same potential as b. If the guard ring had been directly earthed the capacitance between the l.v. electrode of C_1 and its guard-ring would shunt R; by bringing e to the potential of b this source of error is avoided. Successive adjustments of the main bridge and of Y are made until balance is secured whether a is joined to b or to e. The shielding of the bridge is indicated by the dotted lines.

There is no difficulty in determining the values of all the components of the bridge well within 0·02 per cent, so that ratio measurements can be guaranteed to this figure. Residuals in R, r_1, r_2, and C_1 are quite negligible. M is a 0·01 henry Campbell standard with a phase-angle of about 0·2 minutes at 50 cycles per sec. No difficulty is experienced, therefore, in measuring the phase-angle within 1 minute. The sensitivity is of the order of 0·01 per cent in ratio and 0·3 minute in phase-angle.

With C joined across r_1, and L_1, the operator for the apparatus joined across the secondary of the transformer is

$$z_s = r_2 + \frac{(r_1 + j\omega L_1)}{(1 - \omega^2 L_1 C + j\omega C r_1)}.$$

This impedance imposes a burden of 1·5 VA at 110 volts, and is usually negligible, but can in any case be allowed for by an equivalent reduction of the burden B. The current in it is $\mathbf{v}_s/z_s$ and the p.d. over the r_1 branch is $\mathbf{v}_s(z_s - r_2)/z_s$, so that the current in the primary of M is

$$\frac{\mathbf{v}_s}{z_s}\cdot\frac{(z_s - r_2)}{(r_1 + j\omega L_1)},$$

and its secondary voltage is,

$$j\omega M\frac{\mathbf{v}_s}{z_s}\cdot\frac{(z_s - r_2)}{(r_1 + j\omega L_1)}.$$

The drop of voltage over R is equal and opposite to the secondary voltage of M, i.e.

$$\frac{j\omega C_1 R \mathbf{v}_p}{1 + j\omega C_1 R} = -j\omega M\frac{\mathbf{v}_s}{z_s}\cdot\frac{(z_s - r_2)}{(r_1 + j\omega L_1)}$$

Substituting for z_s,

$$\frac{\mathbf{v}_p}{\mathbf{v}_s} = -\frac{M}{C_1 R}\cdot\frac{1 + j\omega C_1 R}{r_1 + r_2(1 - \omega^2 L_1 C) + j\omega(L_1 + C r_1 r_2)}$$

Assuming the current in R to be exactly in quadrature with $\mathbf{v}_p$, enables the upper quadrature term to be omitted; then neglecting $\omega^2 L_1 C$ in comparison with unity and remembering that the lower quadrature term is small,

$$K_v = V_p/V_s \doteq M/C_1 R(r_1 + r_2)$$

and
$$\tan\gamma \doteq \omega(L_1 + C r_1 r_2)/(r_1 + r_2)$$

provided γ is positive, i.e. $-V_s$ leads on V_p. When $-V_s$ lags on V_p or leads by an angle less than $\omega L_1/(r_1 + r_2)$, it is necessary to shunt C across r_2 instead of r_1, as shown dotted. Then

$$\tan\gamma \doteq \omega(L_1 - C r_2^2)/(r_1 + r_2).$$

13. **The use of a.c. potentiometers.** When a suitable a.c. potentiometer is available, voltage transformers can be readily tested by connecting voltage-dividers across both primary and secondary windings, appropriate tappings being selected upon them to get approximately equal voltages lying within the range of the potentiometer; this does not usually exceed 1·5 volts. The process is to measure the voltage across the primary potential fraction and that across the secondary fraction; from the known fractions of the voltage-dividers used the ratio is calculated at once. The phase-angle is obtained either by direct observation of the angle between the primary and secondary partial voltages or better still, since γ is usually small, by measuring the angle between the resultant of these voltages and that measured on the primary. Let R_p be the resistance of the primary voltage-divider, r_p the resistance of the tapped fraction, and v_p the voltage measured across r_p; let the corresponding secondary magnitudes be R_s, r_s and v_s. Further let ϕ be the angle between v_p and the resultant of v_p and v_s, these being in approximate opposition but for the angle γ; ϕ is more easily measured since it is a much larger angle than γ. Then if v be the resultant,

$$K_v = (v_p/v_s)\,(r_s/r_p)\,(R_p/R_s)$$

$$\sin\gamma = (v/v_s)\sin\phi \doteq \gamma.$$

CHAPTER XXVIII

RELATIVE DEFLECTIONAL METHODS FOR THE MEASUREMENT OF RATIO AND PHASE-ANGLE ERRORS

1. **Two-voltmeter method.** Two voltage transformers of the same nominal ratio can be compared by means of two voltmeters connected as in Fig. 276. In this diagram S is a standard transformer of known ratio; X is the transformer to be compared with S; V_1 and V_2 are two similar voltmeters which can

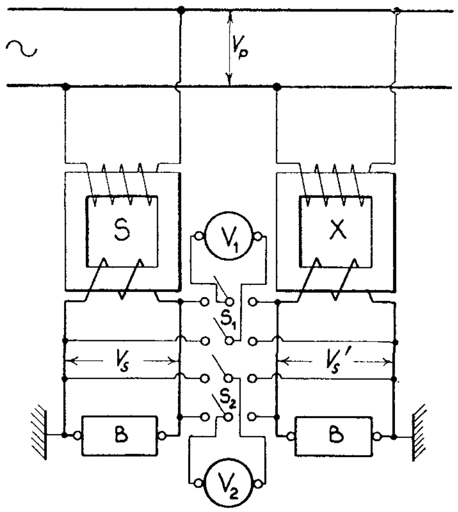


FIG. 276. TWO-VOLTMETER RELATIVE METHOD

be put at will either across the secondary of S or of X by operating the switches S_1 and S_2. With S_1 to the left and S_2 to the right let the secondary terminal voltages of S and X be V_s and V_s' respectively. The readings of V_1 across the secondary of S and of V_2 across the secondary of X will be v_1 and v_2 respectively; then if k_1 and k_2 are the correction factors for the voltmeter scales at these readings,

$$V_s = k_1 v_1 \text{ and } V_s' = k_2 v_2'.$$

Now throw both switches over, thus interchanging the voltmeters with respect to S and X. Then since the transformers

and the voltmeters are similar the burdens are practically unchanged, so that V_s and V_s' remain sensibly as before; the voltmeter readings become v_2 and v_1', so that

$$V_s = k_2 v_2 \text{ and } V_s' = k_1 v_1'$$

From these expressions

$$V_s^2 = k_1 k_2\, v_1 v_2 \text{ and } V_s'^2 = k_1 k_2\, v_1' v_2'$$

If V_p is the common primary voltage the ratio of S is

$$K_v = V_p / V_s$$

and that of X is

$$K_{vx} = V_p / V_s' = V_s K_v / V_s'.$$

Substituting,

$$K_{vx} = [\sqrt{(v_1 v_2 / v_1' v_2')}] K_v,$$

which eliminates the characteristics of the instruments. The method is suitable for ratio tests on site and gives fair precision if the voltmeters work near the tops of their scales. It is not possible without auxiliary means to find the phase angle.

