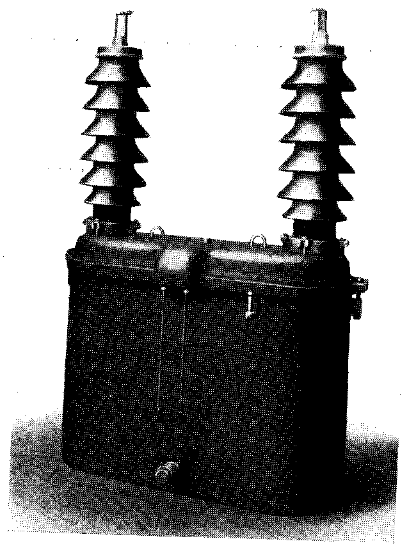
Performance
of
Instrument Transformers

Instruction Book 5215



66,000-Volt Outdoor Oil-insulated Voltage Transformer

Westinghouse Electric & Manufacturing Co.

East Pittsburgh, Pa.

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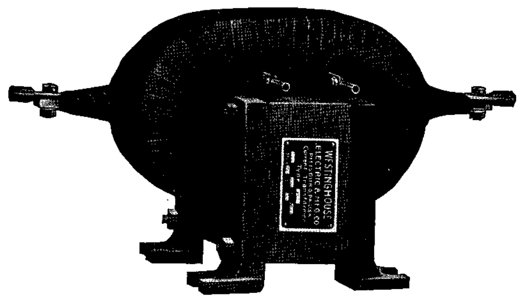
INSTRUMENT TRANSFORMERS



Switchboard Type KA
Current Transformer (Dry Type) Indoor

Instrument transformers are used for two reasons; first, to protect station operators from contact with high voltage circuits, and second, to permit the use of instruments with a reasonable amount of insulation and a reasonable current carrying capacity. The function of instrument transformers is to deliver to the instruments a current and voltage which shall be always proportional to the primary current and voltage, and which shall not exceed a safe potential above ground. Generally, the secondary of a voltage transformer is designed for about 115 volts and the secondary of a current transformer for 5 amperes, and both these secondary circuits are grounded, together with the cases of the meters to which they are connected.

Types and Ratings*—There are two general classes, of instrument transformers, dry and oil-insulated. Dry-type transformers are listed for primary voltages up to the 6900-Volt Class and the oil-insulated type up to the 66,000-Volt Class. Current transformers are listed for primary currents up to 10,000 amperes. For voltage classes up to 23,000 volts, the dry type of current transformer is used, and for the higher voltages the oil-insulated type. The demand for transformers of higher ratings than those given is so small that they are not listed, although they can be built on special order.

*See Westinghouse Annual Catalogue of Electrical Supplies, Section 3-B, for standard types and ratings.

Oil is used in oil-insulated instrument transformers, chiefly for its insulating properties. It is extremely important, therefore, that it be of the proper quality and that it be kept free from dirt and moisture.

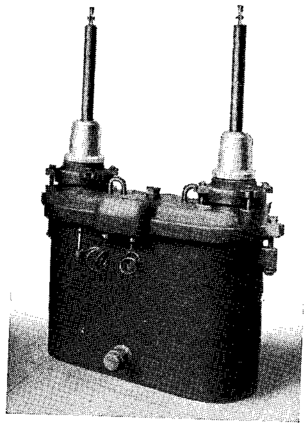
Polarity—In connecting instrument transformers to wattmeters, watthour meters, power factor meters, etc., it is necessary to know the relative instantaneous direction of currents in the leads. For this reason one primary and one secondary lead of each Westinghouse transformer is marked with a white polarity marker. The relation of the marked leads is such that the instantaneous direction of the current in them is the same; **that is, toward the transformer in the marked primary lead and from the transformer in the marked secondary lead, or vice versa.** This marking of the leads is carefully checked by a polarity test.

Grounding of Secondary—All instrument transformers should be grounded on the secondary side as an extra precaution against danger from the high voltage in case the insulation should be punctured by lightning or other abnormal stresses. In polyphase groups, any point of the secondary may be grounded, but it is preferable to use a neutral point or a common wire between two transformers.

Insulation—The insulation of instrument transformers protects the meters and control apparatus as well as the power station operators from the high voltage circuits. It is highly important, therefore, that it be able to withstand the strains of service. For this reason, the insulation of Westinghouse instrument transformers is designed with special care. Dry type transformer coils are impregnated with a compound impervious to moisture. Coils for oil insulated transformers are dipped in varnish or impregnated so as to seal them against moisture.

Insulation Tests—The insulation tests conform to the Standardization Rules of the A. I. E. E.

VOLTAGE TRANSFORMERS



23,000-Volt Indoor Oil-Insulated Voltage Transformer

Uses—Voltage transformers are used with voltmeters, wattmeters, watthour meters, power factor meters, frequency meters, synchronoscopes and synchronizing apparatus, protective and regulating relays, and the no-voltage and over-voltage trip coils of automatic circuit-breakers. One transformer can be used for a number of instruments at the same time if the total current taken by the instruments does not exceed that for which the transformer is designsigned and compensated.

Voltage transformers have a capacity of 200 volt-amperes, but are compensated to give correct ratio at 40 volt-amperes, as this is the average load demanded of a voltage transformer. Special transformers may be compensated for correct ratio at any load up to the full capacity of 200 volt-amperes.

The standard secondary voltage is 115 volts (nominal) to suit standard instruments. Special secondary voltages can be made if necessary, but are seldom required.

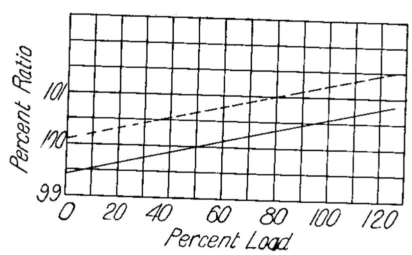


Fig. 1—Ratio Error Curves

Principle of Operation—The voltage transformer is, in principle, an ordinary constant potential transformer specially designed for close regulation, so that the secondary voltage under any conditions will be as nearly as possible a fixed percentage of the primary voltage.

The secondary voltage can never be exactly proportional to the primary voltage or exactly opposite to the primary voltage in phase, on account of the losses in the transformer and the magnetic leakage between coils. This is shown by the vector diagram, Fig. 2.

OE_s represents the reversed secondary voltage delivered to the meters.

OI_s represents the reversed secondary current delivered to the meters.

θ represents the angle of lag of the secondary current behind the secondary voltage and is determined by the relation of resistance to reactance in the instruments.

OI_i represents the current in the primary winding to supply the iron loss of the transformer (hysteresis and eddy currents).

OI_m the current to magnetize the core.

OI_e the total exciting current. This is the vector sum of OI_i and OI_m and it flows in the primary winding only.

IR is the voltage drop due to the load current I_s and the resistance of both primary and secondary windings. It is parallel to OI_s.

IX is the reactance drop due to the load current and is perpendicular to OI_s.

OD would therefore be the primary voltage if the iron required no exciting current. But the exciting current, flowing in the primary coil only, causes a drop in voltage.

I_eR_p due to the resistance of the primary coil and parallel to OI_e.

I_eX_p due to the reactance of the primary coil and perpendicular to OI_e.

OE_p therefore, represents the total primary voltage necessary to deliver the load current OI_s at the secondary voltage OE_s. It differs from OE_s both in magnitude and in phase position.

ϕ_1 represents the phase angle between primary and secondary voltages.

Thus, there are two classes of errors inherent in voltage transformers; ratio error and phase-angle error. The part of these errors due to the exciting current is constant for any applied voltage. It can be reduced to a minimum by choosing the best quality of iron and working it at a low magnetic density. The part of the errors due to the load current varies directly with the load and can be minimized by making the resistance and reactance of the windings very low.

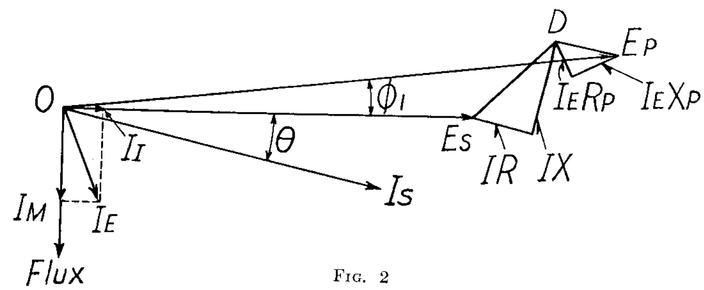


FIG. 2

In any transformer, the ratio error can be neutralized for one particular condition of load by "compensating" the transformer. This means that the actual ratio of turns differs from the marked ratio of the transformer by an amount just sufficient to make up for the voltage drop at the specified load. This is illustrated in Fig. 1. The dotted curve shows the percentage of marked ratio for an uncompensated transformer, and the full line shows the same transformer compensated to deliver correct voltage at half load.

Phase Displacement Error—The effect of the phase displacement of the secondary voltage need not be considered when using voltmeters, frequency meters, synchronoscopes, or protective and regulating relays, which depend on voltage only. With wattmeters, watthour meters, and similar apparatus, whose indications depend not only on the voltage but also on its phase relation to the line current, the phase error has some effect. This is shown in Fig. 3. OE_p and OE_s represent respectively the primary voltage and the secondary voltage corrected for the ratio error. The primary voltage differs in phase from the secondary voltage by a small angle ϕ_1. The indication of the wattmeter will be proportional to the component of the voltage that is in phase with the line current OI_p. It can be readily seen that the wattmeter reading which is proportional to On will be less than the true power, which is proportional to Om and that the effect of this error will be greater as θ increases. That is, the lower the power factor of the load in the main circuit, the greater the effect of the phase displacement of the voltage transformer on the wattmeter reading.

