.292	0.058	0.091	0.772	3457.	120
	345	1500	10150	6930	1.412	0.546	0.375	0.285	0.050	0.077	0.697	3208.	125
	345	1750	11450	7690	1.526	0.592	0.365	0.279	0.044	0.067	0.665	3008.	125
	345	2000	12600	8290	1.632	0.633	0.357	0.273	0.040	0.060	0.611	2843.	130
35000 (ungrounded)	455	2/0	3490	3200	0.418	0.159	0.525	0.337	0.494	0.816	1.274	9307.	105
	455	3/0	3710	3350	0.470	0.178	0.511	0.333	0.392	0.644	1.233	8685.	105
	455	4/0	3990	3540	0.528	0.200	0.497	0.328	0.311	0.513	1.187	8078.	105
	455	250	4250	3710	0.575	0.221	0.485	0.324	0.264	0.435	1.151	7650.	105
	455	300	4580	3940	0.630	0.242	0.474	0.320	0.221	0.363	1.063	7207.	110
	455	350	4910	4160	0.681	0.262	0.464	0.317	0.189	0.311	1.033	6842.	110
	455	400	5250	4390	0.728	0.280	0.456	0.314	0.166	0.272	1.005	6539.	110
	455	500	5860	4790	0.814	0.312	0.443	0.308	0.134	0.219	0.918	6056.	115
	455	600	6470	5180	0.893	0.345	0.431	0.303	0.112	0.183	0.881	5665.	115
	455	750	7360	5750	0.998	0.385	0.417	0.296	0.091	0.147	0.797	5225.	120
	455	1000	8660	6510	1.152	0.445	0.400	0.288	0.070	0.111	0.744	4694.	120
	455	1250	9940	7260	1.289	0.499	0.386	0.280	0.058	0.091	0.668	4307.	125
	455	1500	11200	7980	1.412	0.546	0.375	0.273	0.050	0.077	0.611	4011.	130
	455	1750	12450	8690	1.526	0.592	0.365	0.268	0.044	0.067	0.560	3771.	135
	455	2000	13700	9420	1.632	0.633	0.357	0.263	0.040	0.060	0.538	3573.	135
46000 (grounded)	445	4/0	3940	3490	0.528	0.200	0.497	0.330	0.311	0.513	1.202	7966.	105
	445	250	4220	3680	0.575	0.221	0.485	0.326	0.264	0.435	1.165	7541.	105
	445	300	4550	3910	0.630	0.242	0.474	0.322	0.221	0.363	1.076	7102.	110
	445	350	4830	4080	0.681	0.262	0.464	0.318	0.189	0.311	1.045	6740.	110
	445	400	5220	4360	0.728	0.280	0.456	0.315	0.166	0.272	1.016	6440.	110
	445	500	5830	4760	0.814	0.312	0.443	0.309	0.134	0.219	0.928	5962.	115
	445	600	6400	5110	0.893	0.345	0.431	0.304	0.112	0.183	0.890	5575.	115
	445	750	7310	5700	0.998	0.385	0.417	0.297	0.091	0.147	0.805	5140.	120
	445	1000	8660	6510	1.152	0.445	0.400	0.289	0.070	0.111	0.751	4616.	120
	445	1250	9870	7180	1.289	0.499	0.386	0.281	0.058	0.091	0.677	4233.	125
	445	1500	11000	7780	1.412	0.546	0.375	0.274	0.050	0.077	0.615	3941.	130
	445	1750	12250	8490	1.526	0.592	0.365	0.269	0.044	0.067	0.587	3705.	130
	445	2000	13650	9330	1.632	0.633	0.357	0.263	0.040	0.060	0.542	3509.	135
69000 (grounded)	650	500	7660	6590	0.814	0.312	0.443	0.284	0.134	0.219	0.694	7701.	125
	650	600	8250	6960	0.893	0.345	0.431	0.280	0.112	0.183	0.671	7244.	125
	650	750	9220	7610	0.998	0.385	0.417	0.274	0.091	0.147	0.615	6725.	130
	650	1000	10650	8500	1.152	0.445	0.400	0.267	0.070	0.111	0.556	6091.	135
	650	1250	12100	9420	1.289	0.499	0.386	0.260	0.058	0.091	0.528	5623.	135
	650	1500	13400	10150	1.412	0.546	0.375	0.255	0.050	0.077	0.488	5263.	140
	650	1750	14700	10950	1.526	0.592	0.365	0.250	0.044	0.067	0.451	4969.	145
	650	2000	15950	11650	1.632	0.633	0.357	0.246	0.040	0.060	0.436	4724.	145

Table 8—60-Cycle Characteristics of Self-Supporting Aerial Cable Rubber-Insulated, Neoprene-Jacketed

Voltage Class	Conductor Size	Stranding	Insulation Thickness	Shielding	Jacket Thickness	Diameter	Messenger Used with Copper Conductors	Wt. Per 1000 Ft. Messenger and Copper	Messenger Used with Aluminum Conductors	Wt. Per 1000 Ft. Messenger and Aluminum	POSITIVE SEQUENCE 60~ AC OHMS/MI.				ZERO SEQUENCE(3) 60~ AC OHMS/MI.				
											Resistance (1)		Reactance		Resistance (1)		Reactance		
																	Series Inductive		
											Copper	Aluminum	Series Inductive	Shunt Capacitive(2)	Copper	Aluminum	Copper	Aluminum	Shunt Capacitive(2)
3-kv Ungrounded Neutral 5-kv Grounded Neutral	6	7	10/64	No	3/64	0.59	5/16" 30% CCS	1020	5/16" 30% CCS	854	2.52	4.13	0.258	......	3.592	5.082	3.712	3.712	......
	4	7	10/64	No	3/64	0.67	5/16" 30% CCS	1230	5/16" 30% CCS	956	1.58	2.58	0.246	......	2.632	3.572	3.662	3.662	......
	2	7	10/64	No	3/64	0.73	5/16" 30% CCS	1530	5/16" 30% CCS	1100	1.00	1.64	0.229	......	2.025	2.605	3.615	3.615	......
	1	19	10/64	No	3/64	0.77	5/16" 30% CCS	1780	5/16" 30% CCS	1250	0.791	1.29	0.211	......	1.815	2.275	3.582	3.582	......
	1/0	19	10/64	No	3/64	0.81	5/16" 30% CCS	2070	5/16" 30% CCS	1390	0.635	1.03	0.207	......	1.644	2.015	3.555	3.555	......
	2/0	19	10/64	No	3/64	0.85	3/8" 30% CCS	2510	5/16" 30% CCS	1530	0.501	0.816	0.200	......	1.622	1.803	3.162	3.526	......
	3/0	19	10/64	No	3/64	0.91	3/8" 30% CCS	2890	5/16" 30% CCS	1690	0.402	0.644	0.194	......	1.517	1.637	3.135	3.499	......
	4/0	19	10/64	No	4/64	0.99	1/2" 30% CCS	3570	5/16" 30% CCS	1900	0.318	0.518	0.191	......	1.401	1.508	2.665	3.459	......
	250	37	11/64	No	4/64	1.08	1/2" 30% CCS	4080	5/16" 30% CCS	2160	0.269	0.437	0.189	......	1.351	1.430	2.635	3.429	......
	300	37	11/64	No	4/64	1.13	1/2" 30% CCS	4620	3/8" 30% CCS	2500	0.228	0.366	0.184	......	1.308	1.465	2.612	3.042	......
	350	37	11/64	No	4/64	1.18	1/2" 30% CCS	5290	3/8" 30% CCS	2780	0.197	0.316	0.180	......	1.277	1.415	2.591	3.021	......
	400	37	11/64	No	4/64	1.23	1/2" 30% CCS	5800	3/8" 30% CCS	3040	0.172	0.276	0.176	......	1.252	1.377	2.576	3.006	......
	500	37	11/64	No	4/64	1.32	1/2" 30% CCS	6860	1/2" 30% CCS	3650	0.141	0.223	0.172	......	1.219	1.290	2.543	2.543	......
5-kv Ungrounded Neutral	6	7	10/64	Yes	4/64	0.74	5/16" 30% CCS	1310	5/16" 30% CCS	1140	2.52	4.13	0.292	4970	......	......	......	......	......
	4	7	10/64	Yes	4/64	0.79	5/16" 30% CCS	1540	5/16" 30% CCS	1270	1.58	2.58	0.272	4320	......	......	......	......	......
	2	7	10/64	Yes	5/64	0.88	5/16" 30% CCS	1950	5/16" 30% CCS	1520	1.00	1.64	0.257	3630	......	......	......	......	......
	1	19	10/64	Yes	5/64	0.92	5/16" 30% CCS	2180	5/16" 30% CCS	1640	0.791	1.29	0.241	3330	......	......	......	......	......
	1/0	19	10/64	Yes	5/64	0.96	5/16" 30% CCS	2450	5/16" 30% CCS	1770	0.655	1.03	0.233	3080	......	......	......	......	......
	2/0	19	10/64	Yes	5/64	1.00	5/16" 30% CCS	2910	5/16" 30% CCS	1930	0.501	0.816	0.223	2830	......	......	......	......	......
	3/0	19	10/64	Yes	5/64	1.06	3/8" 30% CCS	3320	5/16" 30% CCS	2120	0.402	0.644	0.215	2580	......	......	......	......	......
	4/0	19	10/64	Yes	5/64	1.11	3/8" 30% CCS	4030	5/16" 30% CCS	2350	0.318	0.518	0.207	2380	......	......	......	......	......
	250	37	11/64	Yes	5/64	1.20	1/2" 30% CCS	4570	3/8" 30% CCS	2770	0.269	0.437	0.206	2380	......	......	......	......	......
	300	37	11/64	Yes	6/64	1.29	1/2" 30% CCS	5260	3/8" 30% CCS	3140	0.228	0.366	0.203	2280	......	......	......	......	......
	350	37	11/64	Yes	6/64	1.34	1/2" 30% CCS	5840	3/8" 30% CCS	3380	0.197	0.316	0.199	2090	......	......	......	......	......
	400	37	11/64	Yes	6/64	1.39	1/2" 30% CCS	6380	3/8" 30% CCS	3610	0.172	0.276	0.194	1890	......	......	......	......	......
	500	37	11/64	Yes	6/64	1.47	1/2" 30% CCS	7470	1/2" 30% CCS	4240	0.141	0.223	0.187	1740	......	......	......	......	......
15-kv Grounded Neutral	6	19	19/64	Yes	5/64	1.05	5/16" 30% CCS	2090	5/16" 30% CCS	1920	2.52	4.13	0.326	7150	3.846	5.346	3.396	3.396	7150
	4	19	19/64	Yes	5/64	1.10	5/16" 30% CCS	2350	5/16" 30% CCS	2080	1.58	2.58	0.302	6260	2.901	3.831	3.364	3.364	6260
	2	19	19/64	Yes	5/64	1.16	3/8" 30% CCS	2860	3/8" 30% CCS	2430	1.00	1.64	0.279	5460	2.459	3.039	2.851	2.851	5460
	1	19	19/64	Yes	5/64	1.20	3/8" 30% CCS	3120	3/8" 30% CCS	2580	0.791	1.29	0.268	5110	2.238	2.701	2.837	2.837	5110
	1/0	19	19/64	Yes	6/64	1.27	3/8" 30% CCS	3560	3/8" 30% CCS	2880	0.655	1.03	0.260	4720	2.052	2.426	2.825	2.825	4720
	2/0	19	19/64	Yes	6/64	1.32	1/2" 30% CCS	4120	3/8" 30% CCS	3070	0.501	0.816	0.249	4370	1.896	2.214	2.251	2.801	4370
	3/0	19	19/64	Yes	6/64	1.37	1/2" 30% CCS	4580	1/2" 30% CCS	3510	0.402	0.644	0.241	4120	1.782	2.008	2.240	2.240	4120
	4/0	19	19/64	Yes	6/64	1.43	1/2" 30% CCS	5150	1/2" 30% CCS	3790	0.318	0.518	0.231	3770	1.681	1.864	2.235	2.235	3770
	250	37	19/64	Yes	6/64	1.47	1/2" 30% CCS	5590	1/2" 30% CCS	3980	0.269	0.437	0.223	3570	1.630	1.782	2.227	2.227	3570
	300	37	19/64	Yes	6/64	1.53	1/2" 30% CCS	6260	1/2" 30% CCS	4330	0.228	0.366	0.217	3330	1.577	1.701	2.226	2.226	3330
	350	37	19/64	Yes	6/64	1.59	1/2" 30% CCS	6870	1/2" 30% CCS	4600	0.197	0.316	0.212	3130	1.536	1.640	2.226	2.226	3130
	400	37	19/64	Yes	6/64	1.63	1/2" 30% CCS	7450	1/2" 30% CCS	4860	0.172	0.276	0.208	2980	1.500	1.592	2.216	2.216	2980
	500	37	19/64	Yes	7/64	1.75	1/2" 30% CCS	8970	1/2" 30% CCS	5560	0.141	0.223	0.204	2830	1.454	1.524	2.198	2.198	2830

(1) AC resistance based on 65°C with allowance for stranding, skin effect and proximity effect.

(2) Dielectric constant assumed 6.0.

(3) Zero-sequence impedance based on return current both in the messenger and in 100 meter-ohm earth.