2. **Two-dynamometer method.** Barbagelata* has described a simple two-dynamometer method for comparing the ratio and phase-angle of one voltage transformer with those of another; the arrangement is shown in Fig. 277 (*a*) and is analogous to the method for current transformers shown in Fig. 243 (*a*) on p. 490. The current coils of the two dynamometers are supplied in series with a current I from a phase-shifter. The volt-coil of D_s is joined across the secondary of the standard transformer S; this instrument serves to check the phase setting of the auxiliary current I and also to measure the secondary voltage V_s of S. The volt-coil of the detector dynamometer D is joined to the secondary windings so that it measures the difference between V_s and V_s'. The current I is first set in phase with V_s by regulating the phase-shifter until D_s gives a maximum reading of W_s watts, then

$$W_s = V_s I = (V_p / K_v) I$$

so that $\quad V_p = K_v W_s / I.$

As Fig. 277 (*b*) shows, the reading of D will be

$$W_1 = V_s I - V_s' I \cos (\gamma_x - \gamma).$$

* A. Barbagelata, loc. cit. (1921).

The phase of I is now advanced by 90° so that D_s reads zero; the reading of D becomes

$$W_2 = -V_s'I\cos[(\pi/2) - \gamma_x + \gamma] = -V_s'I\sin(\gamma_x - \gamma).$$

From the expression for W_1, remembering that the angles are small,

$$W_1/IV_p \doteqdot (V_s/V_p) - (V_s'/V_p)$$

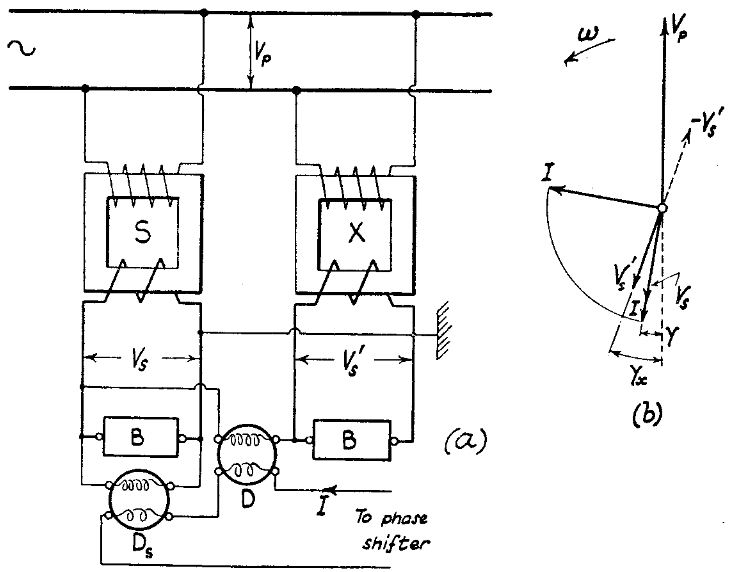


FIG. 277. TWO-DYNAMOMETER RELATIVE METHOD

substituting IV_p from W_s,

$$W_1/K_vW_s \doteqdot (1/K_v) - (1/K_{vx}) = -(\varepsilon_{vx} - \varepsilon_v)/K_{nv}$$

or

$$K_{vx} \doteqdot \frac{K_v}{1 - (W_1/W_s)} \doteqdot K_v\left(1 + \frac{W_1}{W_s}\right)$$

From the expression for W_2,

$$-(W_2/V_s'I) = \sin(\gamma_x - \gamma) \doteqdot \gamma_x - \gamma.$$

Hence,

$$\gamma_x - \gamma \doteqdot -\frac{W_2K_{vx}}{V_pI} \doteqdot -\frac{W_2}{W_s}\cdot\frac{K_{vx}}{K_v} \doteqdot -\frac{W_2}{W_s}\left(1 + \frac{W_1}{W_s}\right),$$

which determines the difference between the phase-angles of the transformers.

3. **Single-dynamometer method.** A single-dynamometer method due to Brooks* is shown in Fig. 278 (a), and proves very useful in tests made on site; for this purpose the dynamometer D may conveniently be a low-reading precision wattmeter. Readings of D are taken first with the current coil of the instrument carrying a current in phase with V_p, and second when this current is advanced by 90°, see Fig. 278 (b). The

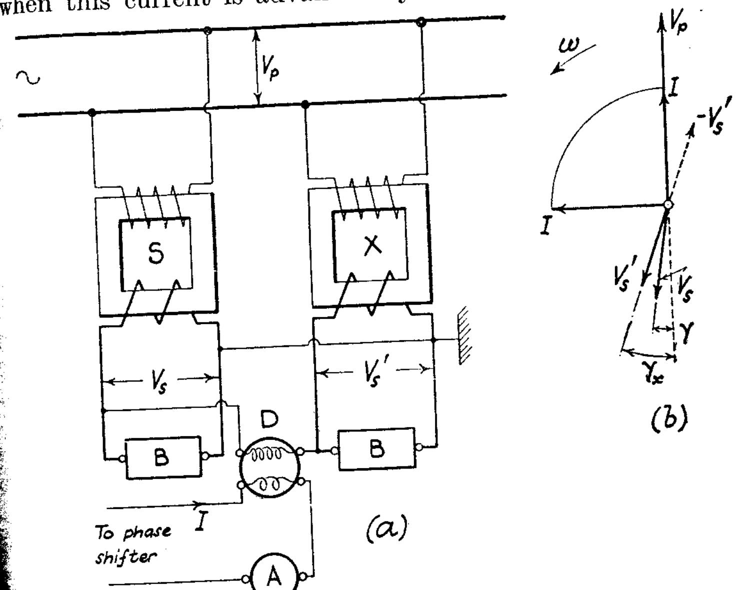


FIG. 278. SINGLE-DYNAMOMETER RELATIVE METHOD (BROOKS)

voltage coil is excited by the vector difference of the two secondary voltages. If W_1 and W_2 are the readings of D in these two circumstances,

$$W_1 = V_sI\cos(\pi - \gamma) - V_s'I\cos(\pi - \gamma_x)$$
$$= I[V_s'\cos\gamma_x - V_s\cos\gamma];$$
$$W_2 = V_sI\cos[(\pi/2) - \gamma] - V_s'I\cos[(\pi/2) - \gamma_x]$$
$$= I[V_s\sin\gamma - V_s'\sin\gamma_x].$$

Dividing the first by V_s and remembering that γ and γ_x are small,

$$W_1/V_sI \doteqdot (V_s'/V_s) - 1 \doteqdot (K_v/K_{vx}) - 1 \doteqdot (\varepsilon_{vx} - \varepsilon_v)$$

* H. B. Brooks, "Testing potential transformers," *Bull. Bur. Stds.*, vol. 10, pp. 419–424 (1914); F. A. Kartak, loc. cit. on p. 424 (1920); H. M. Crothers, *Elec. World*, vol. 74, pp. 119–121 (1919).

so that $$K_{vx} \doteq \frac{K_v}{1 + (W_1/V_sI)} \doteq K_v\left(1 - \frac{W_1}{V_sI}\right).$$

Similarly from the second relation,

$$\gamma_x - \gamma = -(W_2/V_sI).$$

The voltage V_s is read on a voltmeter forming part of the burden of S; the current I is read on the ammeter A.