The effect of the phase displacement cannot, therefore, be compensated for in the transformer, as it depends not only on the constants of the transformer, but on the power factor of the load to be measured as well. By making the phase displacement as small as possible by proper design, its effect on readings for commercial purposes becomes negligible.

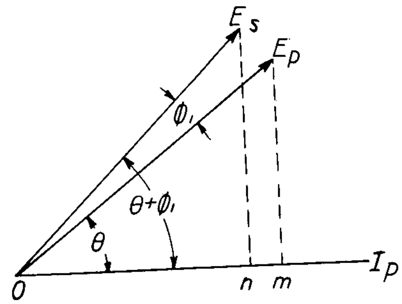


FIG. 3—EFFECT OF PHASE DISPLACEMENT OF VOLTAGE TRANSFORMER.

The effect of the voltage transformer's phase displacement can be calculated by the formula:

$$\text{Final correction factor, Kf} = K_1 \frac{\text{Cos } \theta}{\text{Cos}(\theta + \phi_1)}$$

where

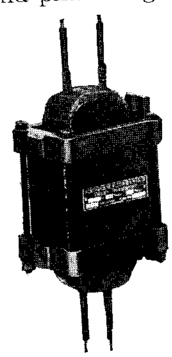
K_1 = Ratio correction factor.

θ = Angle of lag in the line.

ϕ_1 = Angle of transformer leading phase displacement.

In using this formula, it must be noted that ϕ_1, represents the angle of leading phase displacement, such as is obtained with an induction wattmeter. If this angle is lagging, as with a dynamometer wattmeter, ϕ_1 must be considered negative.

In general, both ratio error and phase angle are very small in first-class voltage transformers, and may be neglected in most commercial measurements. If extreme accuracy is required, ratio and phase angle curves must be obtained for the particular transformer in use at the particular load condition which exists, and correction must be made as indicated above.



DRY-TYPE VOLTAGE TRANSFORMER

Ratio and phase-angle curves for individual transformers are not furnished unless specially ordered by the customer, in which case an extra charge is made. Typical curves for various standard types of voltage transformers are shown on pages 35 to 37 and the volt-ampere load represented by various instruments is shown on page 28.

Permanence of Calibration—The only thing which can affect the accuracy of a voltage transformer without entirely destroying it, is a change in the iron which would change the exciting current. Inasmuch as the effect of the exciting current is small, and modern transformer iron is non-aging, it is safe to assume that the original calibration of a first-class modern transformer is permanent.

Effect of Variation in Primary Voltage—Voltage transformers are compensated for their iron losses at their rated voltage. When used on some other voltage, either higher or lower, an error is introduced. In general, this error will not be more than 0.15 percent when the applied voltage is from 50 percent to 110 percent of rated voltage. A voltage transformer should never be used on a circuit whose voltage is more than 10 percent above the rated voltage of the transformer.

Effect of Frequency Variation and Wave Shape—Ordinary frequency variation and wave shape also affect the iron losses, but their effects on the accuracy of the transformer cannot be detected.

Effect of Variation of Line Current—As the operation of the voltage transformer depends only on the voltage applied at its terminals, variations in the line current have no effect whatever on its accuracy.

Tests—All voltage transformers are tested for ratio, polarity, iron loss, exciting current, and insulation. In addition, the first unit of any design is tested for resistance and reactance as well as the determination of temperature rise.

Temperature Rise—As voltage transformers are designed for close regulation, they have a temperature rise well within the A. I. E. E. limit of 55 degrees Centigrade.

CONNECTIONS

Polyphase Groupings—In general, two voltage transformers are sufficient for any two-phase or three-phase circuit. Figs. 4 and 5 show various groupings of transformers on two-phase and three-phase circuits respectively. The numbers shown on the vector diagrams of secondary connections show the voltage between the points indicated, in percentage of the voltage between lines (corrected for ratio of the transformers). In case a different secondary voltage between these points is desired, transformers of suitable ratio should be selected. The highest accuracy is

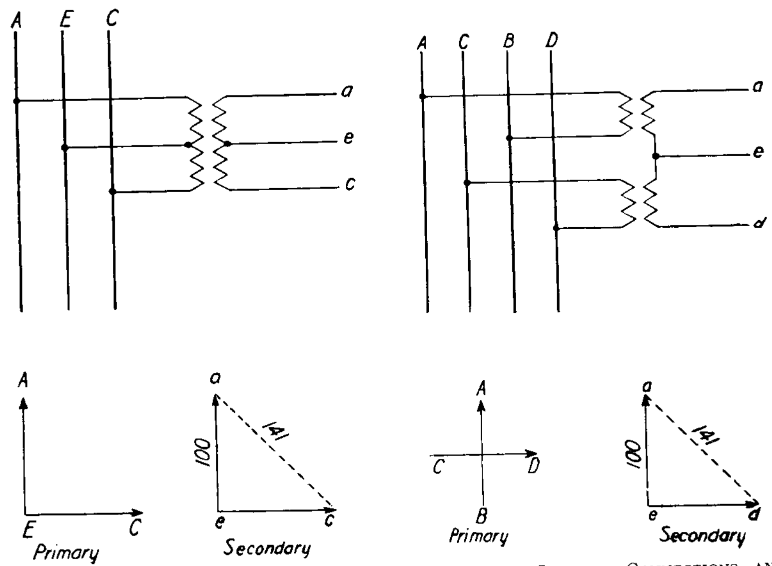


FIG. 4—TWO-PHASE GROUPINGS OF VOLTAGE TRANSFORMER SHOWING CONNECTIONS AND VOLTAGE VECTORS.

attained with standard transformers when the secondary voltage of the transformers is 100 volts, but in some cases 58 volts is required to produce proper registration of the meters.

It should be noted that the V-primary to V-secondary connection (b), Fig. 5 produces the same results as the "Delta-Delta" connection (a) and saves one transformer. The "Delta-Delta" connection is therefore never used commercially. The V-V connection under some conditions produces slightly higher error, but the difference is seldom considered of sufficient importance to warrant the expense of the extra transformer.

If voltage only is required, one transformer may be used, connected between the lines whose voltage is to be measured. The following apparatus requires voltage only:—

Voltmeters.
Voltage-regulating relay.
No-voltage release coil.
Auxiliary control circuit.
Frequency meter.
Synchronoscope.
Synchronizing lamps.

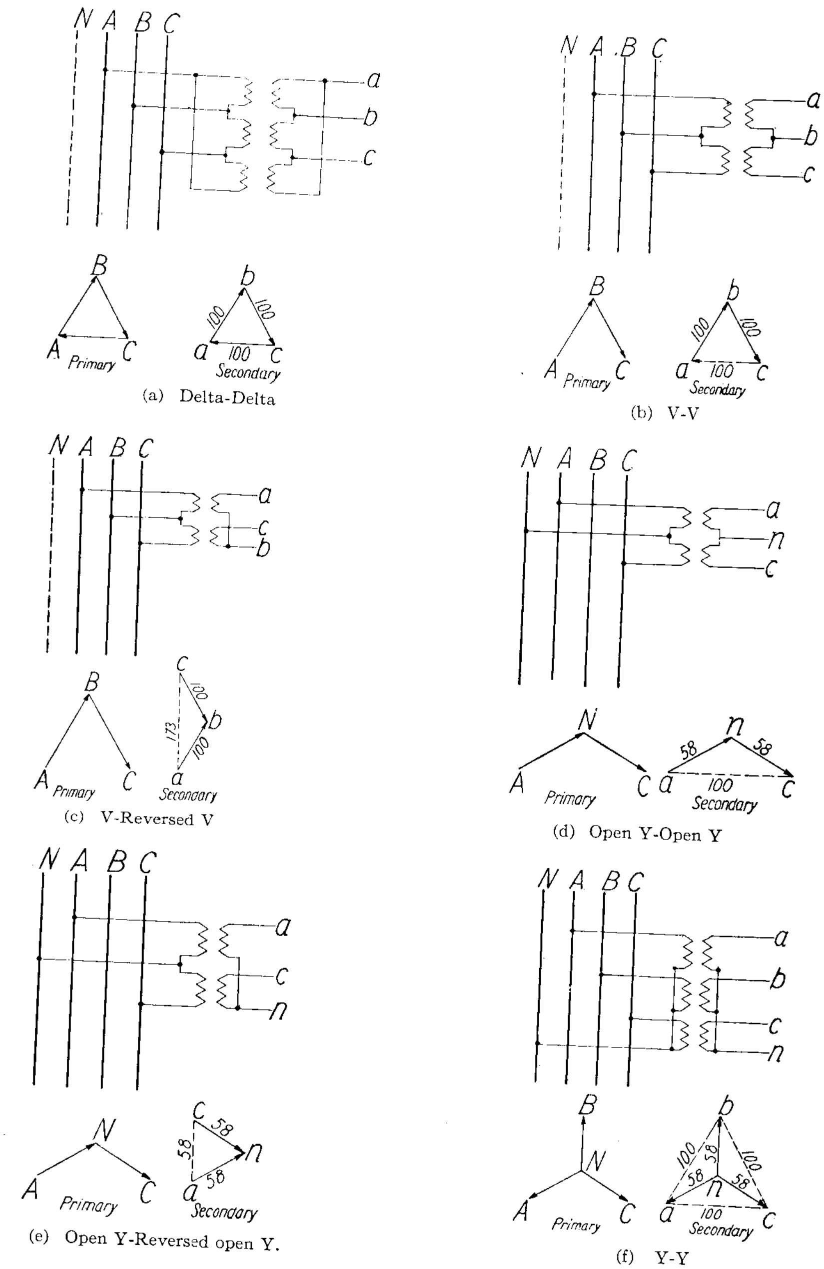


FIG. 5—THREE-PHASE GROUPINGS OF VOLTAGE TRANSFORMERS SHOWING CONNECTIONS AND VOLTAGE VECTORS.