Table 9—60-Cycle Characteristics of Rubber-Insulated Neoprene-Jacketed Cables in Ducts

Voltage Class	Conductor Size	Stranding	Insulation Thickness	Shielding	Jacket Thickness	Diameter (Single Cable)	Duct Size(4)	COPPER CONDUCTOR					ALUMINUM CONDUCTOR					Shunt Capacitive(2) Reactance—Ohms Per Mile—Copper or Aluminum
									Positive Sequence		Zero (3) Sequence			Positive Sequence		Zero (3) Sequence		
								Weight Per 1000 Feet	Resistance(1) Ohms Per Mi.	Reactance Ohms Per Mi.	Resistance(1) Ohms Per Mi.	Reactance Ohms Per Mi.	Weight Per 1000 Feet	Resistance(1) Ohms Per Mi.	Reactance Ohms Per Mi.	Resistance(1) Ohms Per Mi.	Reactance Ohms Per Mi.	
5-kv Unshielded Cable Typical Circuit 2400 Volts	6	7	10/64	No	3/64	0.59	4″	212	2.52	0.458	2.856	3.856	156	4.13	0.458	4.35	3.856	....
	4	7	10/64	No	3/64	0.67	4″	297	1.58	0.429	1.906	3.836	207	2.58	0.429	2.84	3.836	....
	2	7	10/64	No	3/64	0.73	4″	395	1.00	0.398	1.306	3.811	252	1.64	0.398	1.89	3.811	....
	1	19	10/64	No	3/64	0.77	4″	462	0.791	0.375	1.096	3.794	283	1.29	0.375	1.56	3.794	....
	1/0	19	10/64	No	3/64	0.81	4″	544	0.655	0.361	0.925	3.783	317	1.03	0.361	1.30	3.783	....
	2/0	19	10/64	No	3/64	0.85	4″	645	0.501	0.344	0.793	3.772	359	0.816	0.344	1.08	3.772	....
	3/0	19	10/64	No	3/64	0.91	4″	772	0.402	0.330	0.685	3.764	412	0.644	0.330	0.919	3.764	....
	4/0	19	10/64	No	4/64	0.99	4″	958	0.318	0.311	0.608	3.754	504	0.518	0.311	0.790	3.754	....
	250	37	11/64	No	4/64	1.08	4″	1130	0.269	0.295	0.558	3.750	589	0.437	0.295	0.713	3.750	....
	300	37	11/64	No	4/64	1.13	4″	1300	0.228	0.283	0.512	3.744	660	0.366	0.283	0.642	3.744	....
	350	37	11/64	No	4/64	1.18	4″	1480	0.197	0.271	0.481	3.738	729	0.316	0.271	0.591	3.738	....
	400	37	11/64	No	4/64	1.23	4″	1650	0.172	0.261	0.457	3.734	794	0.276	0.261	0.553	3.734	....
	500	37	11/64	No	4/64	1.32	4″	2000	0.141	0.242	0.422	3.730	924	0.223	0.242	0.500	3.730	....
5-kv Shielded Cable Typical Circuit 4160 Volts	6	7	10/64	Yes	4/64	0.74	4″	344	2.52	0.454	2.856	3.863	288	4.13	0.454	4.35	3.863	4970
	4	7	10/64	Yes	4/64	0.79	4″	420	1.58	0.424	1.906	3.839	330	2.58	0.424	2.84	3.839	4320
	2	7	10/64	Yes	5/64	0.88	4″	557	1.00	0.393	1.306	3.817	414	1.64	0.393	1.89	3.817	3630
	1	19	10/64	Yes	5/64	0.92	4″	632	0.791	0.370	1.096	3.807	453	1.29	0.370	1.56	3.807	3330
	1/0	19	10/64	Yes	5/64	0.96	4″	721	0.655	0.355	0.925	3.795	494	1.03	0.355	1.30	3.795	3080
	2/0	19	10/64	Yes	5/64	1.00	4″	833	0.501	0.339	0.793	3.784	547	0.816	0.339	1.08	3.784	2830
	3/0	19	11/64	Yes	5/64	1.06	4″	970	0.402	0.322	0.685	3.775	610	0.644	0.322	0.919	3.775	2580
	4/0	19	10/64	Yes	5/64	1.11	4″	1140	0.318	0.305	0.608	3.766	685	0.518	0.305	0.790	3.766	2380
	250	37	11/64	Yes	5/64	1.20	4″	1320	0.269	0.291	0.558	3.761	783	0.437	0.291	0.713	3.761	2380
	300	37	11/64	Yes	6/64	1.29	4″	1650	0.228	0.276	0.512	3.758	906	0.366	0.276	0.642	3.758	2280
	350	37	11/64	Yes	6/64	1.34	4″	1740	0.197	0.264	0.481	3.754	985	0.316	0.264	0.591	3.754	2090
	400	37	11/64	Yes	6/64	1.39	4″	1920	0.172	0.253	0.457	3.750	1060	0.276	0.253	0.553	3.750	1890
	500	37	11/64	Yes	6/64	1.47	4″	2280	0.141	0.236	0.422	3.743	1210	0.223	0.236	0.500	3.743	1740
8-kv Shielded Cable Typical Circuit 4800 Volts	6	19	12/64	Yes	4/64	0.80	4″	385	2.52	0.445	2.856	3.867	329	4.13	0.445	4.35	3.867	5570
	4	19	12/64	Yes	5/64	0.88	4″	490	1.58	0.414	1.906	3.845	400	2.58	0.414	2.84	3.845	4780
	2	19	12/64	Yes	5/64	0.94	4″	602	1.00	0.384	1.306	3.821	459	1.64	0.384	1.89	3.821	4130
	1	19	12/64	Yes	5/64	0.98	4″	684	0.791	0.368	1.096	3.811	505	1.29	0.368	1.56	3.811	3780
	1/0	19	12/64	Yes	5/64	1.03	4″	774	0.655	0.352	0.925	3.801	547	1.03	0.352	1.30	3.801	3480
	2/0	19	12/64	Yes	5/64	1.08	4″	888	0.501	0.335	0.793	3.790	602	0.816	0.335	1.08	3.790	3230
	3/0	19	12/64	Yes	5/64	1.12	4″	1030	0.402	0.320	0.685	3.781	667	0.644	0.320	0.919	3.781	2930
	4/0	19	12/64	Yes	5/64	1.18	4″	1200	0.318	0.303	0.608	3.770	744	0.518	0.303	0.790	3.770	2740
	250	37	12/64	Yes	6/64	1.26	4″	1390	0.269	0.288	0.558	3.767	855	0.437	0.288	0.713	3.767	2540
	300	37	12/64	Yes	6/64	1.32	4″	1580	0.228	0.274	0.512	3.762	936	0.366	0.274	0.642	3.762	2340
	350	37	12/64	Yes	6/64	1.37	4″	1770	0.197	0.262	0.481	3.756	1020	0.316	0.262	0.591	3.756	2190
	400	37	12/64	Yes	6/64	1.41	4″	1960	0.172	0.252	0.457	3.752	1100	0.276	0.252	0.553	3.752	2090
	500	37	12/64	Yes	6/64	1.50	5″	2320	0.141	0.276	0.422	3.665	1250	0.223	0.276	0.500	3.665	1890
15-kv Shielded Cable Typical Circuit 13,800 Volts	6	19	19/64	Yes	5/64	1.05	4″	597	2.52	0.435	2.856	3.887	541	4.13	0.435	4.35	3.887	7150
	4	19	19/64	Yes	5/64	1.10	4″	685	1.58	0.405	1.906	3.863	595	2.58	0.405	2.84	3.863	6260
	2	19	19/64	Yes	5/64	1.16	4″	810	1.00	0.375	1.306	3.839	667	1.64	0.375	1.89	3.839	5460
	1	19	19/64	Yes	5/64	1.20	4″	894	0.791	0.359	1.096	3.829	715	1.29	0.359	1.56	3.829	5110
	1/0	19	19/64	Yes	6/64	1.27	4″	1040	0.655	0.342	0.925	3.821	813	1.03	0.342	1.30	3.821	4720
	2/0	19	19/64	Yes	6/64	1.32	4″	1160	0.501	0.325	0.793	3.810	878	0.816	0.325	1.08	3.810	4370
	3/0	19	19/64	Yes	6/64	1.37	4″	1310	0.402	0.309	0.685	3.803	954	0.644	0.309	0.919	3.803	4120
	4/0	19	19/64	Yes	6/64	1.43	4″	1500	0.318	0.292	0.608	3.792	1050	0.518	0.292	0.790	3.792	3770
	250	37	19/64	Yes	6/64	1.47	4″	1640	0.269	0.279	0.558	3.785	1100	0.437	0.279	0.713	3.785	3570
	300	37	19/64	Yes	6/64	1.53	5″	1860	0.228	0.306	0.512	3.698	1220	0.366	0.306	0.642	3.698	3330
	350	37	19/64	Yes	6/64	1.59	5″	2060	0.197	0.294	0.481	3.692	1310	0.316	0.294	0.591	3.692	3130
	400	37	19/64	Yes	6/64	1.63	5″	2250	0.172	0.284	0.457	3.688	1390	0.276	0.284	0.553	3.688	2980
	500	37	19/64	Yes	7/64	1.75	5″	2690	0.141	0.267	0.422	3.683	1610	0.223	0.267	0.500	3.683	2830

(1) A-C resistance based on 65°C. with allowance for stranding, skin effect and proximity effect.

(2) Dielectric constant assumed 6.0.

(3) Zero-sequence impedance based on all return current in 100 meter-ohm earth.

(4) Duct size assumed so that three cables fill not more than 40% of duct cross section. Random spacing assumed within duct.

Table 10—**Inductive** Reactance Spacing Factor (x_d) Ohms per Conductor per Mile

25 CYCLES

SEPARATION

Feet	INCHES											
	0	1	2	3	4	5	6	7	8	9	10	11
0	—	−0.1256	−0.0906	−0.0701	−0.0555	−0.0443	−0.0350	−0.0273	−0.0205	−0.0145	−0.0092	−0.0044
1	0	0.0040	0.0078	0.0113	0.0145	0.0176	0.0205	0.0232	0.0258	0.0283	0.0306	0.0329
2	0.0350	0.0371	0.0391	0.0410	0.0428	0.0446	0.0463	0.0480	0.0496	0.0511	0.0527	0.0541
3	0.0555	0.0569	0.0583	0.0596	0.0609	0.0621	0.0633	0.0645	0.0657	0 0668	0.0679	0.0690
4	0.0701	0.0711	0.0722	0.0732	0.0741	0.0751	0.0760	0.0770	0.0779	0.0788	0.0797	0.0805
5	0.0814	0.0822	0.0830	0.0838	0.0846	0.0854	0.0862	0.0869	0.0877	0.0884	0.0892	0.0899
6	0.0906	0.0913	0.0920	0.0927	0.0933	0.0940	0.0946	0.0953	0.0959	0.0965	0.0972	0.0978
7	0.0984	0.0990	0.0996	0.1002	0.1007	0.1013	0.1019	0.1024	0.1030	0.1035	0.1041	0.1046
8	0.1051											
9	0.1111											
10	0.1164											
11	0.1212											
12	0.1256											
13	0.1297											
14	0.1334											
15	0.1369											
16	0.1402											
17	0.1432											
18	0.1461											
19	0.1489											
20	0.1515											
21	0.1539											
22	0.1563											
23	0.1585											
24	0.1607											
25	0.1627											
26	0.1647											
27	0.1666											
28	0.1685											
29	0.1702											
30	0.1720											
31	0.1736											
32	0.1752											
33	0.1768											
34	0.1783											
35	0.1798											
36	0.1812											
37	0.1826											
38	0.1839											
39	0.1852											
40	0.1865											
41	0.1878											
42	0.1890											
43	0.1902											
44	0.1913											
45	0.1925											
46	0.1936											
47	0.1947											
48	0.1957											
49	0.1968											

x_d at
25 cycles
$x_d=0.1164 \log_{10} d$
d=separation, feet.

FUNDAMENTAL EQUATIONS

$$z_1=z_2=r_a+j(x_a+x_d)$$

$$z_o=r_a+r_e+j(x_a+x_e-2x_d)$$

50 CYCLES

SEPARATION

Feet	Inches											
	0	1	2	3	4	5	6	7	8	9	10	11
0	—	−0.2513	−0.1812	−0.1402	−0.1111	−0.0885	−0.0701	−0.0545	−0.0410	−0.0291	−0.0184	−0.0088
1	0	0.0081	0.0156	0.0226	0.0291	0.0352	0.0410	0.0465	0.0517	0.0566	0.0613	0.0658
2	0.0701	0.0742	0.0782	0.0820	0.0857	0.0892	0.0927	0.0960	0.0992	0.1023	0.1053	0.1082
3	0.1111	0.1139	0.1166	0.1192	0.1217	0.1242	0.1267	0.1291	0.1314	0.1337	0.1359	0.1380
4	0.1402	0.1423	0.1443	0.1463	0.1483	0.1502	0.1521	0.1539	0.1558	0.1576	0.1593	0.1610
5	0.1627	0.1644	0.1661	0.1677	0.1693	0.1708	0.1724	0.1739	0.1754	0.1769	0.1783	0.1798
6	0.1812	0.1826	0.1839	0.1853	0.1866	0.1880	0.1893	0.1906	0.1918	0.1931	0.1943	0.1956
7	0.1968	0.1980	0.1991	0.2003	0.2015	0.2026	0.2037	0.2049	0.2060	0.2071	0.2081	0.2092
8	0.2103											
9	0.2222											
10	0.2328											
11	0.2425											
12	0.2513											
13	0.2594											
14	0.2669											
15	0.2738											
16	0.2804											
17	0.2865											
18	0.2923											
19	0.2977											
20	0.3029											
21	0.3079											
22	0.3126											
23	0.3170											
24	0.3214											
25	0.3255											
26	0.3294											
27	0.3333											
28	0.3369											
29	0.3405											
30	0.3439											
31	0.3472											
32	0.3504											
33	0.3536											
34	0.3566											
35	0.3595											
36	0.3624											
37	0.3651											
38	0.3678											
39	0.3704											
40	0.3730											
41	0.3755											
42	0.3779											
43	0.3803											
44	0.3826											
45	0.3849											
46	0.3871											
47	0.3893											
48	0.3914											
49	0.3935											

x_d at
50 cycles
$x_d=0.2328 \log_{10} d$
d=separation, feet.