To determine which transformer has the smaller ratio and which the smaller phase-angle, the following procedure may be adopted. With no-load on the secondary of X arrange the reading to be up the scale when taking the reading W_1. If on applying the load the reading increases, then the ratio of X at no-load is less than that of S. When taking the reading W_2, if X be further loaded its secondary current will lag more with respect to V_p. If, therefore, W_2 is increased on adding non-inductive load to X the secondary voltage thereof lags behind that of S, i.e. γ_x exceeds γ.

The method gives results in good agreement with laboratory methods; it is quick to use and has the great practical advantage of using only portable instruments of ordinary commercial pattern.

Bercovitz* has described a simple arrangement of apparatus that is worthy of notice. The primary voltage for S and X is derived from a step-up transformer, the primary of which is connected to two lines of a low tension, three-phase supply. In place of the phase-shifter, a three-phase-to-two-phase Scott-connected transformer is used, its secondaries giving 110 volts displaced by the required quarter-period. As a detector Bercovitz uses a centre-zero Weston dynamometer-voltmeter having ranges of 250–0–250, 25–0–25, and 2·5–0–2·5 volts, obtaining excellent agreement with absolute methods. As the scale is calibrated in volts a knowledge of I is unnecessary.

4. **Watt-hour meter method.** Agnew's watt-hour meter method described on p. 497 for testing current transformers is easily modified, as in Fig. 279, to compare two voltage transformers; the method is virtually an adaptation of the two-voltmeter method of Fig. 276, using watt-hour meters to secure greater sensitivity and to give the possibility of finding the phase-angle error in addition to the ratio. Two similar meters a, b are arranged so that their voltage circuits may be connected at will to the secondary windings of either transformer by operating the switches S_1, S_2; the current circuits are supplied in series from a phase-shifter. The process is

* D. Bercovitz, "Eichung von Spannungswandlern," *Elekt. Zeits.*, vol. 49, pp. 95–96 (1928). For a rough method using a voltmeter and omitting a phase-shifter, see C. W. Evans, "Measuring instrument transformer characteristics," *El. World*, vol. 91, p. 1017 (1928).

exactly the same as that used with current transformers, see p. 498. With the phase-shifter adjusted so that the meters work at unity power-factor, the revolutions made in a given time by the meter discs are observed (i) with meter a joined to S and meter b to X; (ii) with a joined to X and b to S. Then

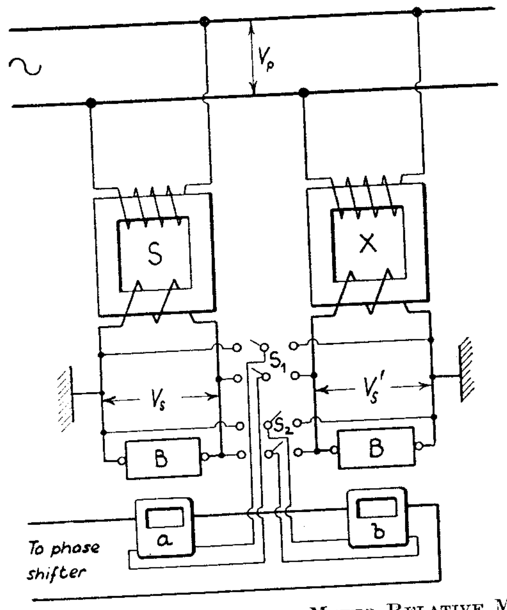


FIG. 279. AGNEW'S WATT-HOUR METER RELATIVE METHOD

if a_s, b_x, a_x, b_s are the observed numbers of revolutions it is easy to show, as on p. 499, that

$$K_{vx}/K_v \doteq \sqrt{(a_sb_s/a_xb_x)} \doteq 1 - (\varepsilon_{vx} - \varepsilon_v)$$

A second set of readings, a_s', b_x', a_x', b_s', is taken when the phase-shifter is regulated to make the meters work at a power-factor of 0·5 or less; if ϕ is the phase displacement then as before

$$\gamma_x - \gamma \doteq -\frac{1}{2\tan\phi}\left[1 - \frac{a_x'\,b_x'}{a_s'\,b_s'} \cdot \frac{a_s\,b_s}{a_x\,b_x}\right],$$

the signs being correct if both secondary voltages lag and $\gamma_x > \gamma$. To test which transformer has the greater errors, add a further non-inductive load to X; then if the differences are increased

X had originally the greater errors, since the addition of load increases the ratio and phase-angle of a voltage transformer.

The method is invaluable for tests on site and gives very high precision. Its main defect is that it is rather slow to use, but this can be overcome by the use of double-element meters in the way introduced by Slavik, see p. 501.

CHAPTER XXIX

RELATIVE NULL METHODS FOR THE MEASUREMENT OF RATIO AND PHASE-ANGLE ERRORS

1. **Shotter's double-dynamometer method.** The double-dynamometer method described on p. 504 for the testing of current transformers is easily adapted for use with voltage transformers; the necessary alteration in the connections can readily be understood by reference to Fig. 249. The current coils of the dynamometer are joined in series and supplied with a current of 5 amperes from a phase-shifter. The secondary of the standard transformer supplies one voltage element through the fixed resistance r_1; the secondary winding of the unknown transformer is loaded with an appropriate test burden in parallel with the second voltage element with its fixed resistance r_2 and the adjustable resistance r_3. The procedure is exactly the same as for current transformers and precisely similar formulae may be deduced; Shotter's paper (loc. cit.) should be consulted for details.