To check the correctness of the connections of voltage transformers on three-phase lines, three voltage readings are necessary. These three voltage readings should bear the relations shown in the diagram.

OPERATION

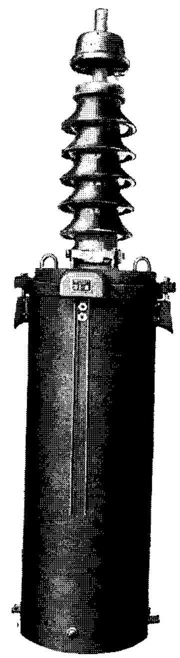
Short Circuiting—The secondary terminals of a voltage transformer should never be short circuited. If they should become short circuited, a heavy current will flow which, if continued, will burn out the windings.

Fuses—It is practically impossible to protect a voltage transformer with fuses, for the reason that any fuse wire small enough and long enough to open the transformer circuit with certainty during an overload would be mechanically too frail to be handled. Some companies have adopted the practice of connecting the voltage transformers directly to the lines without fuses. This is dangerous, because a short circuit within the transformer might cause a high voltage lead to burn off and fall in such a way as to short circuit the system. To prevent this the Westinghouse Electric and Manufacturing Co. recommends the use of resistors and fuses in the high voltage leads of voltage transformers. The resistors limit the short circuit current to 20 to 40 amperes while the fuses are designed to open such a current.

In normal operation, the resistors carry only the very small primary current of the voltage transformer, and the drop in voltage which they cause is inappreciable.

CURRENT TRANSFORMERS

General—When the current in a circuit is so large that to connect measuring or operating instruments directly in the circuit would be impracticable, or when the voltage is so high that to do so would be unsafe, the current transformer provides a means of reproducing the primary current on a scale suited to the instrument and of insulating the instrument from the main circuit. It is a special development of the transformer principle in which a constant ratio of primary to secondary current is the important consideration instead of the usual constant ratio of primary to secondary voltage.



Type OC Current Transformer (Oil Insulated) Outdoor

Uses—Current transformers are used with ammeters, wattmeters, power factor meters, watthour meters, compensators, protective and regulating relays, and the trip coils of circuit-breakers.

One current transformer can be used to operate several instruments provided that the combined load does not exceed that for which the transformer is designed and compensated.

PRINCIPLE OF OPERATION

The ordinary voltage or distributing transformer is connected across the line and the magnetic flux in the core depends upon the primary voltage. For a given voltage the flux is, therefore, fixed, while the current in the winding rises and falls as the load of the secondary winding changes.

The current transformer is connected directly in series with the line. For a fixed number of instruments in the secondary (which is the usual condition) a rise or fall in the line current requires a corresponding rise or fall in the secondary voltage to force the secondary current through the impedance of the meter load. The magnetic flux in the iron, which supplies this voltage, thus follows the rise and fall of the primary or line current.

compensation, low magnetic densities, and the use of the very best grade of iron all combine to keep the ratio errors in Westinghouse transformers to a minimum, as shown in the typical curves on pages 38 to 40.

Phase Displacement Error—The error due to phase displacement, like the ratio error, is a function of the core losses. As before, the effect is relatively greater as the primary current decreases and the resulting curve of phase displacement is as shown in Fig. 9. The phase displacement error has no effect on an ammeter, which simply measures the amount of current without regard to its phase position. It has an effect, however, on instruments such as wattmeters and power-factor meters, whose indications depend not only upon the amount of current but also upon its phase relation to the line voltage. By referring to Fig. 6, it will be seen that the reversed-secondary current OI_s leads the primary current OI_p by a small angle (and this is the usual condition). In Fig. 10, these two current vectors are reproduced, OI_p being corrected by the ratio correction factor K. The indication of the wattmeter will be proportional to that component

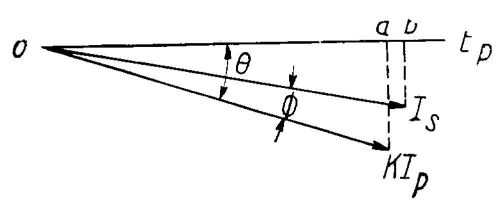


Fig. 10—Diagram Showing Effect of Phase Displacement.

of the current which is in phase with the primary voltage. It will readily be seen that the actual wattmeter reading which will be proportional to Ob will differ from the true power which is proportional to Oa. It will also be noted that for a fixed phase displacement in the transformer, the effect of this error is greater as the angle θ, increases that is, the lower the power factor in the line itself, the greater will be the effect of the phase displacement error. This error, therefore, cannot be compensated, as it depends not only upon the conditions in the transformer itself, but also upon the power factor of the line. The best that can be done is to reduce it to a minimum by careful design and the use of the best magnetic material.

The effect of the current transformer's phase displacement may be calculated from the formula:

$$\text{Final correction factor} = K \frac{\cos \theta}{\cos(\theta - \phi)}$$

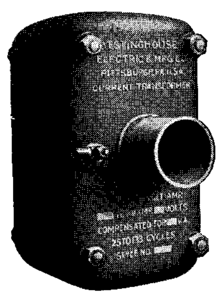
where K = ratio correction factor.

θ = angle of lag in line in degrees.

ϕ = angle of transformer phase displacement in degrees.

In using this formula it should be noted that ϕ represents an angle of leading phase displacement that is the reversed secondary current leads the total primary current. If this angle is lagging, ϕ is negative.

Ratio and Phase Angle—Ratio and phase displacement curves are made in the Testing Department for standard lines of Westinghouse transformers, but are not included in the ordinary commercial tests made at the Works. Where curves are required by a customer, a charge is made for them unless a typical curve, giving the ratio and phase displacement within specified limits is satisfactory, in which case the curve is furnished without charge. Usually such a curve should be all that is required. Typical curves for several standard series transformers are given on pages 38 to 40.



Type FS Current Transformer (Dry Type) Indoor

Iron Aging—As the iron loss affects the accuracy of the transformers, aging of the iron would tend to increase the errors slightly, and in transformers built before the adoption of silicon-steel, about 1908, this effect may be perceptible. The modern silicon-steel, however, is non-aging, and no change in accuracy need be expected from this cause.

Magnetization of Core—The magnetic history of the iron also affects its losses. If the core has been magnetized, either by passing direct current through the coil, by opening the secondary circuit with a load on the primary, or by a heavy overload on the primary, the iron loss and magnetizing current will be abnormally high and the ratio and phase-angle errors will be slightly greater than normal. Such a transformer can be demagnetized and restored to normal condition by passing about 150 percent of normal current through the primary, with the secondary connected to a resistance of 20 to 30 ohms and gradually reducing the resistance to zero. Great care should be taken not to come in contact with the secondary leads during this operation as dangerous voltages may be induced.

Effect of Secondary Load—The instruments connected in the secondary circuit of the transformer are placed in series, so that the secondary current will pass through each. As instruments are added, higher voltage is required to force the current through them. This requires higher magnetic density in the iron. As pointed out in the discussion under "Ratio Error" and "Phase Displacement Error," higher magnetic density increases both the iron loss and the magnetizing current, hence both the ratio and the phase-angle errors are magnified. For the sake of accuracy, therefore, there is a limit to the number of instruments that should be placed on a single current transformer.

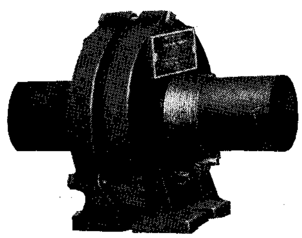
The ordinary measuring instruments are not non-inductive. The power factor of the load of instruments varies with the different combinations used. In general, and within the limits of the usual groups of meters, it may be said that for the same volt-ampere load, the greater the inductive element in the meter load, the less will be the phase displacement error and the greater the ratio error. While the variations in the errors are not enough to affect the accuracy to a great extent, the power factor of the load must be recognized in preparing performance curves of current transformers. For that reason, the curves shown in this book are based on a power factor corresponding to a typical load of instruments of the volt-amperes specified. The choice of this power factor represents as closely as practicable an average condition.

Compensation—For a given instrument load on the transformer the secondary ampere-turns, OI_s bear a definite relation to the primary ampere turns, OI_p for each value of the primary load current. Therefore, by properly proportioning the number of turns in the windings, it is possible to raise the secondary current to overcome the ratio error. However, owing to the inherent variation of the ratio error, this compensation will not be exactly correct for other values of the primary current.

A Westinghouse current transformer is compensated to give, as closely as possible, the correct ratio at 65 percent of its rated current. As meters and transformers should be selected with a rating 50 percent greater than the normal current of the circuit, to allow for peaks and overloads, the full-load current of the circuit represents about 65 percent of the current rating of the transformer and meter. Therefore, the greatest accuracy of meter readings is attained with full load current in the circuit.