60 CYCLES

SEPARATION

Feet	**Inches**											
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0	—	−0.3015	−0.2174	−0.1682	−0.1333	−0.1062	−0.0841	−0.0654	−0.0492	−0.0349	−0.0221	−0.0106
1	0	0.0097	0.0187	0.0271	0.0349	0.0423	0.0492	0.0558	0.0620	0.0679	0.0735	0.0789
2	0.0841	0.0891	0.0938	0.0984	0.1028	0.1071	0.1112	0.1152	0.1190	0.1227	0.1264	0.1299
3	0.1333	0.1366	0.1399	0.1430	0.1461	0.1491	0.1520	0.1549	0.1577	0.1604	0.1631	0.1657
4	0.1682	0.1707	0.1732	0.1756	0.1779	0.1802	0.1825	0.1847	0.1869	0.1891	0.1912	0.1933
5	0.1953	0.1973	0.1993	0.2012	0.2031	0.2050	0.2069	0.2087	0.2105	0.2123	0.2140	0.2157
6	0.2174	0.2191	0.2207	0.2224	0.2240	0.2256	0.2271	0.2287	0.2302	0.2317	0.2332	0.2347
7	0.2361	0.2376	0.2390	0.2404	0.2418	0.2431	0.2445	0.2458	0.2472	0.2485	0.2498	0.2511
8	0.2523											
9	0.2666											
10	0.2794											
11	0.2910											
12	0.3015											
13	0.3112											
14	0.3202											
15	0.3286											
16	0.3364											
17	0.3438											
18	0.3507											
19	0.3573											
20	0.3635											
21	0.3694											
22	0.3751											
23	0.3805											
24	0.3856											
25	0.3906											
26	0.3953											
27	0.3999											
28	0.4043											
29	0.4086											
30	0.4127											
31	0.4167											
32	0.4205											
33	0.4243											
34	0.4279											
35	0.4314											
36	0.4348											
37	0.4382											
38	0.4414											
39	0.4445											
40	0.4476											
41	0.4506											
42	0.4535											
43	0.4564											
44	0.4592											
45	0.4619											
46	0.4646											
47	0.4672											
48	0.4697											
49	0.4722											

x_d at
60 cycles
$x_d=0.2794 \log_{10} d$
d=separation, feet.

Zero-Sequence Resistance and Inductive Reactance Factors (r_e, x_e)*

Ohms per Conductor per Mile

	Meter Ohm	FREQUENCY		
		25 Cycles	50 Cycles	60 Cycles
r_e	All	0.1192	0.2383	0.2860
	1	0.921	1.736	2.050
	5	1.043	1.980	2.343
	10	1.095	2.085	2.469
	50	1.217	2.329	2.762
x_e	**100†**	1.270	**2.434**	2.888
	500	1.392	2.679	3.181
	1000	1.444	2.784	3.307
	5000	1.566	3.028	3.600
	10 000	1.619	3.133	3.726

*From Formulas:
$r_e=0.004764f$
$x_e=0.006985f \log_{10} 4\,665\,600\frac{p}{f}$
where f=frequency
p=Resistivity (meter, ohm)

†This is an average value which may be used in the absence of definite information.

Table 11—Shunt Capacitive Reactance Spacing Factor (x_d') Megohms per Conductor per Mile

25 CYCLES

SEPARATION

Feet	INCHES											
	0	1	2	3	4	5	6	7	8	9	10	11
0	—	-0.1769	-0.1276	-0.0987	-0.0782	-0.0623	-0.0494	-0.0384	-0.0289	-0.0205	-0.0130	-0.0062
1	0	0.0057	0.0110	0.0159	0.0205	0.0248	0.0289	0.0327	0.0364	0.0398	0.0432	0.0463
2	0.0494	0.0523	0.0551	0.0577	0.0603	0.0628	0.0652	0.0676	0.0698	0.0720	0.0742	0.0762
3	0.0782	0.0802	0.0821	0.0839	0.0857	0.0875	0.0892	0.0909	0.0925	0.0941	0.0957	0.0972
4	0.0987	0.1002	0.1016	0.1030	0.1044	0.1058	0.1071	0.1084	0.1097	0.1109	0.1122	0.1134
5	0.1146	0.1158	0.1169	0.1181	0.1192	0.1203	0.1214	0.1225	0.1235	0.1246	0.1256	0.1266
6	0.1276	0.1286	0.1295	0.1305	0.1314	0.1324	0.1333	0.1342	0.1351	0.1360	0.1368	0.1377
7	0.1386	0.1394	0.1402	0.1411	0.1419	0.1427	0.1435	0.1443	0.1450	0.1458	0.1466	0.1473
8	0.1481											
9	0.1565											
10	0.1640											
11	0.1707											
12	0.1769											
13	0.1826											
14	0.1879											
15	0.1928											
16	0.1974											
17	0.2017											
18	0.2058											
19	0.2097											
20	0.2133											
21	0.2168											
22	0.2201											
23	0.2233											
24	0.2263											
25	0.2292											
26	0.2320											
27	0.2347											
28	0.2373											
29	0.2398											
30	0.2422											
31	0.2445											
32	0.2468											
33	0.2490											
34	0.2511											
35	0.2532											
36	0.2552											
37	0.2571											
38	0.2590											
39	0.2609											
40	0.2627											
41	0.2644											
42	0.2661											
43	0.2678											
44	0.2695											
45	0.2711											
46	0.2726											
47	0.2742											
48	0.2756											
49	0.2771											

x_d' at
25 cycles
$x_d' = .1640 \log_{10} d$
d=separation, feet.

FUNDAMENTAL EQUATIONS

$$x_1' = x_2' = x_a' + x_d'$$

$$x_o' = x_a' + x_e' - 2x_d'$$

50 CYCLES

SEPARATION

Feet	Inches											
	0	1	2	3	4	5	6	7	8	9	10	11
0	—	-0.0885	-0.0638	-0.0494	-0.0391	-0.0312	-0.0247	-0.0192	-0.0144	-0.0102	0.0065	-0.0031
1	0	0.0028	0.0055	0.0079	0.0102	0.0124	0.0144	0.0164	0.0182	0.0199	0.0216	0.0232
2	0.0247	0.0261	0.0275	0.0289	0.0302	0.0314	0.0326	0.0338	0.0349	0.0360	0.0371	0.0381
3	0.0391	0.0401	0.0410	0.0420	0.0429	0.0437	0.0446	0.0454	0.0463	0.0471	0.0478	0.0486
4	0.0494	0.0501	0.0508	0.0515	0.0522	0.0529	0.0535	0.0542	0.0548	0.0555	0.0561	0.0567
5	0.0573	0.0579	0.0585	0.0590	0.0596	0.0601	0.0607	0.0612	0.0618	0.0623	0.0628	0.0633
6	0.0638	0.0643	0.0648	0.0652	0.0657	0.0662	0.0666	0.0671	0.0675	0.0680	0.0684	0.0689
7	0.0693	0.0697	0.0701	0.0705	0.0709	0.0713	0.0717	0.0721	0.0725	0.0729	0.0733	0.0737
8	0.0740											
9	0.0782											
10	0.0820											
11	0.0854											
12	0.0885											
13	0.0913											
14	0.0940											
15	0.0964											
16	0.0987											
17	0.1009											
18	0.1029											
19	0.1048											
20	0.1067											
21	0.1084											
22	0.1100											
23	0.1116											
24	0.1131											
25	0.1146											
26	0.1160											
27	0.1173											
28	0.1186											
29	0.1199											
30	0.1211											
31	0.1223											
32	0.1234											
33	0.1245											
34	0.1255											
35	0.1266											
36	0.1276											
37	0.1286											
38	0.1295											
39	0.1304											
40	0.1313											
41	0.1322											
42	0.1331											
43	0.1339											
44	0.1347											
45	0.1355											
46	0.1363											
47	0.1371											
48	0.1378											
49	0.1386											

x_d' at
50 cycles
$x_d' = 0.08198 \log_{10} d$
d=separation, feet.

60 CYCLES

SEPARATION

Feet	Inches											
	0	1	2	3	4	5	6	7	8	9	10	11
0	—	-0.0737	-0.0532	-0.0411	-0.0326	-0.0260	-0.0206	-0.0160	-0.0120	-0.0085	-0.0054	-0.0026
1	0	0.0024	0.0046	0.0066	0.0085	0.0103	0.0120	0.0136	0.0152	0.0166	0.0180	0.0193
2	0.0206	0.0218	0.0229	0.0241	0.0251	0.0262	0.0272	0.0282	0.0291	0.0300	0.0309	0.0318
3	0.0326	0.0334	0.0342	0.0350	0.0357	0.0365	0.0372	0.0379	0.0385	0.0392	0.0399	0.0405
4	0.0411	0.0417	0.0423	0.0429	0.0435	0.0441	0.0446	0.0452	0.0457	0.0462	0.0467	0.0473
5	0.0478	0.0482	0.0487	0.0492	0.0497	0.0501	0.0506	0.0510	0.0515	0.0519	0.0523	0.0527
6	0.0532	0.0536	0.0540	0.0544	0.0548	0.0552	0.0555	0.0559	0.0563	0.0567	0.0570	0.0574
7	0.0577	0.0581	0.0584	0.0588	0.0591	0.0594	0.0598	0.0601	0.0604	0.0608	0.0611	0.0614
8	0.0617											
9	0.0652											
10	0.0683											
11	0.0711											
12	0.0737											
13	0.0761											
14	0.0783											
15	0.0803											
16	0.0823											
17	0.0841											
18	0.0858											
19	0.0874											
20	0.0889											
21	0.0903											
22	0.0917											
23	0.0930											
24	0.0943											
25	0.0955											
26	0.0967											
27	0.0978											
28	0.0989											
29	0.0999											
30	0.1009											
31	0.1019											
32	0.1028											
33	0.1037											
34	0.1046											
35	0.1055											
36	0.1063											
37	0.1071											
38	0.1079											
39	0.1087											
40	0.1094											
41	0.1102											
42	0.1109											
43	0.1116											
44	0.1123											
45	0.1129											
46	0.1136											
47	0.1142											
48	0.1149											
49	0.1155											

x_d' at
60 cycles
$x_d' = 0.06831 \log_{10} d$
d=separation, feet,

Zero-Sequence Shunt Capacitive Reactance Factor x_e'

Megohms per Conductor per Mile

Conductor Height Above Ground Feet	FREQUENCY		
	25 Cycles	50 Cycles	60 Cycles
10	0.640	0.320	0.267
15	0.727	0.363	0.303
20	0.788	0.394	0.328
25	0.836	0.418	0.348
30	0.875	0.437	0.364
40	0.936	0.468	0.390
50	0.984	0.492	0.410
60	1.023	0.511	0.426
70	1.056	0.528	0.440
80	1.084	0.542	0.452
90	1.109	0.555	0.462
100	1.132	0.566	0.472

$$x_e' = \frac{12.30}{f} \log_{10} 2h$$

where h=height above ground.
f=frequency.

TRANSFORMER EQUIVALENT CIRCUITS

The procedure to be followed in calculating the impedance values for a transformer equivalent circuit depends on the form of the original data, and whether the final values are to be expressed in ohms or per cent. Procedure I, below, is convenient for the simpler cases when the original impedances are expressed in per cent on a circuit base and the final values are to be expressed in per cent. Procedure II is generally recommended for the more complicated cases, particularly for the ones involving neutral impedances or series transformers.

Procedure I. The impedances of two- and three-winding transformers are normally given in per cent on a circuit kva base. With the basic data in this form it is convenient to calculate the equivalent-circuit impedance values directly in per cent. The equivalent circuits and equations for calculating the sequence quantities are given in Table 12 for 13 of the more common transformer connections. The following notation is employed in the table:

1. Terminal designations.
    Circuit 4—abc terminals.
    Circuit 5—a′b′c′ terminals.
    Circuit 6—a″b″c″ terminals.
2. Impedances.
    $Z_{45}\%$—impedance circuit 4 to circuit 5 in per cent on 3-phase rated kva of circuit 4.
    $Z_{46}\%$—impedance circuit 4 to circuit 6 in per cent on 3-phase rated kva of circuit 4.
    $Z_{56}\%$—impedance circuit 5 to circuit 6 in per cent on 3-phase rated kva of circuit 5.
    $Z_1\%$, $Z_0\%$, $Z_{H1}\%$, $Z_{M1}\%$, $Z_{L1}\%$, $Z_{H0}\%$, $Z_{M0}\%$, and $Z_{L0}\%$ are all in per cent on the 3-phase rated kva of circuit 4.
    U_4, U_5, and U_6 designate the 3-phase kva ratings of circuits 4, 5 and 6, respectively.