2. **Leeds & Northrup's dynamometer method.** The Leeds & Northrup Company of Philadelphia has introduced a useful testing set described in full detail in the company's Bulletin No. 716 of 1927, the general principle being illustrated by Fig. 280. The burden of S consists of a voltmeter V, which serves merely to set the secondary voltage to the desired value, and a resistance in parallel therewith; a second similar resistance is put in parallel with the test burden on the secondary of X. It is clear that if the two transformers had similar phase-angles and the contact A were fixed at the middle of the resistor then the difference of ratio between the transformers could be measured by sliding the contact B until the detector gives null indication. Actually there is a phase-difference between the two secondary voltages, and this is allowed for by means of the condenser C which shunts a portion of the resistor connected to S; the sliders of C are rigidly attached together so that a change in the position of one is accompanied by a similar change in the other, their position relative to A giving compensation for leading or lagging phase-differences. It is found that the phase-angle adjustment interferes with that for ratio; to overcome this A is made

adjustable, its position being automatically regulated by the motion of B so that the interference is allowed for. By these means the ratio and phase-angle settings are made independent, direct-reading, and free from corrections. It will be noted that all sliding contacts are in positions where their contact-resistances cannot cause any errors. The balance conditions are somewhat complicated, and it is usual to calibrate the

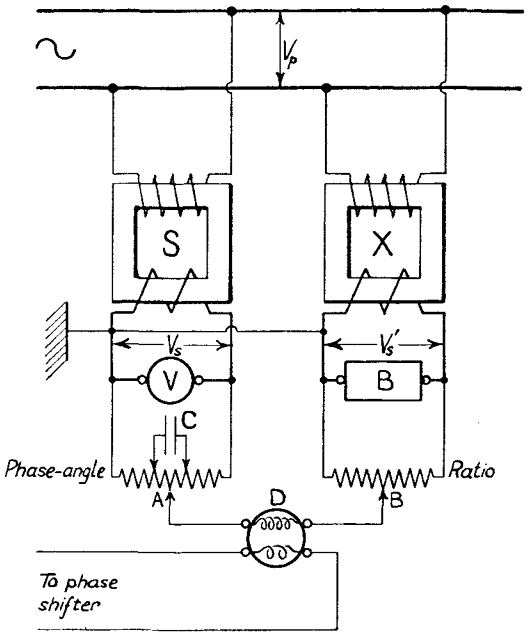


FIG. 280. LEEDS & NORTHRUP'S RELATIVE METHOD

scales by direct application of voltages in known ratio with known phase-displacements.

The balance settings are readily made with accuracy by the use of a portable dynamometer, taking advantage of its phase-selectivity.* Starting with the ratio-contact at about 100 per cent, the dynamometer reading is reduced to zero by adjustment of the phase-shifter; then changing the phase by 90° the resulting deflection is balanced out by the phase-angle dial. Now turning the phase-shifter back it will be necessary to adjust the ratio dial to obtain a null reading; a further change of 90° is made and the phase-angle dial regulated, and so on

* It will be clear, of course, that this is not essential and that a vibration galvanometer might advantageously be substituted.

until no deflection occurs with the phase-shifter in both positions. When the ratio-scale is read the factor obtained is multiplied by the ratio of S to obtain that of X; the phase-angle reading is algebraically added to the angle of S to give that of X. The angle-scale is provided with black figures for the positive angles and red for negative values, thus rendering mistakes of sign very unlikely to occur. The ratio and phase-angle dials, the dynamometer, and all necessary switches are contained in a portable case; only a voltmeter and portable phase-shifting transformer are necessary to complete the equipment. The apparatus and its operation are in every way similar to the Silsbee testing set made by the same firm (see p. 510). The testing set imposes a burden of about 3·1 volt-amperes at a power factor of 0·995 leading on the secondaries of S and X; the time taken for a single-point test is about 2 minutes. The range is ± 5 per cent in ratio and ± 2 degrees in phase-angle.

Another method somewhat similar to this has been recently described by Berghahn and Janssen.* The secondary voltages of X and S are opposed through a vibration galvanometer, X being loaded with its test-burden. The secondary of S supplies a small transformer provided with two secondary windings, one of which is closed through a resistor with a sliding potential contact. The other secondary supplies a second similar slide-wire resistor in series with a condenser, a resistor being shunted across the combination and a second condenser joined in series with the whole. By these means the current in the second slide-wire can be adjusted to be in quadrature with that in the first. Voltages tapped off these two slide-wires are inserted in the galvanometer branch and by moving the sliders an exact balance of the secondary voltages of X and S can be obtained. The reading of the first slide-wire measures ε_v and of the second γ; full details of the theory, adjustment and use of the method are given in the paper.

3. **Barbagelata's bridge method.** In the method shown in Fig. 281 (a)† the dynamometer is used to set the phase of the current I, balance being secured by regulation of the phase-shifter and r until the vibration galvanometer gives no deflection. Let W be the reading of D in watts, V_s the reading of the voltmeter V, and ϕ the phase-displacement between V_s and I when balance occurs. Then

$$W = V_s I \cos \phi.$$

* A. Berghahn and H. Janssen, "Eine billige Kompensationseinrichtung zur vergleichenden Spannungswandlerprüfung bei grosser Empfindlichkeit," *Arch. f. Elekt.*, vol. 29, pp. 356–361 (1935).

† A. Barbagelata, loc. cit. on p. 433 (1921).

From the geometry of the vector diagram, Fig. 281 (*b*), since rI balances the resultant v of V_s and $-V_s'$,

$$rI \cos(\phi - \gamma_x + \gamma) + V_s \cos(\gamma_x - \gamma) = V_s',$$
$$rI \sin(\phi - \gamma_x + \gamma) = V_s \sin(\gamma_x - \gamma).$$

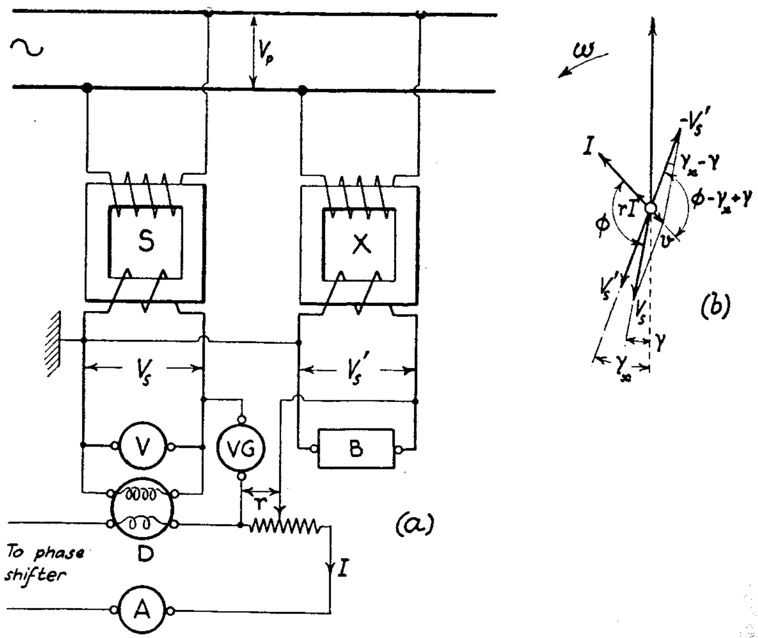


FIG. 281. BARBAGELATA'S BRIDGE RELATIVE METHOD

Neglecting $\gamma_x - \gamma$ in comparison with ϕ and remembering that γ_x and γ are both very small the first relation becomes,

$$rI \cos\phi + V_s \doteqdot V_s',$$

or

$$V_s' - V_s \doteqdot rI \cos\phi.$$

Dividing by $V_p = K_v V_s$ and substituting $I \cos\phi = W/V_s$ makes

$$K_{vx} \doteqdot \frac{K_v}{1 + (rW/V_s^2)} \doteqdot K_v\left(1 - \frac{rW}{V_s^2}\right).$$

The second relation becomes

$$rI \sin\phi \, . \cos(\gamma_x - \gamma) \doteqdot V_s \sin(\gamma_x - \gamma)$$

or

$$\tan(\gamma_x - \gamma) \doteqdot (rI/V_s)\sin\phi \doteqdot (r/V_s^2)\sqrt{(V_s^2 I^2 - W^2)}$$
$$\doteqdot \gamma_x - \gamma.$$

4. **A.C. potentiometer method.** If an a.c. potentiometer is available, the ratios and phase-angles of two voltage transformers can be compared by measuring the magnitude and phase of their secondary voltages and that of the vector difference between them, in the way described on p. 567.