Effect of Frequency Variation—Higher frequencies produce lower magnetizing current and lower iron loss, and therefore result in lower percentage of ratio error and smaller phase angle. The variations are small, however, and Westinghouse current transformers may be used at any frequency from 25 to 133 cycles.

Effect of Variation of Line Voltage—As the operation of the current transformer depends on current only, variation of line voltage has no effect on accuracy. A type of current transformer must be chosen, however, having insulation suitable for the voltage of the line on which it is to be used.



TYPE FR CURRENT TRANSFORMER (DRY TYPE) INDOOR

Effect of Wave Form—The shape of the primary current wave affects, to a certain extent, the maximum induction and therefore the iron losses, and also affects the shape of the secondary current wave, which may introduce slight errors in some meters. These effects are, however, negligible.

Tests—The first current transformer built according to a new design is given a complete test including ratio, and phase angle curves, resistance, polarity, and insulation tests. Subsequent units of the same design are tested for ratio at one point (65% of full load) and are given polarity and insulation test.

Temperature Rise—Rise of temperature increases the resistnace drop in the windings, which necessitates an increase in the secondary voltage. This, in turn, necessitates an increase in the magnetic density required in the iron and thus affects the accuracy. The resistance drop is, however, only a small part of the induced voltage, and the temperature rise of Westinghouse transformers is within the A. I. E. E. limit of 55 degrees Centigrade. The variations of accuracy due to temperature rise are, therefore, very slight.

Fig. 11 shows typical temperature curves for a type KA transformer. For these curves "normal current" is the full-load line current, which, as the transformers are ordinarily applied, is 65 percent of the rated primary current of the transformer.

"Through-Type" Transformers—Transformers of this type have no primary winding, but use the current carried by the cable or bus-bar to energize the core. The general type designation F in combination with a qualifying symbol, will be found applied to this type of transformer. They are listed in catalog section 3-B.

A current transformer, to be accurate, requires at least 600 ampere-turns (based on normal primary current). In the "through-type" there is only one primary turn, so that this type cannot be made for normal currents of less than 600 amperes without sacrificing accuracy. In cases where accuracy is required over only a limited range, as for relays or trip coils, the use of this type is entirely satisfactory for normal current as low as 100 amperes. Where it is possible to calibrate the instrument with

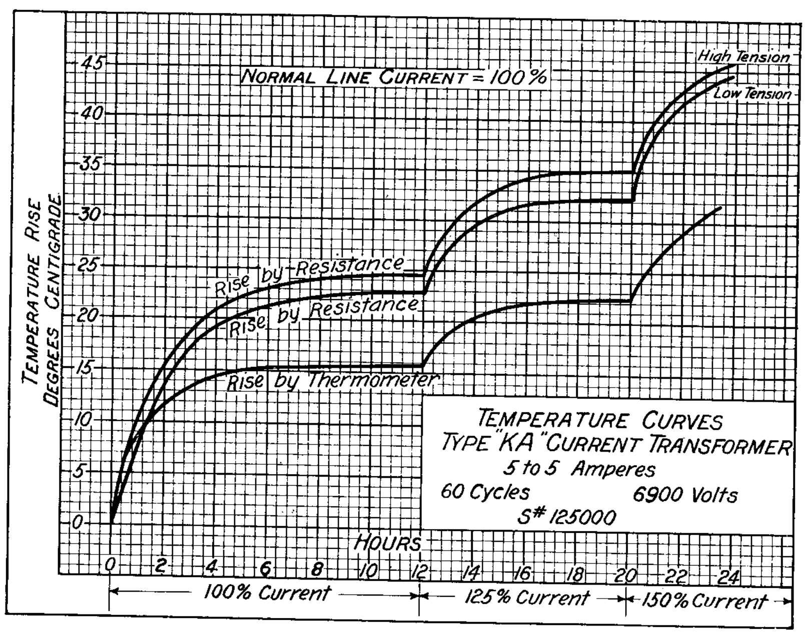


Fig. 11—Temperature Curves of KA Transformer.

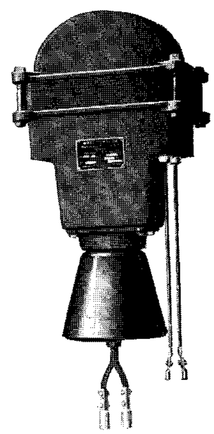
the transformer, it is entirely satisfactory to use this type of transformer with an ammeter.

The momentary current due to a heavy short circuit on a large system is extremely great and the mechancial stresses set up between the primary and secondary windings of a current transformer due to this current are very large. In the "through-type" of transformer, these stresses are balanced within the transformer itself. This is a good type, therefore, to apply where there is a liability of short circuits.

The objection has been put forward that the accuracy of the "through-type" of transformer is affected by the position of the primary conductor in the transformer opening. This would be true to a slight extent if the conductor were very small in proportion to the transformer opening. In practice it amounts to a laboratory refinement which is of no commercial importance.

GROUPINGS

Where it is desired to read the total current or power in a number of circuits of the same phase it is possible to connect the secondaries of the transformers in multiple to the terminals of one meter. It is obviously necessary that all transformers so connected have the same ratio, and that the current coil of the meter be suitable for the sum of the transformer currents. Each transformer in such a group acts as a shunt for the currents in the other transformers, and introduces a slight error in the meter reading, particularly when one of the primaries is carrying no current. The results obtained are, however, sufficiently accurate for most commercial requirements.



Type MA Current Transformer (Dry Type) Outdoor

Single-Phase—For single-phase circuits a transformer is required for each circuit to be metered. In the case of three-wire circuits, either two ordinary transformers or one three-wire transformer may be used, connected as shown in Fig. 12 and Fig. 13. The type A three-wire transformer is so connected that the secondary carries current proportional to the average of the currents in the outside wires of the circuit. When two single transformers are used, connected like Fig. 13, the current in the meter circuit is the sum of the two secondary currents. To use

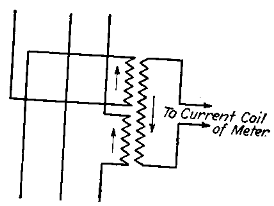


FIG. 12—CONNECTION OF THREE-WIRE TRANSFORMER ON THREE-WIRE SINGLE-PHASE CIRCUIT.

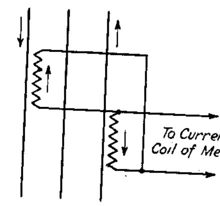


FIG. 13—CONNECTIONS OF TWO-TRANSFORMERS ON THREE-WIRE SINGLE-PHASE CIRCUIT.

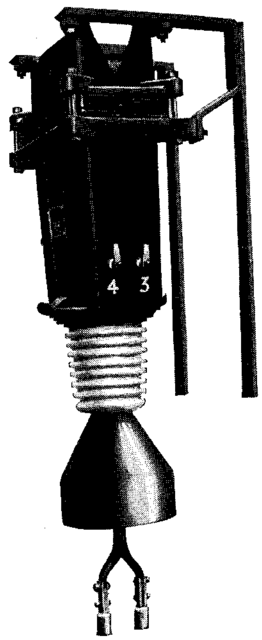
standard apparatus throughout it would be necessary to use transformers of double the actual ratio required so that the sum of the secondary currents would not exceed the five amperes for which the meter coil is designed. Such transformers would then be operating at one-half their normal primary current, and their accuracy would accordingly suffer somewhat.

Two-Phase—Fig. 14 shows a number of possible groupings of current transformers on various two-phase circuits, with the corresponding vector diagrams. Assuming that the transformers have standard 5-ampere secondary windings, the numbers on the vector diagrams show the currents in the corresponding branches of the circuits. The preferable arrangement for any case depends on the type of instrument to be energized. For ammeters, a reading in each phase is all that is usually necessary, while protective relays should be so connected that trouble on any line will be detected. Arrangement "V" permits the use of two relays for the protection of all lines.

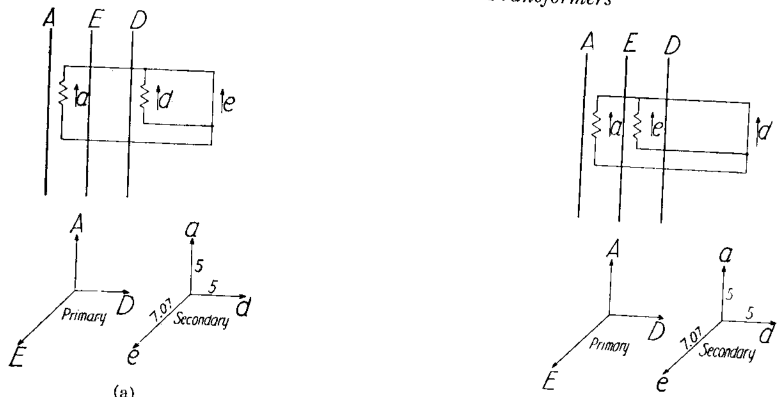
Three-Phase—Fig. 15 shows similar arrangements for three-phase circuits. Particular attention is called to the Z-connection (e) which permits the use of two relays for the protection of the three lines.

OPERATION

Opening of Secondary--The secondary circuit of a current transformer should never be opened while the primary is **carrying current.** If it is necessary to disconnect instruments the secondary should first be short-circuited. If the secondary circuit is opened a difference of potential is developed between terminals which is dangerous to anyone coming in contact with the meters or leads. The cause of this high voltage is that with open secondary circuit all of the primary ampere-turns are effective in producing flux in the core, whereas normally but a very small portion of the total perform this function. The danger is magnified by the fact that the wave form of this secondary voltage is peaked, producing a high maximum value. A high flux produced in this way may also permanently change the magnetic condition of the core so that the accuracy of the transformer will be impaired.