    The impedances can be converted from one base to another by the relations,

$$Z_{46}\% = \frac{U_4}{U_6} Z_{64}\%.$$

$$Z_{56}\% = \frac{U_5}{U_6} Z_{65}\%.$$

$$Z_{45}\% = \frac{U_4}{U_5} Z_{54}\%.$$

Procedure II. In many cases, particularly the ones involving neutral impedances or series transformers, less confusion results if the equivalent-circuit impedance values are calculated in ohms, rather than in per cent. However, as the basic data are normally in per cent, it is first necessary to convert to ohms using the following relations:

$$Z_{45} = \frac{10 Z_{45}\% E_4^2}{U_4}$$

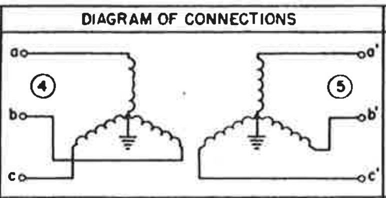
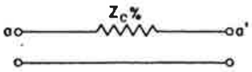
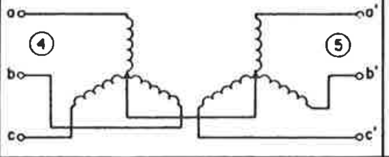
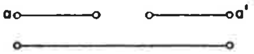
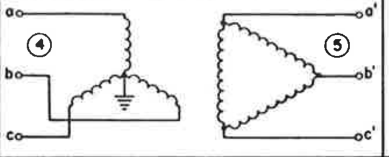
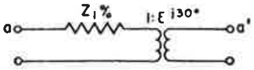
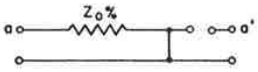
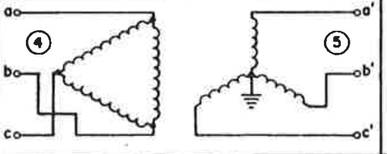
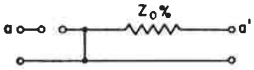
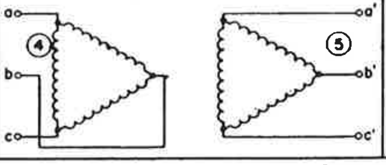
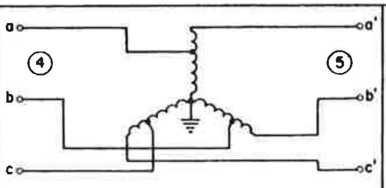
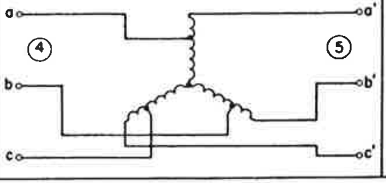
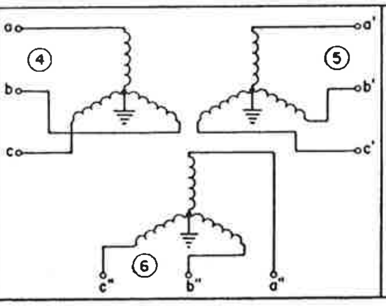
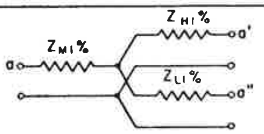
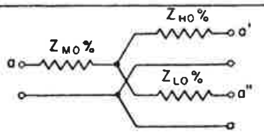
$$Z_{46} = \frac{10 Z_{45}\% E_4^2}{U_4}$$

$$Z_{56} = \frac{10 Z_{56}\% E_5^2}{U_5} \text{, where}$$

$Z_{45}\%$, $Z_{46}\%$, $Z_{56}\%$ are as defined in I.

E_4, E_5 and E_6 = line-to-line voltages, in kv, in circuits 4, 5 and 6, respectively.
U_4, U_5 and U_6 = 3-phase kva ratings of circuits 4, 5 and 6, respectively.
Z_{45} = impedance between circuits 4 and 5 in ohms on circuit 4 voltage base.
Z_{46} = impedance between circuits 4 and 6 in ohms on circuit 4 voltage base.
Z_{56} = impedance between circuits 5 and 6 in ohms on circuit 5 voltage base.

Table 12—Transformer Equivalent Circuits Used in Procedure I

DESCRIPTION	DIAGRAM OF CONNECTIONS	POSITIVE-SEQUENCE EQUIVALENT CIRCUIT	ZERO-SEQUENCE EQUIVALENT CIRCUIT
TWO-CIRCUIT TRANSFORMERS			
A-1 STAR/STAR SOLIDLY GROUNDED NEUTRALS (NOT FOR 3 PHASE CORE TYPE)		 $Z_1\% = Z_{45}\%$	 $Z_0\% = Z_{45}\%$
A-4 STAR/STAR NEUTRALS CONNECTED BUT UNGROUNDED (NOT FOR 3 PHASE CORE TYPE)		SAME AS A-1	 $Z_0\% = \infty$
A-5 STAR/DELTA SOLIDLY GROUNDED NEUTRAL		 $Z_1\% = Z_{45}\%$	 $Z_0\% = Z_{45}\%$
A-6 DELTA/STAR SOLIDLY GROUNDED NEUTRAL		SAME AS A-5	 $Z_0\% = Z_{45}\%$
A-7 DELTA-DELTA		SAME AS A-1	SAME AS A-4
TWO-CIRCUIT AUTOTRANSFORMERS			
B-1 STAR/STAR SOLIDLY GROUNDED NEUTRAL (NOT FOR 3 PHASE CORE TYPE)		SAME AS A-1	SAME AS A-1
B-3 STAR/STAR UNGROUNDED NEUTRAL (NOT FOR 3 PHASE CORE TYPE)		SAME AS A-1	SAME AS A-4
THREE-CIRCUIT TRANSFORMER			
C-1 STAR/STAR/ STAR SOLIDLY GROUNDED NEUTRALS		 $Z_{M1}\% = \frac{1}{2}\left[Z_{45}\% + Z_{46}\% - \frac{U_4}{U_5} Z_{56}\%\right]$ $Z_{L1}\% = \frac{1}{2}\left[Z_{46}\% + \frac{U_4}{U_5} Z_{56}\% - Z_{45}\%\right]$ $Z_{H1}\% = \frac{1}{2}\left[\frac{U_4}{U_5} Z_{56}\% + Z_{45}\% - Z_{46}\%\right]$	 $Z_{M0}\% = Z_{M1}\%$ $Z_{L0}\% = Z_{L1}\%$ $Z_{H0}\% = Z_{H1}\%$

Concluded on next page

Table 12—Transformer Equivalent Circuits Used in Procedure I (Concluded)

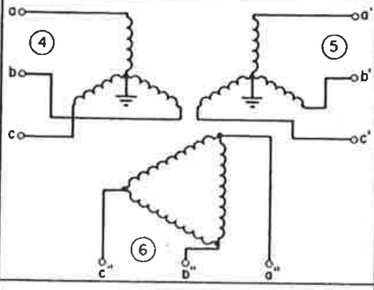
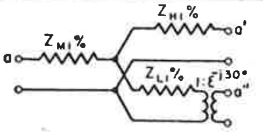
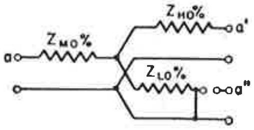
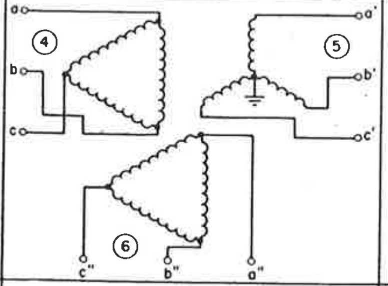
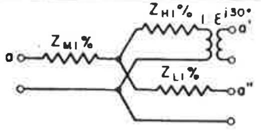
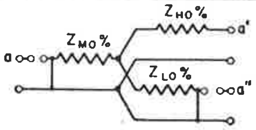
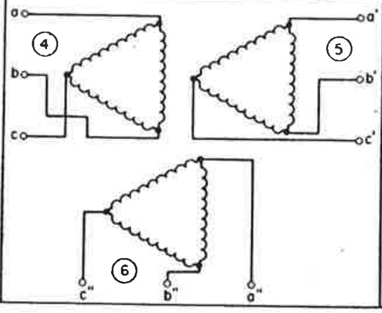
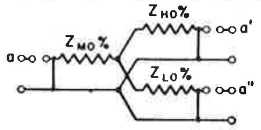
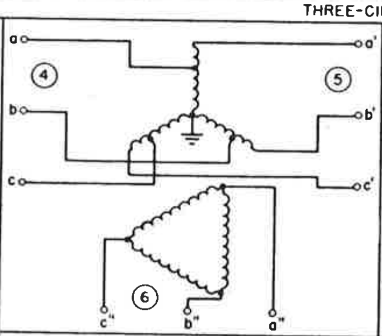
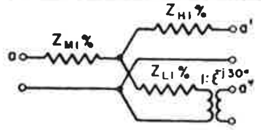
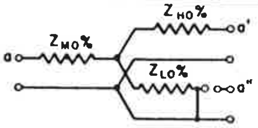
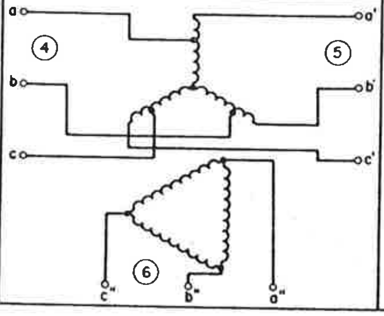
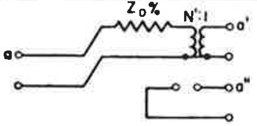
THREE-CIRCUIT TRANSFORMERS (CONT'D.)			
DESCRIPTION	DIAGRAM OF CONNECTIONS	POSITIVE-SEQUENCE EQUIVALENT CIRCUIT	ZERO SEQUENCE EQUIVALENT CIRCUIT
C-3 STAR/STAR/DELTA SOLIDLY GROUNDED NEUTRALS		 $Z_{M1}\% = \frac{1}{2}\left[Z_{45}\% + Z_{46}\% - \frac{U_4}{U_5} Z_{56}\%\right]$ $Z_{L1}\% = \frac{1}{2}\left[Z_{46}\% + \frac{U_4}{U_5} Z_{56}\% - Z_{45}\%\right]$ $Z_{H1}\% = \frac{1}{2}\left[\frac{U_4}{U_5} Z_{56}\% + Z_{45}\% - Z_{45}\%\right]$	 $Z_{M0}\% = Z_{M1}\%$ $Z_{L0}\% = Z_{L1}\%$ $Z_{H0}\% = Z_{H1}\%$
C-6 DELTA/STAR/DELTA SOLIDLY GROUNDED NEUTRAL		 $Z_{M1}\% = \frac{1}{2}\left[Z_{45}\% + Z_{46}\% - \frac{U_4}{U_5} Z_{56}\%\right]$ $Z_{L1}\% = \frac{1}{2}\left[Z_{46}\% + \frac{U_4}{U_5} Z_{56}\% - Z_{45}\%\right]$ $Z_{H1}\% = \frac{1}{2}\left[\frac{U_4}{U_5} Z_{56}\% + Z_{45}\% - Z_{46}\%\right]$	 $Z_{M0}\% = Z_{M1}\%$ $Z_{L0}\% = Z_{L1}\%$ $Z_{H0}\% = Z_{H1}\%$
C-7 DELTA/DELTA/DELTA		SAME AS C-1	 $Z_{M0}\% = Z_{M1}\%$ $Z_{L0}\% = Z_{L1}\%$ $Z_{H0}\% = Z_{H1}\%$
THREE-CIRCUIT AUTOTRANSFORMERS			
D-1 STAR/STAR/DELTA SOLIDLY GROUNDED NEUTRAL		 $Z_{M1}\% = \frac{1}{2}\left[Z_{45}\% + Z_{46}\% - \frac{U_4}{U_5} Z_{56}\%\right]$ $Z_{L1}\% = \frac{1}{2}\left[Z_{46}\% + \frac{U_4}{U_5} Z_{56}\% - Z_{45}\%\right]$ $Z_{H1}\% = \frac{1}{2}\left[\frac{U_4}{U_5} Z_{56}\% + Z_{45}\% - Z_{46}\%\right]$	 $Z_{M0}\% = Z_{M1}\%$ $Z_{L0}\% = Z_{L1}\%$ $Z_{H0}\% = Z_{H1}\%$
D-2 STAR/STAR/DELTA UNGROUNDED NEUTRAL		SAME AS D-1	 $N' = \frac{E_5}{E_4}$ $Z_0\% = N'(N'-1)\left[\frac{U_4}{U_5} Z_{56}\% - \frac{Z_{46}\%}{N'} + \frac{Z_{45}\%}{N'-1}\right]$