CHAPTER XXX

CHOICE OF METHOD FOR MEASUREMENT OF RATIO AND PHASE-ANGLE ERRORS. PRACTICAL PRECAUTIONS

1. **Introductory.** Methods for testing voltage transformers are much less numerous than those introduced for testing current transformers. Consequently, the task of selecting the methods best adapted to the uses of laboratory practice, routine testing and testing on site is a relatively easy one. Moreover, the whole test is much simpler than that of a current transformer; in many cases all that is required is the value of K_v and γ for a specified rated burden and with rated voltage applied to the primary side. In some other cases the variation of the ratio and phase-angle with burden is desired, and as this characteristic is linear only two points are required to fix it definitely.

2. **Methods for laboratory tests. High voltage tests.** For absolute measurements of the highest precision the deflectional dynamometer method of Agnew and Fitch, Fig. 258, and the electrometer methods of Fig. 261 have been used, but have the disadvantage that very special apparatus is required, such as is not readily obtainable. Absolute null methods, using a vibration galvanometer as the detector, do not require any special equipment apart from the resistance voltage-divider, and can be arranged to give an almost equally high accuracy. The best of these is the method of Agnew and Silsbee, Fig. 269, especially in the modification used at the National Physical Laboratory, Fig. 270.

Up to about 30 kV the method mentioned is quite sat factory, but its applicability at higher voltages depends o a suitable shielded resistance voltage-divider being availab These are by no means easy to construct for high-voltage and are now superseded for that purpose by standard ai compressed-gas condensers such as are commonly emplo in Schering bridge technique. Four methods using h.v. co densers have been described, illustrated in Figs. 272, 27 274, and 275; of these, the last named appears to offer t greatest all-round advantages.

3. **Methods for routine testing and for tests on site.** For t routine testing of transformers in the works and also for te

on site relative methods have great advantages in speed, sensitivity, and safety. Since all measurements are made on the secondary sides of the standard and unknown transformers, and none of the apparatus is connected to the h.v. supply, a high degree of safety for the operator is secured; this is a matter of great importance where such testing is done by non-technically trained labour. Since all voltage-dividers are eliminated and all apparatus is connected directly in the secondary circuits, a high sensitivity can be secured even with pointer-type instruments. For works use the dynamometer methods of Brooks, Fig. 278, and the null methods of Shotter, Leeds & Northrup, Fig. 280, and Barbagelata, Fig. 281, can be recommended.

For tests on site portability of the apparatus and adequate sensitivity with pointer instruments are essential features. In this respect Brooks's method, Fig. 278, is perhaps the best. The testing sets designed by Shotter and by Leeds & Northrup are also very suitable and quick to use. Agnew's watt-hour meter method, Fig. 279, gives very high accuracy, and is simple, but has the disadvantage of being rather slow.

4. **Practical precautions.** Just as in current transformer testing, the test circuit must be assembled so that residual errors and the effects of inductive interference are reduced to the least possible amount. Stray magnetic fields are usually very slight and cause no trouble. On account of the high voltage on the primary side, earth-capacitances may cause serious errors unless the l.t. side of the network is suitably shielded and earthed. Various ways of doing this, appropriate to the different methods, have been described in the preceding chapters and need not be referred to here. In absolute methods it is essential that a common point of the primary and secondary shall be earthed; the balancing adjustments must be put into the test circuit on the earthed side, thereby ensuring the operator's safety. All high-voltage portions of the circuit must be well out of reach. Relative methods have the advantage that no part of the measuring gear is joined to the h.v. side; it is nevertheless safer, even in this case, to earth one point in the secondary circuit. It is common practice to shunt a protective device across the secondary terminals to guard against a rise of voltage in case of insulation breakdown. A simple spark-gap, consisting of a pair of small metal plates separated by thin paper, or a neon lamp may be used.

PART 5

ADDITIONAL TESTS ON CURRENT AND VOLTAGE TRANSFORMERS

CHAPTER XXXI

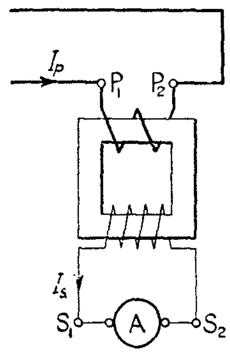
POLARITY AND TERMINAL MARKING

1. **Introductory.** In polyphase power and energy metering and also in the operation of protective apparatus, correct connection of the various instruments with regard to the sequence of their terminals is essential if the indications given by the instruments are to have a definite meaning. For this reason it is usual to mark the polarity of the terminals of the instruments in order that errors in connecting-up may be avoided. When the instruments are operated from the secondaries of instrument transformers it is clearly possible for a wrongly-connected transformer to introduce a reversal of phase; hence, it is essential for the polarity of transformer terminals to be indicated in accordance with some convenient convention.

It has been pointed out on p. 38 that a current transformer is electrically equivalent to a shunt and a voltage transformer to a voltage-divider; these facts enable simple definitions for the relative polarities of the primary and secondary terminals to be easily devised. Let the voltage circuit of a wattmeter be connected to an a.c. supply and let its current coil be supplied from the secondary of a current transformer, the instrument being arranged to read up-scale. Conventionally regarding one terminal of the current coil as positive, the secondary terminal to which it is connected should be noted and marked. Now transfer the current coil from the secondary terminals to the primary terminals, keeping the voltage circuit unchanged, and again arrange the instrument to read up-scale, marking the primary terminal which is then joined to the positive terminal of the current coil. Then the marked primary and secondary terminals have the same polarity. Such a test is not always practicable, but it is the basis of the various national rules and of many methods for testing polarity. It is not our purpose here to discuss the great variety of practical

problems arising out of the correct connection of metering and protective equipment, as these topics are fully dealt with elsewhere;* we shall be solely concerned with the national definitions and with methods by which polarity may be tested.