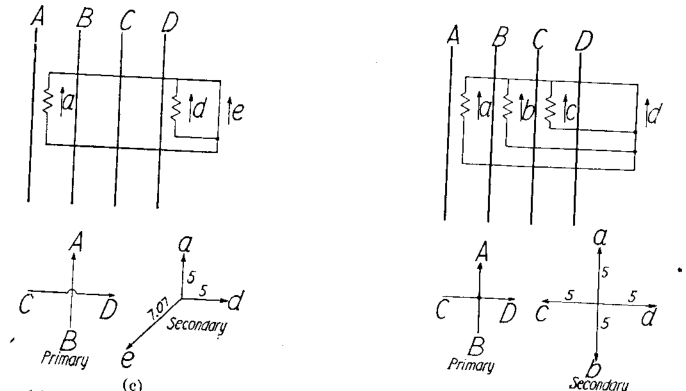


TYPE MC, CURRENT TRANSFORMER (DRY TYPE) OUTDOOR WITH HANGER IRONS



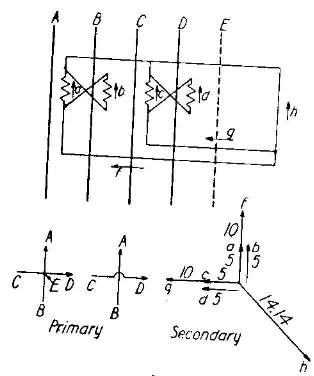
(a) (b)

(a) Three-wire. One transformer in each phase. V-connection.
(b) Three-wire. Transformers in one-phase and common wire. V-Connection.



(c) (d)

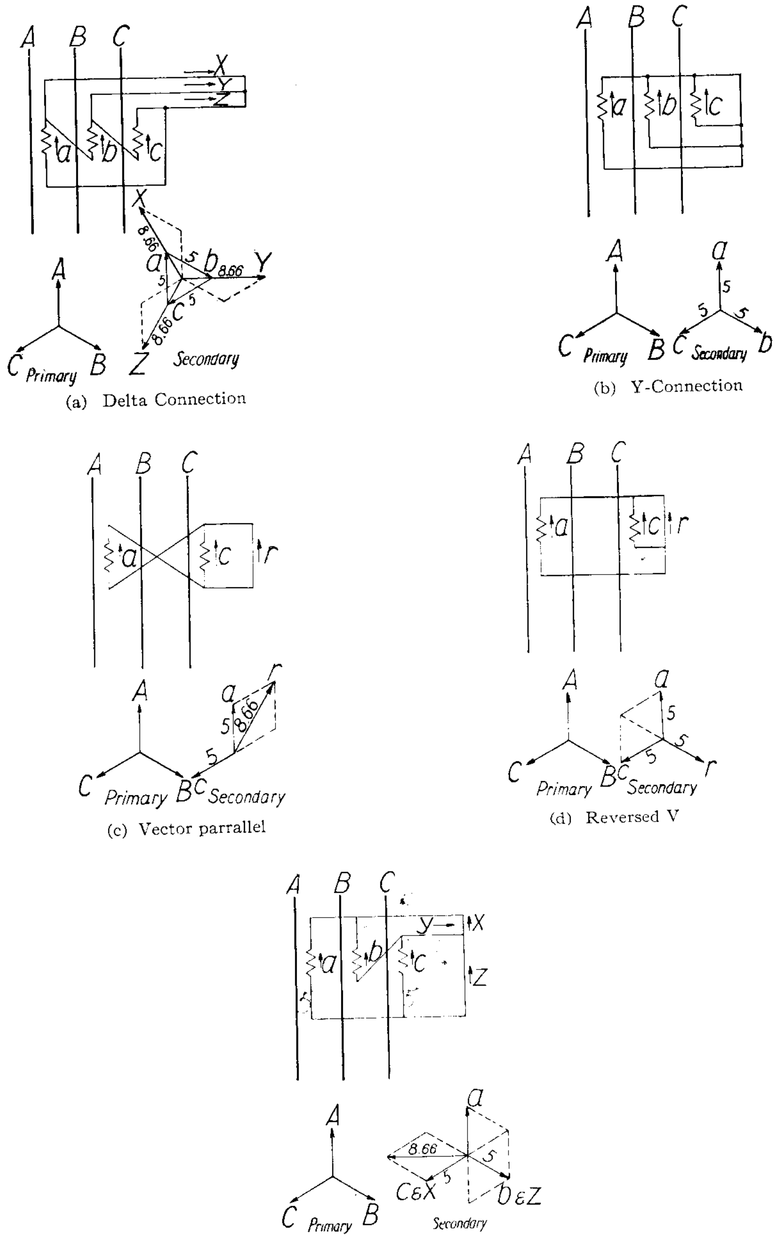
(c) Four-wire, independent. One transformer in each phase. V-Connection.
(d) Four-wire, inter-connected. T-Connection.



(e)

(e) Four-or-five-wire, independent or inter-connected. Double V-connection.

Fig. 14—Two-Phase Groupings of Current Transformers Showing Connections and Current Vectors.



(a) Delta Connection
(b) Y-Connection
(c) Vector parrallel
(d) Reversed V
(e) Z-Connection

Fig. 15—Three Phase Groupings of Current Transformers Showing Connections and Current Vectors.

Load on Voltage Transformers at 110 Volts*

		Voltage Element							
		25 Cycle				60 Cycle			
Instrument	Type	Volt-Amperes	Watts	Reactive Component	Power Factor %	Volt-Amperes	Watts	Reactive Component	Power Factor %
Voltmeter	SM-TM-TK-GM-JM	10.9	9.7	5	89	10.9	9.7	5	89
Voltmeter	PC	6.0	6.0	0	100	6.0	6.0	0	100
Voltmeter-Graphic	U	31.7	28.0	15	91	31.7	28.0	15	91
Voltmeter-Graphic	M	14.5	14.5	0	100	14.5	14.5	0	100
Wattmeter	SM-TM-GM-JM	7.6	6.65	3.7	88	7.6	6.65	3.7	88
Wattmeter	PC	6.0	6.0	0	100	6.0	6.0	0	100
Wattmeter-Graphic	M	9.7	9.7	0	100	9.7	9.7	0	100
Watthour-Meter	OA	12.3	1.6	12.2	13	12.3	1.6	12.2	13
Power Factor Meter / Reactive Factor Meter	SI-TI	9.7	7.3	5.5	79	9.7	7.3	5.5	79
Power Factor Meter, Graphic	M	13.3	12.1	5.5	91	13.3	12.1	5.5	91
Frequency Meter	SD-PD-TD	24.0	18.0	16.0	75	24.0	18.0	16.0	75
Frequency Meter, Graphic	M	42.0	30.0	29.5	72	42.0	30.0	29.5	72
Synchronoscope	SI-TI	13.3	12.1	5.5	91	13.3	12.1	5.5	91
Graphic Control Circuit	M	36.0	24.0	17.0	67	36.0	24.0	17.0	67
Relay	CR	12.5	2.5	12.2	20	22.2	3.3	22.0	15
Relay	CV	13.3	12.1	5.5	91	13.3	12.1	5.5	91
Regulator	AC Generator Voltage	60.0	48.0	36.0	80	60.0	48.0	36.0	80

Load on Current Transformers At 5 Amperes*

		Current Element							
		25 Cycle				60 Cycle			
Instrument	Type	Volt-Amperes	Watts	Reactive Component	Power Factor %	Volt-Amperes	Watts	Reactive Component	Power Factor %
Ammeter	SM-SR-TM-GM-JM	6.3	6.0	1.9	95	3.1	3.0	.8	97
Ammeter	PM-PR-PC	4.5	4.0	2.3	89	4.5	4.0	2.3	89
Ammeter	TK	8.0	5.0	6.25	63	8.0	5.0	6.25	63
Ammeter-Graphic	U	16.0	5.0	15.0	31	16.0	5.0	15.0	31
Ammeter-Graphic	M	10.0	6.0	8.0	60	10.0	6.0	8.0	60
Wattmeter	SM-TM-GM-JM	4.0	4.0	0.	100	4.0	4.0	0.	100
Wattmeter	PC	2.0	2.0	0.	100	2.0	2.0	0.	100
Wattmeter-Graphic	M	3.5	3.5	0.	100	3.5	3.5	0.	100
Watthour-Meter	OA	1.5	.7	1.3	47	1.5	.7	1.3	47
Power Factor Meter / Reactive Factor Meter	SI-TI	1.5	1.5	0.	100	1.5	1.5	0.	100
Power Factor Meter, Graphic	M	3.5	3.5	0.	100	3.5	3.5	0.	100
Relay	CO	16.0	9.6	12.8	60	17.0	8.5	14.8	50
Relay	CR	18.0	11.0	14.3	61	17.0	10.0	13.8	59
Relay	BT Transfer	16.0	4.0	15.5	25	34.0	8.5	32.9	25
Trip Coil	Light Pull S-62072	21.3	10.1	18.8	48	44.3	15.4	41.6	35
Trip Coil	Heavy Pull S-224185	25.0	11.8	22.0	47	70.5	24.7	66.0	35
Direct Trip Attachment And Trip Coil	S-209741, S-224185	55.2	22.0	50.6	25	125.0	56.0	114.0	22

*Values given are for single element. Usual polyphase instruments have two elements therefore the values given, power factor excepted, should be double.