Table 13—Trigonometric Functions

Angle in degrees	Name of function	Value of function for each tenth of a degree										Angle in degrees	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9			0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	sin	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157	25	sin	0.4226	0.4242	0.4258	0.4274	0.4289	0.4305	0.4321	0.4337	0.4352	0.4368
	cos	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999		cos	0.9063	0.9056	0.9048	0.9041	0.9033	0.9026	0.9018	0.9011	0.9003	0.8996
	tan	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157		tan	0.4663	0.4684	0.4706	0.4727	0.4748	0.4770	0.4791	0.4813	0.4834	0.4856
1	sin	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332	26	sin	0.4384	0.4399	0.4415	0.4431	0.4446	0.4462	0.4478	0.4493	0.4509	0.4524
	cos	0.9998	0.9998	0.9998	0.9997	0.9997	0.9997	0.9996	0.9996	0.9995	0.9995		cos	0.8988	0.8980	0.8973	0.8965	0.8957	0.9849	0.8942	0.8934	0.8926	0.8918
	tan	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332		tan	0.4877	0.4899	0.4921	0.4942	0.4964	0.4986	0.5008	0.5029	0.5051	0.5073
2	sin	0.0349	0.0366	0.0384	0.0401	0.0419	0.0436	0.0454	0.0471	0.0488	0.0506	27	sin	0.4540	0.4555	0.4571	0.4586	0.4602	0.4617	0.4633	0.4648	0.4664	0.4679
	cos	0.9994	0.9993	0.9993	0.9992	0.9991	0.9990	0.9990	0.9989	0.9988	0.9987		cos	0.8910	0.8902	0.8894	0.8886	0.8878	0.8870	0.8862	0.8854	0.8846	0.8838
	tan	0.0349	0.0367	0.0384	0.0402	0.0419	0.0437	0.0454	0.0472	0.0489	0.0507		tan	0.5095	0.5117	0.5139	0.5161	0.5184	0.5206	0.5228	0.5250	0.5272	0.5295
3	sin	0.0523	0.0541	0.0558	0.0576	0.0593	0.0610	0.0628	0.0645	0.0663	0.0680	28	sin	0.4695	0.4710	0.4726	0.4741	0.4756	0.4772	0.4787	0.4802	0.4818	0.4833
	cos	0.9986	0.9985	0.9984	0.9983	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977		cos	0.8829	0.8821	0.8813	0.8805	0.8796	0.8788	0.8780	0.8771	0.8763	0.8755
	tan	0.0524	0.0542	0.0559	0.0577	0.0594	0.0612	0.0629	0.0647	0.0664	0.0682		tan	0.5317	0.5340	0.5362	0.5384	0.5407	0.5430	0.5452	0.5475	0.5498	0.5520
4	sin	0.0698	0.0715	0.0732	0.0750	0.0767	0.0785	0.0802	0.0819	0.0837	0.0854	29	sin	0.4848	0.4863	0.4879	0.4894	0.4909	0.4924	0.4939	0.4955	0.4970	0.4985
	cos	0.9976	0.9974	0.9973	0.9972	0.9971	0.9969	0.9968	0.9966	0.9965	0.9963		cos	0.8746	0.8738	0.8729	0.8721	0.8712	0.8704	0.8695	0.8686	0.8678	0.8669
	tan	0.0699	0.0717	0.0734	0.0752	0.0769	0.0787	0.0805	0.0822	0.0840	0.0857		tan	0.5543	0.5566	0.5589	0.5612	0.5635	0.5658	0.5681	0.5704	0.5727	0.5750
5	sin	0.0872	0.0889	0.0906	0.0924	0.0941	0.0958	0.0976	0.0993	0.1011	0.1028	30	sin	0.5000	0.5015	0.5030	0.5045	0.5060	0.5075	0.5090	0.5105	0.5120	0.5135
	cos	0.9962	0.9960	0.9959	0.9957	0.9956	0.9954	0.9952	0.9951	0.9949	0.9947		cos	0.8660	0.8652	0.8643	0.8634	0.8625	0.8616	0.8607	0.8599	0.8590	0.8581
	tan	0.0875	0.0892	0.0910	0.0928	0.0945	0.0963	0.0981	0.0998	0.1016	0.1033		tan	0.5774	0.5797	0.5820	0.5844	0.5867	0.5890	0.5914	0.5938	0.5961	0.5985
6	sin	0.1045	0.1063	0.1080	0.1097	0.1115	0.1132	0.1149	0.1167	0.1184	0.1201	31	sin	0.5150	0.5165	0.5180	0.5195	0.5210	0.5225	0.5240	0.5255	0.5270	0.5284
	cos	0.9945	0.9943	0.9942	0.9940	0.9938	0.9936	0.9934	0.9932	0.9930	0.9928		cos	0.8572	0.8563	0.8554	0.8545	0.8536	0.8526	0.8517	0.8508	0.8499	0.8490
	tan	0.1051	0.1069	0.1086	0.1104	0.1122	0.1139	0.1157	0.1175	0.1192	0.1210		tan	0.6009	0.6032	0.6056	0.6080	0.6104	0.6128	0.6152	0.6176	0.6200	0.6224
7	sin	0.1219	0.1236	0.1253	0.1271	0.1288	0.1305	0.1323	0.1340	0.1357	0.1374	32	sin	0.5299	0.5314	0.5329	0.5344	0.5358	0.5373	0.5388	0.5402	0.5417	0.5432
	cos	0.9925	0.9923	0.9921	0.9919	0.9917	0.9914	0.9912	0.9910	0.9907	0.9905		cos	0.8480	0.8471	0.8462	0.8453	0.8443	0.8434	0.8425	0.8415	0.8406	0.8396
	tan	0.1228	0.1246	0.1263	0.1281	0.1299	0.1317	0.1334	0.1352	0.1370	0.1388		tan	0.6249	0.6273	0.6297	0.6322	0.6346	0.6371	0.6395	0.6420	0.6445	0.6469
8	sin	0.1392	0.1409	0.1426	0.1444	0.1461	0.1478	0.1495	0.1513	0.1530	0.1547	33	sin	0.5446	0.5461	0.5476	0.5490	0.5505	0.5519	0.5534	0.5548	0.5563	0.5577
	cos	0.9903	0.9900	0.9898	0.9895	0.9893	0.9890	0.9888	0.9885	0.9882	0.9880		cos	0.8387	0.8377	0.8368	0.8358	0.8348	0.8339	0.8329	0.8320	0.8310	0.8300
	tan	0.1405	0.1423	0.1441	0.1459	0.1477	0.1495	0.1512	0.1530	0.1548	0.1566		tan	0.6494	0.6519	0.6544	0.6569	0.6594	0.6619	0.6644	0.6669	0.6694	0.6720
9	sin	0.1564	0.1582	0.1599	0.1616	0.1633	0.1650	0.1668	0.1685	0.1702	0.1719	34	sin	0.5592	0.5606	0.5621	0.5635	0.5650	0.5664	0.5678	0.5693	0.5707	0.5721
	cos	0.9877	0.9874	0.9871	0.9869	0.9866	0.9863	0.9860	0.9857	0.9854	0.9851		cos	0.8290	0.8281	0.8271	0.8261	0.8251	0.8241	0.8231	0.8221	0.8211	0.8202
	tan	0.1584	0.1602	0.1620	0.1638	0.1655	0.1673	0.1691	0.1709	0.1727	0.1745		tan	0.6745	0.6771	0.6796	0.6822	0.6847	0.6873	0.6899	0.6924	0.6950	0.6976
10	sin	0.1736	0.1754	0.1771	0.1788	0.1805	0.1822	0.1840	0.1857	0.1874	0.1891	35	sin	0.5736	0.5750	0.5764	0.5779	0.5793	0.5807	0.5821	0.5835	0.5850	0.5864
	cos	0.9848	0.9845	0.9842	0.9839	0.9836	0.9833	0.9829	0.9826	0.9823	0.9820		cos	0.8192	0.8181	0.8171	0.8161	0.8151	0.8141	0.8131	0.8121	0.8111	0.8100
	tan	0.1763	0.1781	0.1799	0.1817	0.1835	0.1853	0.1871	0.1890	0.1908	0.1926		tan	0.7002	0.7028	0.7054	0.7080	0.7107	0.7133	0.7159	0.7186	0.7212	0.7239
11	sin	0.1908	0.1925	0.1942	0.1959	0.1977	0.1994	0.2011	0.2028	0.2045	0.2062	36	sin	0.5878	0.5892	0.5906	0.5920	0.5934	0.5948	0.5962	0.5976	0.5990	0.6004
	cos	0.9816	0.9813	0.9810	0.9806	0.9803	0.9799	0.9796	0.9792	0.9789	0.9785		cos	0.8090	0.8080	0.8070	0.8059	0.8049	0.8039	0.8028	0.8018	0.8007	0.7997
	tan	0.1944	0.1962	0.1980	0.1998	0.2016	0.2035	0.2053	0.2071	0.2089	0.2107		tan	0.7265	0.7292	0.7319	0.7346	0.7373	0.7400	0.7427	0.7454	0.7481	0.7508
12	sin	0.2079	0.2096	0.2113	0.2130	0.2147	0.2164	0.2181	0.2198	0.2215	0.2233	37	sin	0.6018	0.6032	0.6046	0.6060	0.6074	0.6088	0.6101	0.6115	0.6129	0.6143
	cos	0.9781	0.9778	0.9774	0.9770	0.9767	0.9763	0.9759	0.9755	0.9751	0.9748		cos	0.7986	0.7976	0.7965	0.7955	0.7944	0.7934	0.7923	0.7912	0.7902	0.7891
	tan	0.2126	0.2144	0.2162	0.2180	0.2199	0.2217	0.2235	0.2254	0.2272	0.2290		tan	0.7536	0.7563	0.7590	0.7618	0.7646	0.7673	0.7701	0.7729	0.7757	0.7785
13	sin	0.2250	0.2267	0.2284	0.2300	0.2317	0.2334	0.2351	0.2368	0.2385	0.2402	38	sin	0.6157	0.6170	0.6184	0.6198	0.6211	0.6225	0.6239	0.6252	0.6266	0.6280
	cos	0.9744	0.9740	0.9736	0.9732	0.9728	0.9724	0.9720	0.9715	0.9711	0.9707		cos	0.7880	0.7869	0.7859	0.7848	0.7837	0.7826	0.7815	0.7804	0.7793	0.7782
	tan	0.2309	0.2327	0.2345	0.2364	0.2382	0.2401	0.2419	0.2438	0.2456	0.2475		tan	0.7813	0.7841	0.7869	0.7898	0.7926	0.7954	0.7983	0.8012	0.8040	0.8069
14	sin	0.2419	0.2436	0.2453	0.2470	0.2487	0.2504	0.2521	0.2538	0.2554	0.2571	39	sin	0.6293	0.6307	0.6320	0.6334	0.6347	0.6361	0.6374	0.6388	0.6401	0.6414
	cos	0.9703	0.9699	0.9694	0.9690	0.9686	0.9681	0.9677	0.9673	0.9668	0.9664		cos	0.7771	0.7760	0.7749	0.7738	0.7727	0.7716	0.7705	0.7694	0.7683	0.7672
	tan	0.2493	0.2512	0.2530	0.2549	0.2568	0.2586	0.2605	0.2623	0.2642	0.2661		tan	0.8098	0.8127	0.8156	0.8185	0.8214	0.8243	0.8273	0.8302	0.8332	0.8361
15	sin	0.2588	0.2605	0.2622	0.2639	0.2656	0.2672	0.2689	0.2706	0.2723	0.2740	40	sin	0.6428	0.6441	0.6455	0.6468	0.6481	0.6494	0.6508	0.6521	0.6534	0.6547
	cos	0.9659	0.9655	0.9650	0.9646	0.9641	0.9636	0.9632	0.9627	0.9622	0.9617		cos	0.7660	0.7649	0.7638	0.7627	0.7615	0.7604	0.7593	0.7581	0.7570	0.7559
	tan	0.2679	0.2698	0.2717	0.2736	0.2754	0.2773	0.2792	0.2811	0.2830	0.2849		tan	0.8391	0.8421	0.8451	0.8481	0.8511	0.8541	0.8571	0.8601	0.8632	0.8662
16	sin	0.2756	0.2773	0.2790	0.2807	0.2823	0.2840	0.2857	0.2874	0.2890	0.2907	41	sin	0.6561	0.6574	0.6587	0.6600	0.6613	0.6626	0.6639	0.6652	0.6665	0.6678
	cos	0.9613	0.9608	0.9603	0.9598	0.9593	0.9588	0.9583	0.9578	0.9573	0.9568		cos	0.7547	0.7536	0.7524	0.7513	0.7501	0.7490	0.7478	0.7466	0.7455	0.7443
	tan	0.2867	0.2886	0.2905	0.2924	0.2943	0.2962	0.2981	0.3000	0.3019	0.3038		tan	0.8693	0.8724	0.8754	0.8785	0.8816	0.8847	0.8878	0.8910	0.8941	0.8972
17	sin	0.2924	0.2940	0.2957	0.2974	0.2990	0.3007	0.3024	0.3040	0.3057	0.3074	42	sin	0.6691	0.6704	0.6717	0.6730	0.6743	0.6756	0.6769	0.6782	0.6794	0.6807
	cos	0.9563	0.9558	0.9553	0.9548	0.9542	0.9537	0.9532	0.9527	0.9521	0.9516		cos	0.7431	0.7420	0.7408	0.7396	0.7385	0.7373	0.7361	0.7349	0.7337	0.7325
	tan	0.3057	0.3076	0.3096	0.3115	0.3134	0.3153	0.3172	0.3191	0.3211	0.3230		tan	0.9004	0.9036	0.9067	0.9099	0.9131	0.9163	0.9195	0.9228	0.9260	0.9293
18	sin	0.3090	0.3107	0.3123	0.3140	0.3156	0.3173	0.3190	0.3206	0.3223	0.3239	43	sin	0.6820	0.6833	0.6845	0.6858	0.6871	0.6884	0.6896	0.6909	0.6921	0.6934
	cos	0.9511	0.9505	0.9500	0.9494	0.9489	0.9483	0.9478	0.9472	0.9466	0.9461		cos	0.7314	0.7302	0.7290	0.7278	0.7266	0.7254	0.7242	0.7230	0.7218	0.7206
	tan	0.3249	0.3269	0.3288	0.3307	0.3327	0.3346	0.3365	0.3385	0.3404	0.3424		tan	0.9325	0.9358	0.9391	0.9424	0.9457	0.9490	0.9523	0.9556	0.9590	0.9623
19	sin	0.3256	0.3272	0.3289	0.3305	0.3322	0.3338	0.3355	0.3371	0.3387	0.3404	44	sin	0.6947	0.6959	0.6972	0.6984	0.6997	0.7009	0.7022	0.7034	0.7046	0.7059
	cos	0.9455	0.9449	0.9444	0.9438	0.9432	0.9426	0.9421	0.9415	0.9409	0.9403		cos	0.7193	0.7181	0.7169	0.7157	0.7145	0.7133	0.7120	0.7108	0.7096	0.7083
	tan	0.3443	0.3463	0.3482	0.3502	0.3522	0.3541	0.3561	0.3581	0.3600	0.3620		tan	0.9657	0.9691	0.9725	0.9759	0.9793	0.9827	0.9861	0.9896	0.9930	0.9965
20	sin	0.3420	0.3437	0.3453	0.3469	0.3486	0.3502	0.3518	0.3535	0.3551	0.3567	45	sin	0.7071	0.7083	0.7096	0.7108	0.7120	0.7133	0.7145	0.7157	0.7169	0.7181
	cos	0.9397	0.9391	0.9385	0.9379	0.9373	0.9367	0.9361	0.9354	0.9348	0.9342		cos	0.7071	0.7059	0.7046	0.7034	0.7022	0.7009	0.6997	0.6984	0.6972	0.6959
	tan	0.3640	0.3659	0.3679	0.3699	0.3719	0.3739	0.3759	0.3779	0.3799	0.3819		tan	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319
21	sin	0.3584	0.3600	0.3616	0.3633	0.3649	0.3665	0.3681	0.3697	0.3714	0.3730	46	sin	0.7193	0.7206	0.7218	0.7230	0.7242	0.7254	0.7266	0.7278	0.7290	0.7302
	cos	0.9336	0.9330	0.9323	0.9317	0.9311	0.9304	0.9298	0.9291	0.9285	0.9278		cos	0.6947	0.6934	0.6921	0.6909	0.6896	0.6884	0.6871	0.6858	0.6845	0.6833
	tan	0.3839	0.3859	0.3879	0.3899	0.3919	0.3939	0.3959	0.3979	0.4000	0.4020		tan	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686
22	sin	0.3746	0.3762	0.3778	0.3795	0.3811	0.3827	0.3843	0.3859	0.3875	0.3891	47	sin	0.7314	0.7325	0.7337	0.7349	0.7361	0.7373	0.7385	0.7396	0.7408	0.7420
	cos	0.9272	0.9265	0.9259	0.9252	0.9245	0.9239	0.9232	0.9225	0.9219	0.9212		cos	0.6820	0.6807	0.6794	0.6782	0.6769	0.6756	0.6743	0.6730	0.6717	0.6704
	tan	0.4040	0.4061	0.4081	0.4101	0.4122	0.4142	0.4163	0.4183	0.4204	0.4224		tan	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067
23	sin	0.3907	0.3923	0.3939	0.3955	0.3971	0.3987	0.4003	0.4019	0.4035	0.4051	48	sin	0.7431	0.7443	0.7455	0.7466	0.7478	0.7490	0.7501	0.7513	0.7524	0.7536
	cos	0.9205	0.9198	0.9191	0.9184	0.9178	0.9171	0.9164	0.9157	0.9150	0.9143		cos	0.6691	0.6678	0.6665	0.6652	0.6639	0.6626	0.6613	0.6600	0.6587	0.6574
	tan	0.4245	0.4265	0.4286	0.4307	0.4327	0.4348	0.4369	0.4390	0.4411	0.4431		tan	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463
24	sin	0.4067	0.4083	0.4099	0.4115	0.4131	0.4147	0.4163	0.4179	0.4195	0.4210	49	sin	0.7547	0.7559	0.7570	0.7581	0.7593	0.7604	0.7615	0.7627	0.7638	0.7649
	cos	0.9135	0.9128	0.9121	0.9114	0.9107	0.9100	0.9092	0.9085	0.9078	0.9070		cos	0.6561	0.6547	0.6534	0.6521	0.6508	0.6494	0.6481	0.6468	0.6455	0.6441
	tan	0.4452	0.4473	0.4494	0.4515	0.4536	0.4557	0.4578	0.4599	0.4621	0.4642		tan	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875