2. **National Rules.** (*a*) CURRENT TRANSFORMERS. In accordance with the preceding definition Fig. 282 shows diagrammatically the polarity of a current transformer; when P_1 is positive to P_2, S_1 is positive to S_2. In other words, at this



Nomenclature for	P_1	P_2	S_1	S_2
Great Britain.	M	L	(M)	(L)
Germany.	K	L	k	l
Czechoslovakia.	K	L	k	l
France.	P_1	P_2	S_1	S_2
Sweden.	P_1	P_2	S_1	S_2

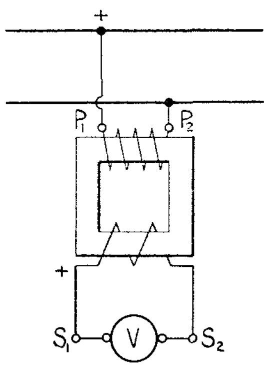
FIG. 282. POLARITY MARKINGS FOR CURRENT TRANSFORMERS

instant, if the transformer were removed and the terminals P_1, P_2 were connected directly to the ammeter A, so that the terminal of the latter which was joined to S_1 is now joined to P_1, the current through the instrument would be in the same sense as before. All the transformer has done is to alter the magnitude of the current through the ammeter without interfering with its direction at a given instant, taking direct connection in the primary lead as the standard of reference. With this idea in mind Fig. 282 gives a table of the terminal markings used in five countries, falling into three different groups.

The British Standard Specification 81/1927 merely makes a recommendation in an Appendix which is given for information only and is not mandatory. In all other countries the terminal notation is part of the specification and is obligatory. The German Rules are very detailed. If a transformer has several tappings, either on its primary or its secondary side or on both, the appropriate letters are given subscripts 1, 2, 3, etc., in order of increasing numbers of turns. When several

* J. Auchincloss, "Notes on transformer polarity and connections," *Gen. Elec. Rev.*, vol. 29, pp. 783–796, 862–872 (1926); "Polarity markings of instrument transformers," *Power*, vol. 72, pp. 970–971 (1930).

windings are provided for parallel connection, the terminals of the first have the simple tabulated marking; those of the second are given a subscript a, of the third b, and so on. If a transformer has several cores and a single bar primary the prefixes 1, 2, 3, etc., are added to the terminal letters of their secondary windings. When the transformer is of the bushing type in an oil switch the outer end of the primary conductor is marked K and the inner end under oil is L. The French Rules state very clearly the definition given in Section 1. In all the Rules it is laid down that the terminal marking must be indelible.



Nomenclature for	P_1	P_2	S_1	S_2
Great Britain	V+	V	(V+)	(V)
Germany	U	V	u	v
Czechoslovakia	M	N	m	n
France	P_1	P_2	S_1	S_2
Sweden	A	B	a	b

Fig. 283. Polarity Markings for Single-phase Voltage Transformers

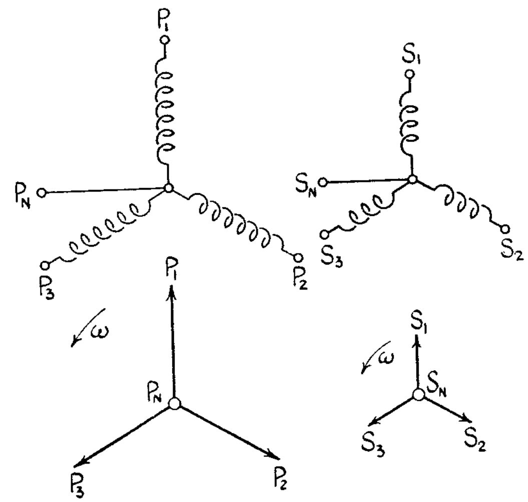
(*b*) Single-phase Voltage Transformers. Fig. 283 shows in a similar way the polarity of a voltage transformer and the terminal markings adopted in the same five countries; all the recommendations are different. When P_1 is positive to P_2, S_1 is positive to S_2, and the instrument could be removed and put across P_1, P_2 without the instantaneous direction of the current through it undergoing any change.

(*c*) Three-phase Voltage Transformers. The normal arrangement for three-phase transformers is with star-connected windings, as in Fig. 284. The connections are made in such way that when P_1 is positive to P_N, S_1 is positive to S_N. Again the nomenclature of the several countries is entirely different, as the table shows.

The British Rules, while recommending the arrangement of Fig. 284 for regular use, also specify markings for (i) star-star transformers with the secondary of reversed polarity, indicated by adding R to the secondary terminal letter; (ii) star-delta

transformers with both windings in the same sequence; and (iii) star-delta transformers with the secondary sequence reversed. Details will be found in B.S.S. No. 81—1927.

(*d*) General Remarks. In addition to the countries mentioned above, Italy and the United States have made some



Nomenclature for	P_1	P_2	P_3	S_1	S_2	S_3	P_N	S_N
Great Britain	A	B	C	(A)	(B)	(C)	N	(N)
Germany	U	V	W	u	v	w	O	o
Czechoslovakia	X	Y	Z	x	y	z	O	o
France	P_1	P_2	P_3	S_1	S_2	S_3	P_0	S_0
Sweden	A	B	C	a	b	c	O	o

Fig. 284. Polarity Markings for Three-phase Voltage Transformers

general recommendations regarding polarity. The Italian Rules state that it is sufficient to indicate corresponding primary and secondary terminals by a similar sign, but no particular sign is suggested. The American Rules also make no specific recommendation but include statements equivalent to our definitions. In particular it is specified that the terminals of all current and voltage transformers shall be similarly arranged as regard instantaneous polarity, and shall be so marked "that when connection is made to a secondary terminal bearing the same marking as a given primary terminal the polarity will be the same as if the primary service conductor itself were detached from the transformer and connected directly to the secondary conductor."

In view of the great diversity of notation used to indicate polarity it would seem that the question is one that might well form the subject of international discussion and agreement.

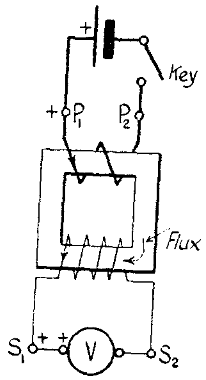


FIG. 285
D.C. METHOD FOR TESTING POLARITY

3. **Testing polarity.** A simple method for testing the polarity of an instrument transformer is shown in Fig. 285. A d.c. moving-coil voltmeter is connected to the secondary winding with its positive terminal joined to S_1; the positive pole of a cell is joined to P_1. If on making momentary contact with the key the voltmeter gives a ballistic throw up-scale, then the instantaneous polarity of the corresponding terminals P_1, S_1 is correct, as a simple application of Lenz's law will show. To avoid permanent magnetization of the core the current used must be very small, and in any case the transformer is best demagnetized after such a d.c. polarity test. A pocket-lamp battery forms a suitable source of current and a central-zero voltmeter has the advantage that deflections in one direction may be labelled "correct" and in the other "incorrect"; Kuhnel* has described a portable testing set on this principle.