The volt-amperes are given for 5 amperes in the current elements and normal voltage on the voltage elements.

COMBINATIONS OF VOLTAGE AND CURRENT TRANSFORMERS

Both voltage and current transformers may be used with the following instruments:

- Watthour meters
- Wattmeters
- Power factor meters
- Reactive factor meters
- Relays with both current and voltage elements

Any error in either the voltage or the current transformer will, of course, affect the reading of these instruments but with good transformers which are not overloaded, this effect is so small that it may usually be disregarded commercially in all instruments except watthour meters. Any error which exists is integrated by the watthour meter over a period of time, and since the reading of this meter is the basis of bills, it is important to have it as accurate as possible.

A clear distinction must be made between the load in the circuit to be measured and the load on the instrument transformers. The load in the primary circuit depends on the motors, lamps, etc., whose power consumption is to be measured, while the load on the instrument transformer depends on the instruments connected to it. With any given load in the main circuit the ratio and phase angle of the instrument transformers depend on their secondary load. Ratio error in the instrument transformers directly affects the reading of the instruments, but the effect of phase displacement depends on the power factor of the load in the main circuit. This is shown vectorially in Fig. 16. The greater the angle between current and voltage the larger will be the effect of

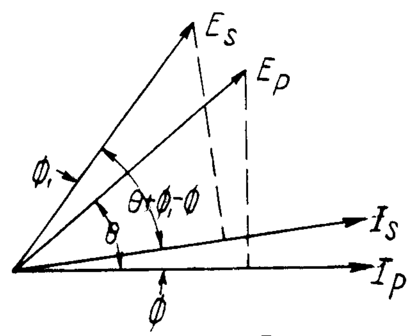


FIG. 16—EFFECT OF PHASE DISPLACEMENT IN CURRENT AND VOLTAGE TRANSFORMERS.

the instrument transformer phase displacement on the wattmeter reading.

In general, when the power factor of the secondary load on a voltage transformer is high the reversed-secondary voltage lags with respect to the primary, i. e. the phase displacement of the transformer is lagging; and when the power factor of the load is low, the phase displacement is leading. The phase displacement of a current transformer is always leading unless the power factor of its meter load falls below the power factor of its exciting current, a condition which is rare.

The combined ratio and phase displacement error of both voltage and current transformers can be calculated from the formula:

$$\text{Final correction factor } Kf = KK_1 \frac{\text{Cos } \theta}{\text{Cos } (\theta - \phi + \phi_1)}$$

Where K_1 = Ratio correction factor of voltage transformer

θ = Angle of lag in the line

ϕ_1 = Angle of voltage transformer phase displacement, leading.

K = Ratio correction factor of the current transformer.

ϕ = Angle of phase displacement of the current transformer, leading.

Fig. 16 illustrates how this formula is obtained for leading phase displacement in both transformers.

In using this formula it must be noted that ϕ_1 represents the angle of leading phase displacement in the voltage transformer, such as is obtained with an induction wattmeter. If this angle is lagging, as with a dynamometer wattmeter, it must be considered negative.

The tables on page 28 show the volt-amperes drawn from the voltage transformer and from the current transformer by various instruments. In selecting transformers for any group of instruments, it is important to see that the transformers are within the necessary accuracy when carrying the specified load. This is shown by the curves on pages 35 to 40, and sample calculations illustrating the use of the curves are given on pages 32 to 34.

GROUPING OF INSTRUMENTS

If several instruments are connected to the same transformer, the combined load may be found as follows:

Let W_1, W_2, W_3, etc. be the true watts required by the several instruments.

And M_1, M_2, M_3, etc. be the magnetizing reactive volt amperes required by the several instruments.

Then the volt-ampere load on the secondary of the transformer will be

$$L = \sqrt{(W_1+W_2+W_3+\dots)^2 + (M_1+M_2+M_3+\dots)^2}$$

and the power factor of this secondary load will be

$$PF = \frac{W_1 + W_2 + W_3 + \dots}{L}$$

Type FB Current Transformer (Dry Type) Indoor

These relations are true in single-phase, or two phase systems where the current from each transformer flows through its own load. As an approximation which is fairly close, the volt amperes of the secondary load may be taken as the sum of the volt amperes of the several instruments. And the power factor of the secondary load may be taken as the sum of the watts divided by the sum of the volt-amperes.

Three phase circuits having a set of transformers for each phase are apoximately equivalent to three single-phase circuits, and the transformer error, calculated as for a single phase system will be the average error. But when only two transformers are used on a three phase system, the calculation of the loads on the individual transformers becomes more complicated and is not included here. When accuracy is required such that exact correction for phase-angle and ratio is necessary, two transformers should not be used on three-phase systems.

USE OF THE CURVES

Below are given typical examples of meter and transformer installations, with calculation of the effect of the transformers on the meter readings.

Example I. On a 2200 volt single-phase 60 cycle system the following instruments are connected to the secondary of the voltage transformer:

1 SM voltmeter
1 SM wattmeter
1 OA watthour meter
1 SD frequency meter
1 Synchronoscope

The voltmeter reads 110 volts. What is the true voltage of the circuit?

Solution: First find the load on the voltage transformer. Take the figures for the seperate instruments from the table on page 28.

	Watts	Reactive Volt-Amperes
SM voltmeter..........	9.7	5.
SM wattmeter.........	6.65	3.7
OA watthour meter.....	1.6	12.2
SD frequency meter....	18.	16.
Synchronoscope	12.1	5.5
	48.05	42.4

L = $\sqrt{(48.05)^2 + (42.4)^2}$ = 64 volt-amperes
P.F. = 48.05 ÷ 64 = .751

Now refer to the curve on page 35 and read the ratio and phase angle for 64 volt-amperes, interpolating between the 80 percent P.F. and the 60 percent P.F. curves.

Per cent ratio = 100.7
Phase angle = 15′ leading

Then the true voltage is

Ep = 110 x 20 x 100.7 = 2215 volts

Example II. The wattmeter and watthour meter in Example I have their current coils connected to a 500 to 5 ratio Type A series transformer, which also carries a Type SM ammeter with a 500 ampere scale, and 5 ampere current coil. If the ammeter reads 425 amperes, what is the true current?

Solution: Refer to the table on page 28 and note the load on the current transformer.

	Watts	Reactive Volt-Amperes
SM wattmeter.	4.	0.
OA watthour meter.	.7	1.3
SM ammeter.	3.	0.8
Leads, 30′ of No. 12 wire*.	1.2	0.0
	8.9	2.1

$$L = \sqrt{(8.9)^2 + (2.1)^2} = 9.15 \text{ volt-amperes}$$

From the curve on page 38, interpolating between the 5 volt-ampere and the 10 volt-ampere curves at $\frac{425}{500} = 85\%$ primary current we find:

Per cent ratio = 99.8
Phase angle = 43′

Then the current, corrected for the transformer ratio error is 425 x .998 = 424.1 amperes.

Example III. Under the conditions described in Examples I and II, the wattmeter reads 750 KW. What is the power, corrected for transformer errors?

Solution: The power factor of the load will be

$$\text{P.F.} = \frac{750{,}000}{2215 \times 424.1} = 80\% \text{ (approximately)}$$

Using the formula on page 30,

the angle whose cosine is .80 is $36° 52' = \theta$

then $\theta - \phi + \phi_1 = 36° 52' - 43' + 15' = 36° 24'$

cos. $36° 24'$ = .8049.

*30 feet of No. 12 wire has a resistance of .048 ohms. Therefore watts at 5 amperes secondary current = $RI^2 = .048 \times (5)^2 = 1.2$. Reactive volt-amperes assumed as zero.

Then the final correction factor,

$$Kf = .998 \times 1.007 \times \frac{.8000}{.8049} = .9989$$

and the wattmeter reading corrected for transformer errors will be

$$P = 750 \times .9989 = 749.18 \text{ kw.}$$

Example IV. Would it be allowable to add a CO relay to the load on the current transformer, under the conditions described in Examples I and II?

Solution: With this addition, the load on the current transformer would be:

	Watts	Reactive Volt-Amperes
SM wattmeter	4.0	0.0
OA watthour meter.	.7	1.3
SM ammeter.	3.0	0.8
CO relay.	8.5	14.8
Leads 30′ of No. 12 wire	1.2	0.0
	17.4	16.9

$$L. = \sqrt{(17.4)^2+(16.9)^2} = 24.3 \text{ volt-amperes}$$

$$P.F. = 17.4 \div 24.3 = .72$$

Referring to the curves for Type A current transformers at 60 cycles, page 38, we find that the highest load for which a curve is plotted is 15 volt-amperes. This curve shows rather a high ratio and phase-angle error, especially at low loads, and the curve for 24-volt amperes would of course be much worse. Therefore the CO relay should not be connected to this current transformer. A seperate Type A current transformer could be used, or another type of transformer could be substituted having a capacity suitable for the new load.

Ratio and Phase-Angle Curves

Voltage Transformers.