Concluded on next page

Table 13—Trigonometric Functions—Concluded

Angle in degrees	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
50	sin	0.7660	0.7672	0.7683	0.7694	0.7705	0.7716	0.7727	0.7738	0.7749	0.7760
	cos	0.6428	0.6414	0.6401	0.6388	0.6374	0.6361	0.6347	0.6334	0.6320	0.6307
	tan	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305
51	sin	0.7771	0.7782	0.7793	0.7804	0.7815	0.7826	0.7837	0.7848	0.7859	0.7869
	cos	0.6293	0.6280	0.6266	0.6252	0.6239	0.6225	0.6211	0.6198	0.6184	0.6170
	tan	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753
52	sin	0.7880	0.7891	0.7902	0.7912	0.7923	0.7934	0.7944	0.7955	0.7965	0.7976
	cos	0.6157	0.6143	0.6129	0.6115	0.6101	0.6088	0.6074	0.6060	0.6046	0.6032
	tan	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3175	1.3222
53	sin	0.7986	0.7997	0.8007	0.8018	0.8028	0.8039	0.8049	0.8059	0.8070	0.8080
	cos	0.6018	0.6004	0.5990	0.5976	0.5962	0.5948	0.5934	0.5920	0.5906	0.5892
	tan	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713
54	sin	0.8090	0.8100	0.8111	0.8121	0.8131	0.8141	0.8151	0.8161	0.8171	0.8181
	cos	0.5878	0.5864	0.5850	0.5835	0.5821	0.5807	0.5793	0.5779	0.5764	0.5750
	tan	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4229
55	sin	0.8192	0.8202	0.8211	0.8221	0.8231	0.8241	0.8251	0.8261	0.8271	0.8281
	cos	0.5736	0.5721	0.5707	0.5693	0.5678	0.5664	0.5650	0.5635	0.5621	0.5606
	tan	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770
56	sin	0.8290	0.8300	0.8310	0.8320	0.8329	0.8339	0.8348	0.8358	0.8368	0.8377
	cos	0.5592	0.5577	0.5563	0.5548	0.5534	0.5519	0.5505	0.5490	0.5476	0.5461
	tan	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5340
57	sin	0.8387	0.8396	0.8406	0.8415	0.8425	0.8434	0.8443	0.8453	0.8462	0.8471
	cos	0.5446	0.5432	0.5417	0.5402	0.5388	0.5373	0.5358	0.5344	0.5329	0.5314
	tan	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941
58	sin	0.8480	0.8490	0.8499	0.8508	0.8517	0.8526	0.8536	0.8545	0.8554	0.8563
	cos	0.5299	0.5284	0.5270	0.5255	0.5240	0.5225	0.5210	0.5195	0.5180	0.5165
	tan	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6577
59	sin	0.8572	0.8581	0.8590	0.8599	0.8607	0.8616	0.8625	0.8634	0.8643	0.8652
	cos	0.5150	0.5135	0.5120	0.5105	0.5090	0.5075	0.5060	0.5045	0.5030	0.5015
	tan	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251
60	sin	0.8660	0.8669	0.8678	0.8686	0.8695	0.8704	0.8712	0.8721	0.8729	0.8738
	cos	0.5000	0.4985	0.4970	0.4955	0.4939	0.4924	0.4909	0.4894	0.4879	0.4863
	tan	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966
61	sin	0.8746	0.8755	0.8763	0.8771	0.8780	0.8788	0.8796	0.8805	0.8813	0.8821
	cos	0.4848	0.4833	0.4818	0.4802	0.4787	0.4772	0.4756	0.4741	0.4726	0.4710
	tan	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728
62	sin	0.8829	0.8838	0.8846	0.8854	0.8862	0.8870	0.8878	0.8886	0.8894	0.8902
	cos	0.4695	0.4679	0.4664	0.4648	0.4633	0.4617	0.4602	0.4586	0.4571	0.4555
	tan	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542
63	sin	0.8910	0.8918	0.8926	0.8934	0.8942	0.8949	0.8957	0.8965	0.8973	0.8980
	cos	0.4540	0.4524	0.4509	0.4493	0.4478	0.4462	0.4446	0.4431	0.4415	0.4399
	tan	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413
64	sin	0.8988	0.8996	0.9003	0.9011	0.9018	0.9026	0.9033	0.9041	0.9048	0.9056
	cos	0.4384	0.4368	0.4352	0.4337	0.4321	0.4305	0.4289	0.4274	0.4258	0.4242
	tan	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348
65	sin	0.9063	0.9070	0.9078	0.9085	0.9092	0.9100	0.9107	0.9114	0.9121	0.9128
	cos	0.4226	0.4210	0.4195	0.4179	0.4163	0.4147	0.4131	0.4115	0.4099	0.4083
	tan	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355
66	sin	0.9135	0.9143	0.9150	0.9157	0.9164	0.9171	0.9178	0.9184	0.9191	0.9198
	cos	0.4067	0.4051	0.4035	0.4019	0.4003	0.3987	0.3971	0.3955	0.3939	0.3923
	tan	2.2460	2.2566	2.2673	2.2781	2.2889	2.2998	2.3109	2.3220	2.3332	2.3445
67	sin	0.9205	0.9212	0.9219	0.9225	0.9232	0.9239	0.9245	0.9252	0.9259	0.9265
	cos	0.3907	0.3891	0.3875	0.3859	0.3843	0.3827	0.3811	0.3795	0.3778	0.3762
	tan	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627
68	sin	0.9272	0.9278	0.9285	0.9291	0.9298	0.9304	0.9311	0.9317	0.9323	0.9330
	cos	0.3746	0.3730	0.3714	0.3697	0.3681	0.3665	0.3649	0.3633	0.3616	0.3600
	tan	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916
69	sin	0.9336	0.9342	0.9348	0.9354	0.9361	0.9367	0.9373	0.9379	0.9385	0.9391
	cos	0.3584	0.3567	0.3551	0.3535	0.3518	0.3502	0.3486	0.3469	0.3453	0.3437
	tan	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326
70	sin	0.9397	0.9403	0.9409	0.9415	0.9421	0.9426	0.9432	0.9438	0.9444	0.9449
	cos	0.3420	0.3404	0.3387	0.3371	0.3355	0.3338	0.3322	0.3305	0.3289	0.3272
	tan	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878
71	sin	0.9455	0.9461	0.9466	0.9472	0.9478	0.9483	0.9489	0.9494	0.9500	0.9505
	cos	0.3256	0.3239	0.3223	0.3206	0.3190	0.3173	0.3156	0.3140	0.3123	0.3107
	tan	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	3.0415	3.0595
72	sin	0.9511	0.9516	0.9521	0.9527	0.9532	0.9537	0.9542	0.9548	0.9553	0.9558
	cos	0.3090	0.3074	0.3057	0.3040	0.3024	0.3007	0.2990	0.2974	0.2957	0.2940
	tan	3.0777	3.0961	3.1146	3.1334	3.1524	3.1716	3.1910	3.2106	3.2305	3.2506
73	sin	0.9563	0.9568	0.9573	0.9578	0.9583	0.9588	0.9593	0.9598	0.9603	0.9608
	cos	0.2924	0.2907	0.2890	0.2874	0.2857	0.2840	0.2823	0.2807	0.2790	0.2773
	tan	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646
74	sin	0.9613	0.9617	0.9622	0.9627	0.9632	0.9636	0.9641	0.9646	0.9650	0.9655
	cos	0.2756	0.2740	0.2723	0.2706	0.2689	0.2672	0.2656	0.2639	0.2622	0.2605
	tan	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062
75	sin	0.9659	0.9664	0.9668	0.9673	0.9677	0.9681	0.9686	0.9690	0.9694	0.9699
	cos	0.2588	0.2571	0.2554	0.2538	0.2521	0.2504	0.2487	0.2470	0.2453	0.2436
	tan	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812
76	sin	0.9703	0.9707	0.9711	0.9715	0.9720	0.9724	0.9728	0.9732	0.9736	0.9740
	cos	0.2419	0.2402	0.2385	0.2368	0.2351	0.2334	0.2317	0.2300	0.2284	0.2267
	tan	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972
77	sin	0.9744	0.9748	0.9751	0.9755	0.9759	0.9763	0.9767	0.9770	0.9774	0.9778
	cos	0.2250	0.2233	0.2215	0.2198	0.2181	0.2164	0.2147	0.2130	0.2113	0.2096
	tan	4.3315	4.3662	4.4015	4.4373	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646
78	sin	0.9781	0.9785	0.9789	0.9792	0.9796	0.9799	0.9803	0.9806	0.9810	0.9813
	cos	0.2079	0.2062	0.2045	0.2028	0.2911	0.1994	0.1977	0.1959	0.1942	0.1925
	tan	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970
79	sin	0.9816	0.9820	0.9823	0.9826	0.9829	0.9833	0.9836	0.9839	0.9842	0.9845
	cos	0.1908	0.1891	0.1874	0.1857	0.1840	0.1822	0.1805	0.1788	0.1771	0.1754
	tan	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140
80	sin	0.9848	0.9851	0.9854	0.9857	0.9860	0.9863	0.9866	0.9869	0.9871	0.9874
	cos	0.1736	0.1719	0.1702	0.1685	0.1668	0.1650	0.1633	0.1616	0.1599	0.1582
	tan	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432
81	sin	0.9877	0.9880	0.9882	0.9885	0.9888	0.9890	0.9893	0.9895	0.9898	0.9900
	cos	0.1564	0.1547	0.1530	0.1513	0.1495	0.1478	0.1461	0.1444	0.1426	0.1409
	tan	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264
82	sin	0.9903	0.9905	0.9907	0.9910	0.9912	0.9914	0.9917	0.9919	0.9921	0.9923
	cos	0.1392	0.1374	0.1357	0.1340	0.1323	0.1305	0.1288	0.1271	0.1253	0.1236
	tan	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285
83	sin	0.9925	0.9928	0.9930	0.9932	0.9934	0.9936	0.9938	0.9940	0.9942	0.9943
	cos	0.1219	0.1201	0.1184	0.1167	0.1149	0.1132	0.1115	0.1097	0.1080	0.1063
	tan	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572
84	sin	0.9945	0.9947	0.9949	0.9951	0.9952	0.9954	0.9956	0.9957	0.9959	0.9960
	cos	0.1045	0.1028	0.1011	0.0993	0.0976	0.0958	0.0941	0.0924	0.0906	0.0889
	tan	9.5144	9.6768	9.8448	10.019	10.199	10.385	10.579	10.780	10.988	11.025
85	sin	0.9962	0.9963	0.9965	0.9966	0.9968	0.9969	0.9971	0.9972	0.9973	0.9974
	cos	0.0872	0.0854	0.0837	0.0819	0.0802	0.0785	0.0767	0.0750	0.0732	0.0715
	tan	11.430	11.665	11.909	12.163	12.429	12.706	12.996	13.300	13.617	13.951
86	sin	0.9976	0.9977	0.9978	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9985
	cos	0.0698	0.0680	0.0663	0.0645	0.0628	0.0610	0.0593	0.0576	0.0558	0.0541
	tan	14.301	14.669	15.056	15.464	15.895	16.350	16.832	17.343	17.886	18.465
87	sin	0.9986	0.9987	0.9988	0.9989	0.9990	0.9990	0.9991	0.9992	0.9993	0.9993
	cos	0.0523	0.0506	0.0488	0.0471	0.0454	0.0436	0.0419	0.0401	0.0384	0.0366
	tan	19.081	19.740	20.447	21.205	22.022	22.904	23.859	24.898	26.031	27.272
88	sin	0.9994	0.9995	0.9995	0.9996	0.9996	0.9997	0.9997	0.9997	0.9998	0.9998
	cos	0.0349	0.0332	0.0314	0.0297	0.0279	0.0262	0.0244	0.0227	0.0209	0.0192
	tan	28.636	30.145	31.821	33.694	35.801	38.189	40.917	44.066	47.740	52.081
89	sin	0.9998	0.9999	0.9999	0.9999	0.9999	1.000	1.000	1.000	1.000	1.000
	cos	0.0175	0.0157	0.0140	0.0122	0.0105	0.0087	0.0070	0.0052	0.0035	0.0017
	tan	57.290	63.657	71.615	81.847	95.490	114.59	143.24	190.98	286.48	572.96