To avoid entirely the danger of unidirectional magnetization a.c. methods† are to be preferred. Any relative method, in which the ratio error and phase-angle of a test transformer are compared with those of a standard transformer, automatically checks the polarity of the one transformer against that of the other. The like is also true of some of the absolute methods where, in order to get balance, the polarity of the primary side must be correctly related to that of the secondary side. If, however, it is desired to establish the polarity by an independent a.c. test as, for example, when the correctness of the terminal markings is suspected, but the errors are known to be satisfactory, several methods are available. The most obvious is

* R. Kühnel, "Prüfgerät für Klemmenbezeichnungen an Messwandlern," *E. u. M.*, vol. 46, pp. 218–219 (1928).

† 'Sigma,' "Instrument transformer polarities," *Elec. Times*, vol. 79, p. 1073 (1931). Also see *Elect. J.*, vol. 27, p. 243 (1930).

the wattmeter test mentioned on p. 582. This can readily be turned into a relative test, when a standard transformer of known polarity is available by exciting the two transformers from a common supply (primaries in series if current transformers and in parallel if voltage transformers are under test) and then observing whether deflections are obtained in the same direction when one of the wattmeter elements is connected in succession, first to the secondary of the test transformer and

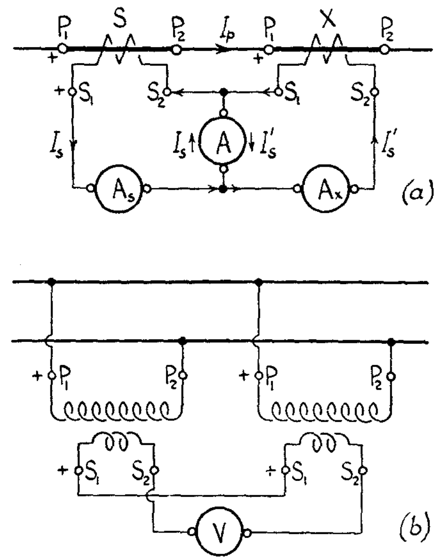


FIG. 286. DIFFERENTIAL METHODS FOR TESTING POLARITY USING STANDARD TRANSFORMER

then to that of the standard, the other element of the wattmeter being separately excited.

Differential methods using a standard transformer are illustrated in Fig. 286. For current transformers the primaries are supplied with a common current I_p and the secondaries are joined in series, bridged by an ammeter A, as in Fig. 286 (*a*). If the polarities are correctly marked, the reading of A will be very small, since I_s and I_s' flow through it almost in opposition of phase; to provide against the possibility of incorrect polarity A should be capable of carrying the sum of the secondary currents, i.e. 10 amperes at rated value. For voltage transformers a differential connection with correct polarity, Fig. 286 (*b*), should result in V reading nearly zero; again to avoid accidental incorrect connection V should have a range of 200 volts.

Differential methods without the use of standard transformers are also easily devised, as shown in Fig. 287. For a current transformer, Fig. 287 (*a*), the current I_p is observed when the switch is on contact *a*. Then if the polarity is correct, the

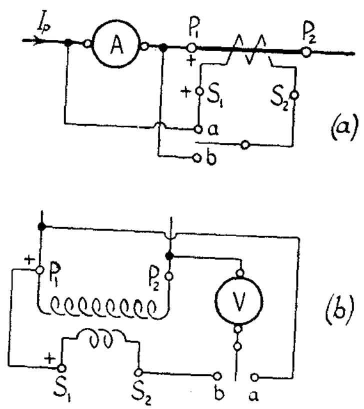


FIG. 287. DIFFERENTIAL METHODS FOR TESTING POLARITY WITHOUT STANDARD TRANSFORMER

ammeter reading should be higher when the switch is turned to *b*. Similarly, for a voltage transformer, Fig. 287 (*b*), about 100 volts is applied to the primary and is measured by putting the switch on *a*. Then with correct polarity the reading will fall if the switch is moved to *b*. The test of Fig. 287 (*b*) gives rise to the term "subtractive polarity," often used in American publications, for transformers with their terminals marked according to our definitions. If, when two adjacent, similarly marked terminals of the primary and secondary windings, e.g. P_1 and S_1, are joined together and a voltage is applied to one of the windings, the voltage across the remaining pair of adjacent terminals (P_2, S_2) is smaller than that applied, then the polarity is termed "subtractive."

CHAPTER XXXII

TEMPERATURE RISE

1. **I.E.C. recommendations. General remarks.** In International Electrotechnical Commission Publication 44, 1931 it is provided that the temperature rise of an instrument transformer under normal rated conditions shall not exceed the limits prescribed for corresponding power transformers in Publication 34, 1930. Taking these recommendations as a basis, we can then pass to the examination of the rules actually in force in the various countries.

The permissible limits of normal temperature rise depend upon a number of factors, of which the most important is the kind of insulating material that is used and the conditions that are provided for cooling it. The I.E.C. distinguishes four classes of insulating materials—

Class O. Cotton, silk, paper, or similar organic materials neither impregnated nor immersed in oil.

Class A. The same materials when impregnated or when immersed in oil. Also enamel insulated wire.

Class B. Mica, asbestos and similar inorganic materials in a built-up form combined with binding cement. If Class A materials are used in small quantities in conjunction with materials of Class B, the insulation is regarded as Class B.

Class C. Mica without cement; porcelain, glass, quartz and other similar materials.

Class O materials are used in the construction of dry-type instrument transformers, usually in association with porcelain which falls into Class C. Materials in Class B are seldom employed, except in mica bushings, for the largest number of instrument transformers are insulated with materials of Class A.

Assuming the surrounding cooling air to have a temperature not exceeding 40° C. and that the height above sea-level is not more than 1000 metres (about 3300 ft.) the limits of temperature rise are prescribed on page 590.

For Class O materials the limits of temperature rise are 15° C. lower than for Class A; limits for Class C are not yet assigned. If the cooling air exceeds 40° C. the limits for windings in air

Limits of Temperature Rise

Insulation of	Temperature Rise	
	Class A	Class B
Transformer Windings—		
In air	55° C.	75° C.
Oil-immersed	60° C.	60° C.
Oil. At top level	50° C.	
Iron core and other parts not in contact with windings	70° C.	
,, ,, ,, in contact with windings .	Same as the windings	

are reduced by 10°, for windings in oil by 15°, and for the oil itself by 10°.

It is recommended that the ambient temperature of the cooling air be measured by the average reading of several thermometers at different points around the transformer at its mean height and at one or two metres distant. The average is to be taken at equal intervals over the last quarter of the test. The thermometers are to be protected from draught and from radiation and their time-lag is to be as small as possible.

The temperature of the windings is to be determined from their increase of resistance. Let R_1 be the resistance of a winding when its temperature is t_1 at the beginning of a test; t_1 should be as nearly as possible equal to the initial temperature of the surrounding air. Then if R_2 is the resistance at the end of the heat run when the winding temperature is t_2,

$$R_2/R_1 = (t_2 + 234{\cdot}5)/(t_1 + 234{\cdot}5),$$

and

$$\textit{Temp. Rise} = t_2 - t_a = [(R_2 - R_1)/R_1]\,(t_1 + 234{\cdot}5) + t_1 - t_a,$$

where t_a is the ambient air temperature at the end of the test. The heat run must be continued long enough to be sure that the limit of temperature rise is not exceeded.