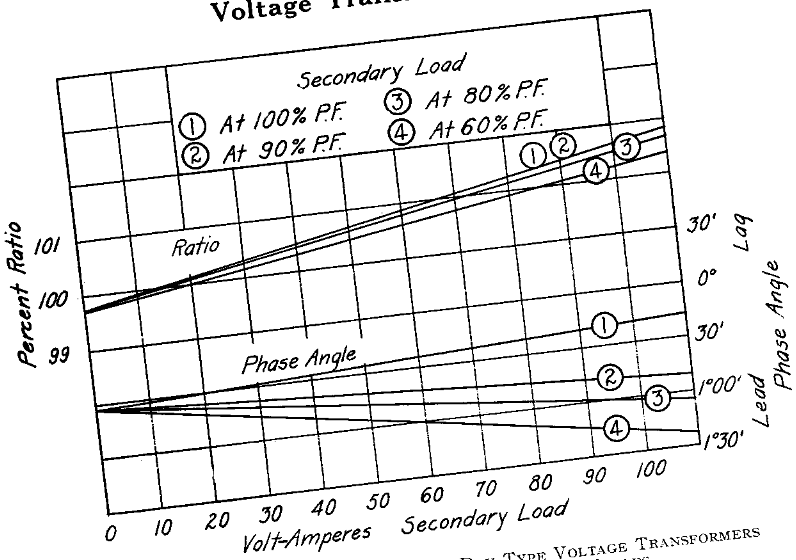


FIG. 17—RATIO AND PHASE-ANGLE CURVES DRY TYPE VOLTAGE TRANSFORMERS 25 CYCLES RATIO 20 TO 1.

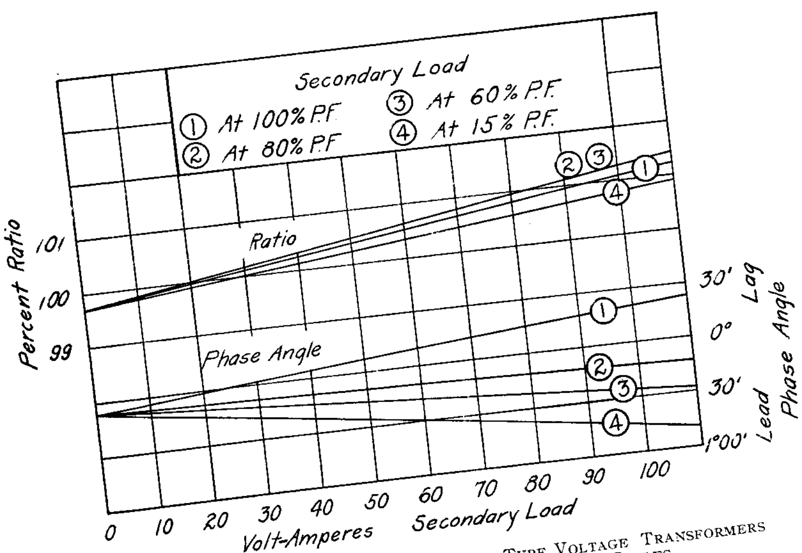


FIG. 18—RATIO AND PHASE-ANGLE CURVES DRY TYPE VOLTAGE TRANSFORMERS 60 CYCLES RATIO 20 TO 1.

Ratio and Phase-Angle Curves—Continued.

Voltage Transformers.

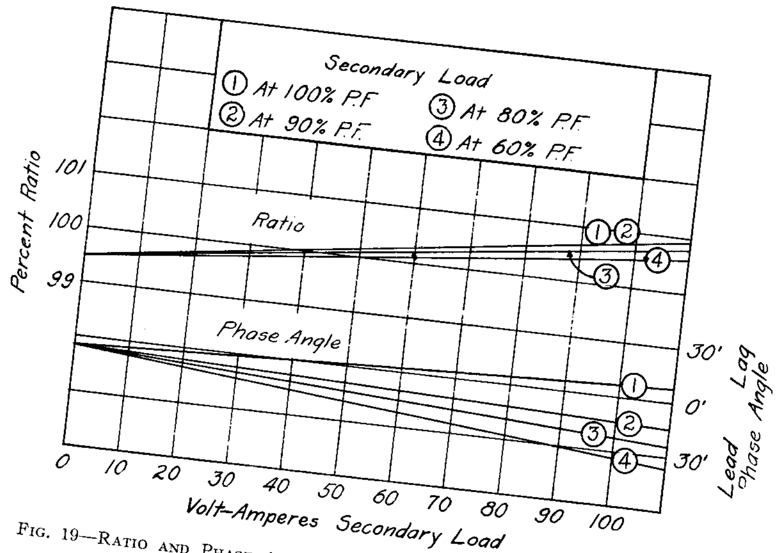


FIG. 19—RATIO AND PHASE ANGLE CURVES DRY-TYPE VOLTAGE TRANSFORMERS
RATIO 60 TO 1 25 CYCLES

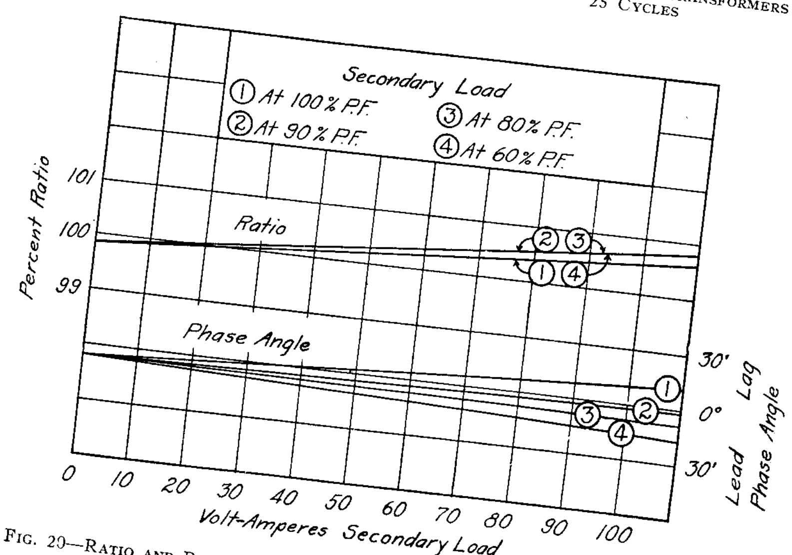


FIG. 20—RATIO AND PHASE ANGLE CURVES OIL INSULATED VOLTAGE TRANSFORMERS.
RATIO 60 TO 1 60 CYCLES.

Ratio and Phase-Angle Curves—Continued

Voltage Transformers.

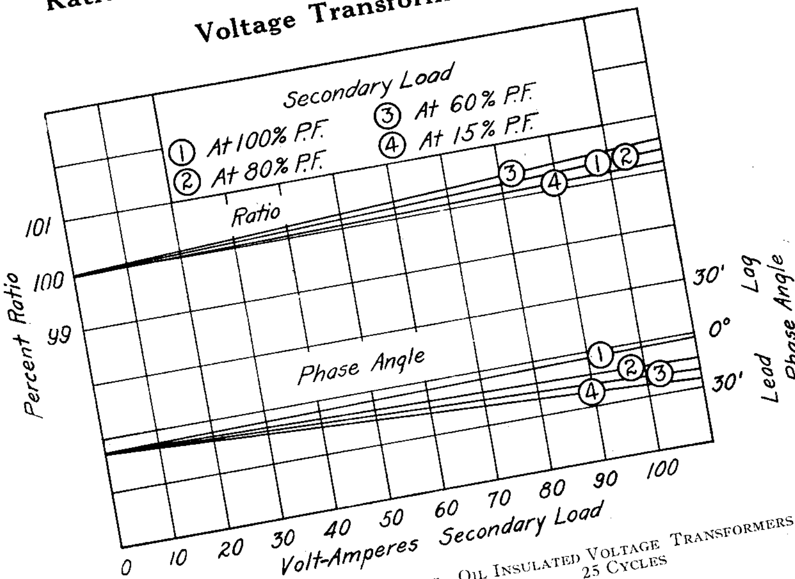


FIG. 21—RATIO AND PHASE-ANGLE CURVES OIL INSULATED VOLTAGE TRANSFORMERS 25 CYCLES RATIO 300 TO 1.

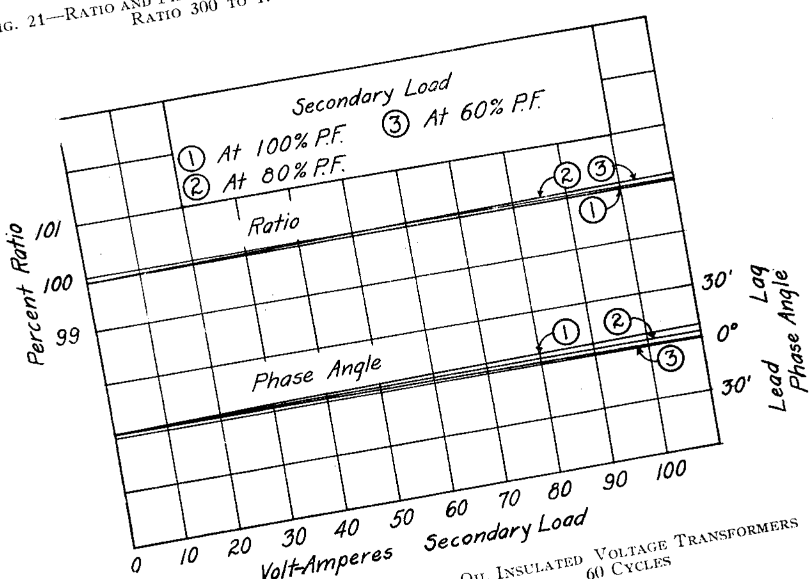


FIG. 22—RATIO AND PHASE-ANGLE CURVES OIL INSULATED VOLTAGE TRANSFORMERS 60 CYCLES RATIO 300 TO 1.