Law of sines

$$\frac{a}{Sin\ A}=\frac{b}{Sin\ B}=\frac{c}{Sin\ C}$$

Law of cosines

$$a^2=b^2+c^2-2\ bc\ Cos\ A$$

Table 14—Residential Underground Distribution Design Practice of 28 Electric Light and Power Companies*

COMPANY	Appalachian Elec Pwr	Boston Edison	California Elec Pwr	Public Service Div. Commonwealth Edison	Public Service Div. Commonwealth Edison	Consumers Pwr	Dallas Pwr & Light	Dayton Pwr & Light	Detroit Edison	Company "X"
Type of area	Residential, single	Residential	Deluxe residential	3,000 unit devel'm'ts	Residential, single	Deluxe single resid's	Deluxe single resid's	Deluxe single resic.'s	Deluxe residential	Resid'l single; group
Primary										
Voltage, kv	7.2/12.5	2.4/4.16	4.8 and 4.16	2.4/4.16	2.4/4.16	2.4/4.16	7.62/13.2	4	4.8 open delta	4.16
Duct or buried	Buried, screened soil	Duct	3-in. non-met duct No concrete	Dir burial	Dir burial	Dir burial	Dir burial	Conduit; manhole	Dir burial	Duct
Depth, inches	42	36	30 Min.	36–42	36–42	30	30	....	36	42 Min.
Cover	Creo board over sec.	Concrete; earth	Earth; concrete at crossings	Soil	Soil	Sand; concrete blocks	Screened earth; slab	....	Crown tile	....
Location	Side of street	Street	Street	Street, inside curb	Usually parkways	Public drives	Rear lot	Parkway; lot	Rear lot	Street
Manhole or handhole	None	Manholes	Pri junct box, concrete	None	None	None	None	Manholes	None	Manholes
Type system	Radial	Radial	Radial	Combin. loop; throwover	Radial taps from OH	Loop	Radial	Radial	Primary ring	Radial
Sectionalizing	None]	None	Positect cutouts in manholes; tsf enclo	Porcelain discon in tsf enclo	Porcelain discon in tsf enclo	....	UG pri sect'liz'd manually at tsf bank	Usually none	Discon pothead in kiosk	Yes, with emerg transfer on primary
Cable Description										
Size & conductor	No. 6 Cu	No. 4 Cu	1/c 2/0; No. 2; 6	2/c conc No. 6; 1/0 Cu	2/c conc No. 6; 1/0 Cu	No. 6 Cu	No. 6 Cu	1/c No. 2 Cu	3/c No. 2	2/c; 4/c No. 6 Cu
Insulation	11/64 ozone resist, shielded	5/64 ozone; resist	10/64 syn 5-kv sh'lded	9/64; 10/64 corona resist rubber	9/64 corona resist rubber	3/64 corona resist	Part VC lead sheath; part rubber	16/64 VC 15 kv	7/64 VC	Paper; lead
Jacket	5/64 Neoprene	6/64	4/64; 5/64 Neoprene	3/64 Neoprene	3/64 Neoprene	3/64 Neoprene	Steel; jute, Neoprene	Lead	5/64 lead; Neoprene	....
Neut cond	Separate common	Sheath neut	No. 2; 4 bare	7 No. 14; 20 No. 14 bare Cu concen over jacket	7 No. 14 bare Cu concen over jacket	7 No. 14 tinned Cu armor wires, spiral	No. 6 bare medium HD common	No. 2 WP common	None	None
Lightning Protection	At OH connect only	At OH connect only	At OH connect only	At OH & tsf connect.	At OH connect;tsf	At OH connec only	At OH connec only	At OH connec only	At tsf	At OH connec only
Cable termination	Rl cable connect at oil cutout in tsf enclo	At tsf tank wiping sleeve	Shield stripped back; gr'nded	Cable end left clear	Cable end left clear	Armor stripped back; grounded	With stress cone at tsf terminal	Wiping sleeve in tsf or oil cutout	Directly to ts	Potheads at term pole Wiping sleeves at tsf
Secondary Mains										
Voltage	120/240, 3-w	120/240	120/240	120/240	120/240	120/240	No secondaries	120/240	120/240 3-ϕ	120/240 3-ϕ
Duct or buried	Dir buried, screened soil, board cover	Fiber pipe in fine dirt; filled with comp'ned, plank cover	2-in. duct	Dir burial	Dir burial	Dir burial	120/240 v 3-ϕ 4-w services from tsf	Duct	Dir burial	Ducts
Depth, inches	36	30	30	36 or 6 above pri	36 or 6 above pri	30	....	Duct bank with pri	36	42 min
Location	Side of street	Street	Street	Street	Street	Separate trench	....	Duct bank with pri	Rear lot lines	Street
In primary trench	Yes	Some	Some	Yes, if on same route	Yes, if on same route	No	....	Yes	Yes	Same duct bank with pri and street light
Cable Description										
Size & conductor	4/0 Cu	1/0 to 4/0 Cu	....	No. 2 Cu	2/0 Cu	1/0 Cu	....	No. 1/0; 300 MCM Cu	4/c 4/0; 4/c 1/0	2-1/c 250 MCM, 2-1/c 500 MCM
Insulation	5/64 RHRW	5/64 Rubber	4/64 thermo-plastic or RWRH Neoprene	4/64 RH	4/64 RH	5/64 RHRW	....	RHRW Neoprene jacket	3/64 RHRW	Paper; lead
Jacket	4/64 Neoprene	Double braid	....	3/64 Neoprene	3/64 Neoprene	3/64 Neoprene	....	Neoprene IPCEA	3/64 Neoprene	....
Neut cond	2/0 bare	No. 4-1/0 bare tinned Cu	No. 4 bare Cu	No. 2 bare Cu	No. 2 bare Cu	....	Common neut	Common	4/0; 1/0 rubber; Neoprene	Sep'te neut 4/0 bare
Services										
Size & differences from main	No. 7 Min.	2 No. 6 in iron pipe R&L; No. 6 bare Cu	As required by load	2 No. 8 insula; jacket same	3-w No. 2 recom. insula; jacket same	....	120/240-v 3-ϕ 4-w	Similar	Installed by customer	2-1/c No. 3 paper; lead; No. 3 bare
Owned by customer	Yes	Yes	2/3	Yes	Yes	Yes	Yes	Yes	Yes	Conduit cust owned except for multiple dwel
Connection arrang'm't	Crab joint in 30-in. concrete handhole	To main in buried wood box filled with comp.	Dir from tsf sec bus; bur'd sec serv box	Dir. No box; pedestal	Dir. No box; pedestal	To fused terminal in junction box	Enter top of tsf housing conn to sec bus	In manholes	Through fuses at serv pedestal	Jointed in manholes
Transformers										
Type	OH conv, sealed tank	Subway	OH CSP, no arrester	OH CSP	OH CSP usually	Conv	CSP OH type	Usually subway	SP OH type	Subway
Size, kva	25–37½	25–50	5–50	15–50	37½ Max	....	Max. 3-ph bank 1-25; 1-15	25-50 /	5-50	25-100
Enclosure	48 in bur'd conc pipe	Manhole	Corrugated steel on conc base; semi-bur'd	Conc tile above or part above grd	Conc tile above or part above grd	Semi-bur'd conc box	Semi-buried vault	Manholes	Kiosk	Manholes
Sectionalizing and switching at tsf	None	None	Sec. switching	Usually	If needed	Galv cover Isolating links	Pri manually sect'lized at tsf bank	None. Pri manually sect'lized at tsf bank	Sec fuses only	Oil cutout at tsf
Street Lighting	Control cable in trench with sec	In split fiber duct with sec	Same trench	Independent	Independent	None yet	None	Separate	Pedestal to light via property line	Series cir in duct bank with pri; sec
Telephone Cable	....	Independent	....	Independent	Independent	....	....	Adjacent	Same trench	Separate
Cost Ratio, UG/OH	3.2:1	....	2.5 to 5:1	2 or 3:1	3.5 to 5.5:1	3.5:1	2.5:1	....	2.5 to 5:1	Depends on conditions

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Table 14—Residential Underground Distribution Design Practice of 28 Electric Light and Power Companies*—Continued