Ratio and Phase-Angle Curves—Continued

Current Transformers.

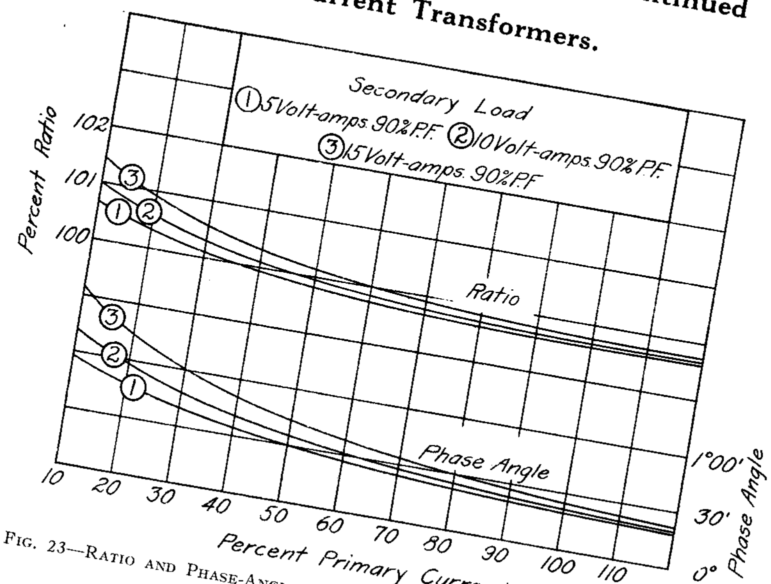


Fig. 23—Ratio and Phase-Angle Curves Type A Current Transformers.
25 Cycles

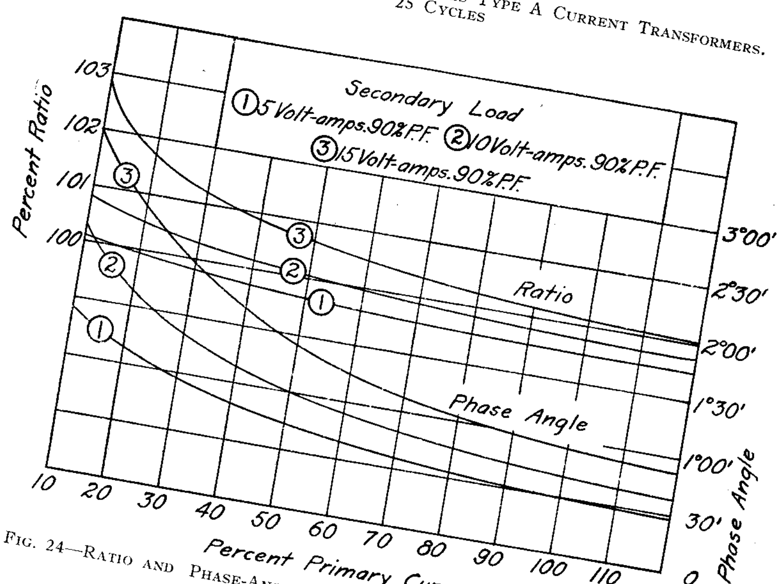


Fig. 24—Ratio and Phase-Angle Curves Type A Current Transformers.
60 Cycles

Ratio and Phase-Angle Curves—Continued

Current Transformers.

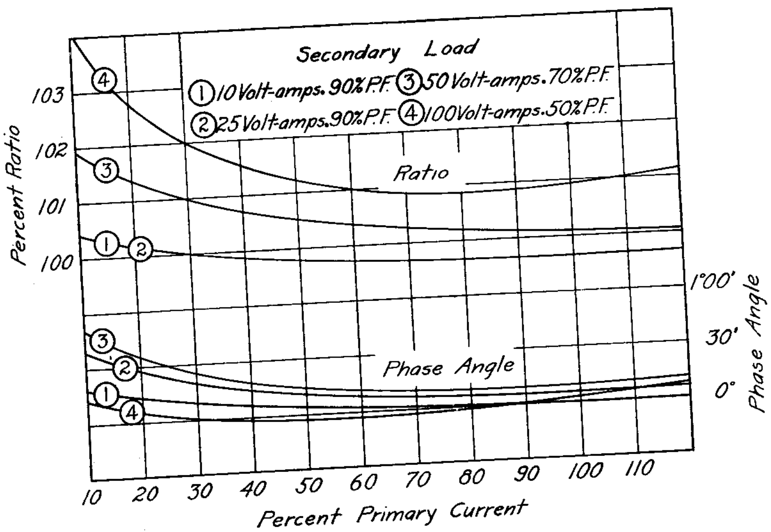


FIG. 25—RATIO AND PHASE-ANGLE CURVES TYPE KA CURRENT TRANSFORMERS. 25 CYCLES

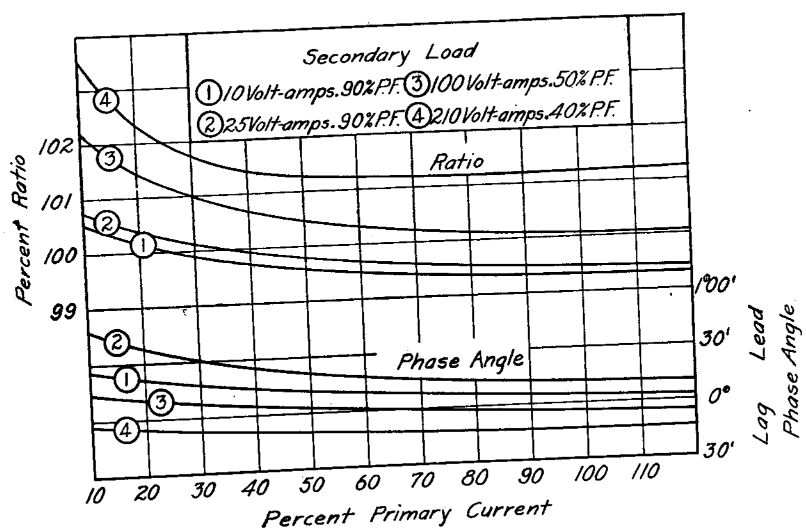


FIG. 26—RATIO AND PHASE-ANGLE CURVES TYPE KA CURRENT TRANSFORMERS. 60 CYCLES

Ratio and Phase-Angle Curves—Continued

Current Transformers.

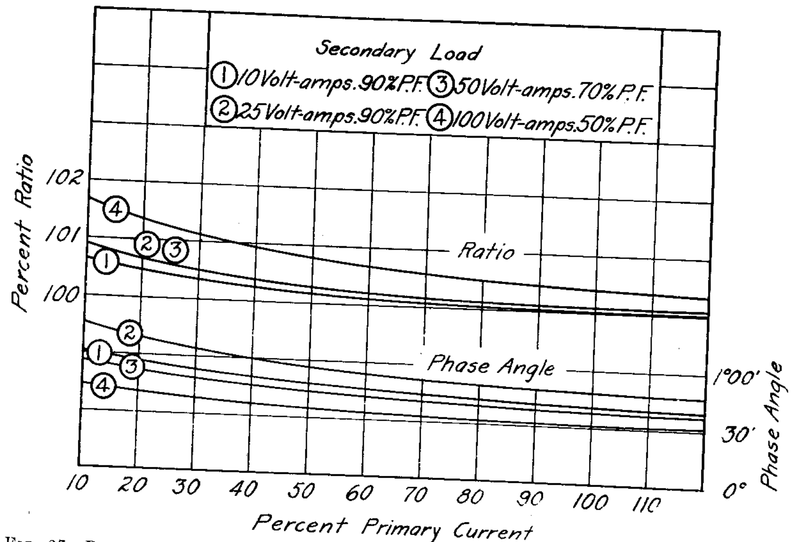


Fig. 27—Ratio and Phase-Angle Curves Type OB and OC Current Transformers. 25 Cycles.

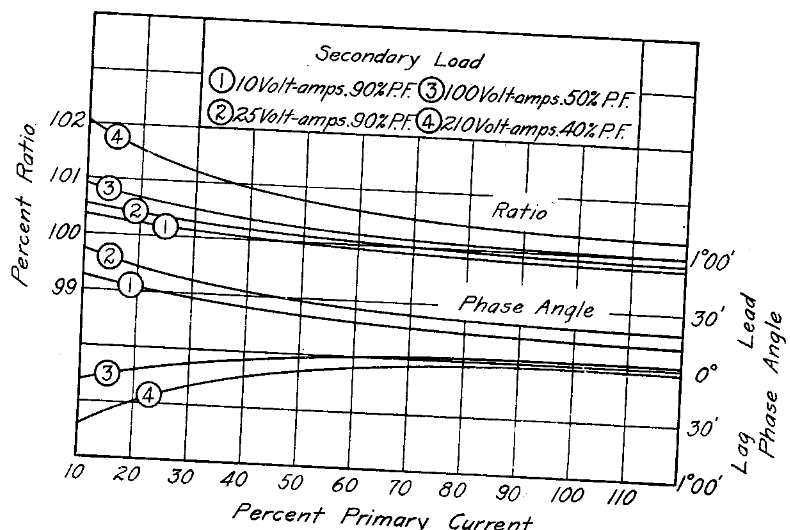


Fig. 28—Ratio and Phase-Angle Curves Type OB and CC Current Transformers. 60 Cycles.