COMPANY	Hawaiian Electric	Iowa Electric L&P	Jackson, Tenn., Municipal System		Kansas City P & L		Long Island Lighting	Los Angeles Dept. W & P	New Orleans P S	Northern States Pwr
			1949	1951	1931	1951				
Type of area	Deluxe single resid's	Apartments	Single residences	Single residences	Deluxe single resid's	Single resid ranch	Deluxe single resid's	Single residences	Deluxe single resid's	Deluxe single resid's
Primary										
Voltage, kv	2.4/4.16	2.4/4.16	2.4/4.16	7.2/12.5	2.4/4.16	2.4/4.16	7.62/13 2.4/4.16	4.8	13.8	2.4/4.16
Duct or buried	Dir burial multiple cables	Dir burial	2-in. Transite	Dir burial	Dir burial	Dir burial	2.3 delta Conc duct	Transite	Duct; manhole system	Ducts; dir burial
Depth, inches	24	30	30	24-30	36	36	24	30	36	24–36
Cover	Screened soil; slab	4-in. sand; creo plank	Old crossarms	Old crossarms	Soil	Soil	Soil-sand	Soil	Soil	Soil; creo planks
Location	Inside of sidewalk	Vaults in rear	Parkway next curb	Parkway next curb	Rear lot	Rear lot	Rear lot; parkways	Rear lot	Btn sidewalk & curb	Rear lot; street
Manhole or handhole	None	Vaults in rear	None	None	For tsf only	None	Tsf vault	None	Yes	Both
Type system	Loop; transfer manual	Radial	Radial tap from OH	Loop	Loop	Loop	....	Radial	Open loop	Radial
Sectionalizing	Discon at tsf	None	None	Discon poth'd in vault	....	....	Sect'lizing switches	None	Load break switch	Yes
Cable Description										
Size & conductor	1/c No. 4; 1/0; 4/0; 350 MCM Cu	No. 6 Cu 5 kv	No. 3 Cu	No. 4 Cu	2/c No. 2	1/c No. 8	13.2 kv 1/c No. 4 4.16 kv 1/c No. 2 Cu	3/c No. 6	No. 2 Cu	....
Insulation	On 350 MCM-11/64 RI 10/64 RI; 5-kv sh'ld'd	GE-Super coronal 10/64 insulation	10/64 rubber 5 kv non-shielded	19/64 rubber 15 kv shielded	Class 1120-11 In. 10/64 in rubber; tape.	8/64 Polyethlyene	13.2 kv-220 mil paper 4.16 kv-110 mil paper	Paper	Rubber-D-574 shielded Neoprene	PILC
Jacket	Neoprene No. 4-4/64; 1/0; 4/0-5/64; 350 MCM 6/64	4/64 in jacket	3/64 in Neoprene	5/64 in Neoprene	Trenchlay	4/64 in PVC	Neoprene	Lead	....	....
Neut cond	Bare common. ½ size of largest pri or sec	No. 6 WP	No. 4 bare same duct	No. 4 bare same trench	1/0, 7 strand bare Cu common neut	Common neut	....	....	Neut common with sec	....
Lightning protection	At OH connec only	At OH connect only	At OH connect only	At OH connect only	At OH connect only	At OH connect only	At OH connect only	None	On OH connect only	At OH connect only
Cable termination	Stress cone	....	Dir tape connect	Potheads at tsf	....	....	1/c potheads	Pothead at pole	Connected to discon	....
Secondary Mains										
Voltage	120/240	120/240	120/240	120/240	115/230	115/230	115/230	120/240	120/240—3 ph	120/240
Duct or buried	Dir burial; slab	Dir burial	Dir burial	No sec	Dir burial	Dir burial	Dir burial	Transite duct	Duct	Dir burial
Depth, inches	24	30	24	....	....	....	24	30	30-36	....
Location	Same as pri	....	Parkway	....	With pri	With pri	Same trench as pri	Rear lot	Parkway with pri	....
In primary trench	Yes, 1 ft from pri	Separate trench	Yes	....	....	....	Yes	Yes	Yes	....
Cable Description										
Size & conductor	1/c No. 4/0 Cu	No. 2 to 250 MCM	1/0 Cu	....	3/c 1/0 to 300 MCM	1/c 1/0 600 v Neoprene	1/c No. 2-1/c 1/0; 1/c 4/0	2-1/0 600 v	4/0 Cu	System purchased
Insulation	5/64 rubber 600 v	GE Versatol Geoprene 600 v 4/64 to 6/64 in.	600 v Okonite	....	....	....	4/64-in.; 5/64 in. rub	Rubberlike	5/64-in. rub	Values unknown
Jacket	4/64 Neoprene	3/64; 5/64-in. jacket	3/64-in. Neoprene	....	....	....	3/64 in. Neoprene	....	4/64-in. Neoprene	....
Neut cond	Bare common. ½ size of largest pri or sec	....	No. 4 bare Cu	....	....	....	....	1-1/0 600 v Rubberlike	Separate 4/0 4/64-in. Neoprene	....
Services										
Size & differences from main	3/c No. 4 RINJ 600-v., 4/64 Insul and 7/64 jacket	....	1/0; No. 3 Cu same insul jacket as sec	Services dir from vault Meters on wall of vault	....	....	Owner's choice	Rubberlike	Owner's choice	Similar
Owned by customer	Yes	Utility owned	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Connection arrang'm't	Moles in concrete box	Connect at tsf terminal	8-in. tile junct box 6 in. below surface	In meter socket	Junct box	Junct box	....	Busbar on pedestal on pad	In manhole at curb Moles; 100-amp fuses	Buried
Transformers										
Type	OH convent	CSP	OH CSP less arresters	OH CSP less arresters	Subway	CSP	OH CSP less arresters	Overhead CSP	OH convent	Most convent on poles; subway in manholes
Size, kva	100-Max	....	50-max	50 max	....	....	Mostly 10 kva	25 kva	1-167; 2-100 kva	....
Enclosure	Steelcylinder&concrete pipe base 2/3 buried	Semi-buried conc tile 26-in. dia. 26-in. high	36-in. conc tile semi-buried	36-in. conc tile semi-buried	Manhole	Semi-buried	Semi-buried vault	Inverted metal container on pad	Brick house above grd	Some manholes
Sectionalizing and switching at tsf.	2 porc cutouts in transfer arrangement	None	None	Potheads at tsf	Transfer switch	No-load switching	None	None	Open disc each way	....
Street Lighting	Independent	No	None as yet	None as yet	No	No	None as yet	No	Cable in duct bank	No
Telephone Cable	Same trench, sep cond't	No	Rear property	Generally separate	....	....	Same trench. 12.in. sep	Same trench. 12-in. sep	Separate	....
Cost Ratio, UG/OH	2.5 to 6:1	1.5 to 3:1	3:1	3:1	....	2.27:1	2:1 to 5:1	2:1 to 4:1	10:1 to 12:1	....

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Table 14—Residential Underground Distribution Design Practice of 28 Electric Light and Power Companies*—Continued

COMPANY	Pacific G & E	Pennsylvania P&L	Philadelphia Electric	Puget Sound P & L	So. California Edison	Union Electric	Utah P & L	The Public Utilities Comm London, Ontario	Hydro Electric Power Comm of Ontario	City of Calgary Alberta
Type of area	Deluxe residences	Deluxe residences	Apartm'ts	Resid'l	Resid'l subdiv	Resid	Deluxe single resid's	Residence	....	New resid's
Primary										
Voltage, kv	2.4/4.16	2.4/4.16	2.4/4.16	2.4/4.16	2.4/4.16	2.4/4.16	7.2/12.47	2.3	4.16	2.4/4.16
Duct or buried	3 in. non-met. No conc	Fiber in conc; dir burial	3-in. fiber, no conc	Min Z in non met duct; conduit	3-in. fiber duct; in conc	Transite duct; no conc	Fiber in conc	2 in fiber in conc	Transite duct	Transite
Depth, inches	30	30	....	24	24 min	24	30	30	9	....
Cover	Soil	Street	....	Sand; treated plank	Soil; conc envelope under streets	Soil	Soil	Earth	Sidewalk	Earth
Location	Street; rear lot	Street	In sidewalk	Rear lot	Rear lot	Parkway	Rear lot	Behind curb	Under street edge	....
Manhole or handhole	Precast conc serv box	Manholes; handholes	None	....	4 x 2½ x 3-ft. pull box	Manholes	Semi-buried tsf house	Handholes at turns	Handholes at crossing	Kiosk
Type system	Loop; radial	Radial	Sectionalized radial	Radial from OH	....	Radial	Radial	1-ph loops from OH	Radial	....
Sectionalizing	Porc box discon OH	Several sect each tsf from diff OH point	Oil fuse CO	Looped through vt	....	None	At tsf vt	At each tsf	No	Yes
Cable Description										
Size & conductor	1/c No. 6 to 1/c No. 2	1/c No. 6 to 1/c 1/0	....	1/c No. 4 Cu min	3/c No. 2 Cu mains 1/c No. 6 tape	No. 6 Cu	No. 4 Cu	1/c No. 6	1/c No. 6; No. 2	1/c No. 6
Insulation	Oil base; ozone resist comp. 5-kv shield IPCEA	VC-P'r or rub LC—5 kv	Rub—5 kv	Syn. RI IPCEA	Rubberlike	11/64-in. oil base rub	19/64-in. rubberlike	Polyethylene	Polyethylene	Polyethylene
Jacket	Neoprene IPCEA specs	Lead	Lead	Syn rubber	Neoprene	4/64-in. Neoprene	Shielded Cu tape. 5/64-in. Neoprene	No jacket	No jacket	No jacket
Neut cond	Bare. Same size, same conduit as insul phase	Bare	Bare Cu separate	No. 4 WP min	No. 4 WP Cu for mains No. 6 WP Cu for taps	6 No. 14 tinned Cu spiral wound	....	No. 6 bare	No. 6 WP or larger	No. 4 WP
Lightning Protection	None	At OH connect only	....	None	....	At OH connect only	At OH connect only	At OH connect only	At OH connect only	....
Cable termination	Stress cones	G & W oil fused CO wiping sleeves	Connected to oil fuse CO or LC tsf lead	In porc box CO	....	In porc box CO	....	Dir into porc CO	....	....
Secondary Mains										
Voltage	120/240	120/240	Sec mains not used; Serv dir from tsf.	120/240	120/240	120/240	No sec	115/230	....	....
Duct or buried	3-in. non-met	Duct	....	None	Fiber duct	Transite duct	Customers bring serv to tsf	Dir burial; covered with concr blocks	Buried-closed loops from each tsf	Dir burial
Depth, inches	30	30	....	24 in. min.	Above pri ducts	24 in.	....	36	6 to 9	36
Location	Same as pri	Streets	....	....	Lot	Parkway	....	Rear of building	Under sidewalk edge.	....
In primary trench	Yes	Same duct	....	....	Same duct	Same duct	....	Generally not	....	Yes
Cable Description										
Size & conductor	1/c 1/0; 250 MCM	1/c; 2/c 600 V	....	....	2 1/0 Cu min to 250 MCM and 2/0 neut	4/0	....	1/c No. 2	1/0	No. 2
Insulation	Oil base; ozone resist comp 600 v—IPCEA	L&R; Rub & Neoprene	Non-leaded rub	....	Rubberlike	5/64-in. rubber	....	Polyvynichloride	Polyvynichloride	Polyvynichloride
Jacket	Neoprene IPCEA	....	....	....	Neoprene	3/64-in. Neoprene	....	No jacket	No jacket	No jacket
Neut cond	Separate No. 2 bare Cu; 1/0	Bare common	....	....	No. 2 Cu for 1/0 ph No 2 Cu for 250 MCM	....	....	No, 2 bare	Common with pri	Bare neut
Services										
Size & differences from main	Customer specifies	Dir burial	....	No. 2 min dir burial	1/c No. 4, rubberlike insul 3/c twisted	No. 2; 4/0 dir burial	Supplied by customer	Same trench as sec No. 4; No. 6 PVC	2 No. 4 PVC; 1-No. 6 bare neut	2-No. 2 PVC 1-No. 4 WP
Owned by customer	Yes	Yes	Yes	Yes	....	Yes to property line	Yes	No	No	....
Connection arrang'm't	Various. Split-bolt con usual	Bugged & taped; or soldered	Bus at tsf	Bus at tsf	Split-bolt or indent type con't'r at term box	Split bolt in handhole taped	Junct box	Connect box on basement wall outside	Solderless-taped; in asphalt filled box	....
Transformers										
Type	OH	Convent; submersible	OH	OH	CP	CSP less arresters	OH CP	Standard OH	Convent'l or CSP OH	CSP
Size, kva	....	....	25-75	50 kva max.	15-25	15-100	....	25	Up to 100	....
Enclosure	3 x 5 x 4-ft. sheet steel	Manholes	Cone block; brick below surface	Recent 42 in. conc tile semi-buried	Semi-buried tsf vault of concr blocks	Precast concr sewer tile	Semi-buried vault	Rectangular kiosks. Reinforced concr	Rectangular kiosks, semi-buried concr	Semi-buried conc sewer tile. Conical steel cover
Sectionalizing and switching at tsf	Yes. At tsf as above	None	Yes	No	....	For multiple tsf	S&C Positect fuses	Yes. Connect to CO	Fused porc box CO	....
Street Lighting	Independent	Yes	Cable buried with pri	None yet	....	Separate system	None as yet.	Yes	Yes. With sec	Yes. With sec
Telephone Cable	Same trench often	Adjacent ducts	....	Same trench 12 in sep	Same duct line	Separate trench	Same duct run	No	No	Yes. With sec
Cost Ratio, UG/OH	Was 2:1; is 4:1 to 5:1	....	....	3:1	3 to 5:1	....	4:1	1.25:1 (1947)	1.22:1	3:1

*Permission has been granted by *Electrical World* to include this material.

Table 15—Application Data For Lightning Arresters**

Classification of Systems

THIS TABLE, based on calculation and experience, is a guide for quick selection of lightning arresters. For the purpose of selecting the proper lightning arrester voltage rating, three-phase systems may be classified as Type A, Type B, etc., on the basis of the magnitudes of the ratios X_0/X_1 and R_0/X_1.

Type A neutral grounded systems are usually well grounded and have a reactance and resistance ratio less than for the Type B systems. The system constants are not known with sufficient detail to establish the limiting ratios. These systems are specifically the grounded Y-distribution systems using distribution-type arresters, for which the application practice has been established by experience.

Type B neutral grounded systems have a reactance ratio X_0/X_1 which is positive and less than 3 and a resistance ratio R_0/X_1 which is positive and is less than 1. These limits correspond to the usually accepted definition of an "effectively grounded" system.

Type C neutral grounded systems have either the reactance ratio greater than plus 3 or the resistance greater than plus 1, or both; systems using ground fault neutralizers are included in this class.

Type D isolated neutral systems are the usual ungrounded systems for which the zero sequence reactance is capacitive, and the ratio X_0/X_1 is negative and lies between minus 40 and minus infinity.

The values of maximum system voltages in the column for Type D systems are those recommended if the risk of abnormal voltages in excess of the arrester rating is to be avoided. However, it has been the general practice to use the same values for Type D isolated neutral systems as used for the Type C neutral grounded systems.

Type E isolated neutral systems are those ungrounded neutral systems that have a reactance ratio X_0/X_1 that is negative and is between 0 and minus 40, over which range partial resonance may occur so that each case must be analyzed and treated upon its own merits.

Example: A 12,000-volt system has a maximum voltage of 12,500 volts. From the table, a Type A system would require a 9,000-volt arrester; a 12,000-volt arrester is required for a Type B system; and if the system is either a Type C or Type D a 15,000-volt arrester is required.

Lightning Arrester Rating	Maximum three-phase system voltage on which arrester should be used				
	Systems with neutrals grounded			Systems with neutrals isolated	
	Type A	Type B	Type C	Type D	Type E
	Volts rms				
175	130/260*	130/260*	......	......	Each case requires special study.
175	260	220	......	......	
650	650	650	650	650	
1,000	1,000	1,000	1,000	1,000	
3,000	4,500	3,750	3,000	2,700	
6,000	9,000	7,500	6,000	5,500	
9,000	12,800	11,250	9,000	8,200	
12,000	15,000	15,000	12,000	11,000	
15,000	18,000	18,000	15,000	13,000	
	Kv rms				
20	Type A systems usually do not occur in these voltages.	25	20	18	
25		30	25	23	
30		37	30	27	
37		46	37	34	
40		50	40	36	
50		60	50	45	
60		73	60	55	
73		90	73	66	
97		121	97	88	
109		136	109	99	
121		150	121	110	
145		180	145	132	
169		200	169	...	
195		245	195	...	
242		300	242	...	

*Single-phase, three-wire.

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