Sometimes, as in bar-type current transformers and other cases of very low-resistance windings, the resistance method is not applicable and the temperature rise must be directly measured by thermocouples or thermometers. These must not be embedded, since it is the surface cooling conditions that are in question. Thermometers or couples are also necessary for measuring the iron surface temperature and that of the oil. In all cases where thermometers are used the indicating fluid should be alcohol rather than mercury, since not only are the

readings of mercury-in-glass thermometers apt to be inaccurate in alternating magnetic fields, but if the glass is broken the mercury may seriously damage the transformer windings by amalgamating with the copper, especially if the coils are of fine wire.

All temperature tests shall be made with the rated secondary burden and with rated current (if a current transformer) or rated voltage (if a voltage transformer). Although not stated in the I.E.C. Recommendations it will be clear that in routine testing of large numbers of similar transformers it is unnecessary to make a heat run on each; a type test carried out on one or two chosen at random from a batch may be taken as evidence that they will all be satisfactory from the standpoint of thermal rating under normal load conditions.

2. **National Rules.** (*a*) Great Britain. B.S.S. No. 81/1927 was formulated before the I.E.C. Recommendations and in the revised edition will be considerably altered (see Appendix IX). For *current transformers* with rated burden at unity power-factor and rated primary current, the maximum permissible temperature rise after a two hour test starting from air temperature shall not exceed the tabulated figures—

Type of Current Transformer	Temp. Rise in ° C.	
	By Thermometer	By Resistance
Open type single turn transformer, or any open type transformer, the primary insulation of which depends on porcelain or micanite	50°	55°
Other open types of transformers	40°	45°
Oil-immersed or compound-filled transformers .	30°	35°

For *voltage transformers* operated continuously with rated voltage, frequency and burden at unity power-factor the following limits of temperature rise are imposed—

Type of Voltage Transformer	Temp. Rise in ° C.	
	By Thermometer	By Resistance
Oil-immersed or compound-filled	30°	35°
Other types	40°	45°

In all cases the cooling air shall not exceed 40° C. and the limits only apply up to an altitude of 3 000 ft. above sea level.

(*b*) GERMANY. The temperature rise limits imposed by the German Rules are definitely based upon the International Electrotechnical Commission Recommendations. Six classes of insulating materials are distinguished, of which three are identical with the corresponding I.E.C. classes, namely, O, B, and C, both as regards notation and materials. The other three classes are modifications of Class A and are designated as follows

Class A. Cotton, silk, paper, and similar fibrous materials impregnated. Enamel insulated wire.
Class A_f. All the materials of Class A in compound-filling.
Class A_o All the materials of Class A under oil.

Insulation is regarded as "impregnated" when the air between the fibres is replaced by some suitable material, but when this material does not necessarily fill completely all the spaces between the separate insulated wires. If these spaces are completely filled up the insulation is regarded as "compound-filled" or "mass filled." Mere dipping of an otherwise untreated insulation without use of pressure or vacuum is not regarded as impregnation.

The temperature rise of any part of a transformer is the difference between its temperature and that of the surrounding cooling medium. The cooling air is assumed to have an average temperature of 20° C. and in no case must it exceed 35° C. for the following tabulated limits of temperature rise to be permissible. The heating of all the windings of a current transformer is to be taken with the rated burden in ohms connected to the secondary and with 1·2 times the rated current; for voltage transformers 1·2 times rated voltage is to be applied with the rated burden in ohms connected in place. In both cases the rise is to be estimated from the change of resistance of the windings, except when these are composed of thick copper bars, when thermometers are to be used. Three-phase transformers with a common three-limbed core are to be tested with 1·2 times rated line-voltage when the middle high-voltage phase is short-circuited. Single-phase transformers that are to be used in three-phase star connection with earthed neutral are to be tested with 1·2 times the star-voltage. In both these cases the duration of the test is 2 hours; in all other cases the test is to be continued until temperature conditions become steady.

	Windings with insulation of Class	O	A and A_f	A_o	B	C
Temperature rise	Windings	50°	60°	70°	80°	Limited only by influence of neighbouring insulating parts
	Iron core					
	Dry-type transformers	60°				
	Oil transformers	70°				
	Oil at surface	60°				
	All other parts.	Limited only by influence of neighbouring insulating parts.				

(*c*) FRANCE. The French Rules specify fairly completely the conditions under which temperature tests are to be made, e.g. normal working connections, etc. Tests are to be caried on until it is clear that the specified limits will not be exceeded; to reduce the time taken the earlier part of the test can be made with current or voltage in excess of normal value, reverting to the rated value for the latter part. Conditions are regarded as stationary when the temperature rises less than 1° C. per hour. Tests must not begin until the transformer is in equilibrium with the surrounding air. The usual resistance change and thermometer methods are used for measuring the temperature rise; ambient temperature is measured according to

Material		Limit of Temp. Rise ° C.
Windings insulated with Class O insulation		40
Windings ,, Class A ,,	Thermometer	50
	Resistance	55
,, with enamelled wire		55
,, insulated with Class B insulation	Thermometer	70
	Resistance	75
Iron core in contact with windings		As for windings
,, ,, not in ,, ,,		70
Metal details other than windings in contact with	marble and slate	60
	fibre or wood	40
Moulded insulators		According to quality
Class C insulators (fireproof)		No practical limit
Metal details in form of springs	Copper or Brass	60
	Phosphor bronze	110
	Steel	160
Metal pieces near a soft soldered joint		60
Oil at surface level		50

the International Electrotechnical Commission Recommendations. Assuming an ambient temperature not greater than 40° C. the following table gives the limits of temperature rise; the limit of observed temperature is obtained by adding 40° C. to the tabulated figures.

(*d*) U.S.A. The American Rules define Classes O and A insulation and give the following limits of temperature rise—

Type of Transformer	Insulation	
	Class O	Class A
Dry-type transformers	40° C.	55° C.
Oil-immersed transformers	—	55° C.

(*e*) ITALY. The Italian Rules adopt the International Electrotechnical Commission Recommendations in their entirety but specify that the limits of temperature rise shall apply when the current in a current transformer or the voltage in a voltage transformer has 1·2 times rated value, the rated burden in ohms being joined in the secondary circuit.

CHAPTER XXXIII

DIELECTRIC TESTS

1. **Secondary winding.** It is provided in the International Electrotechnical Commission (I.E.C.) Recommendations, Publication 44, 1931, that the test-voltage of the secondary circuit, to be applied for one minute between the secondary and the primary, core, frame and/or case, connected together, shall be 2 000 volts. In current transformers having their primaries or secondaries divided into two or more separate sections, these sections shall be capable of withstanding an alternating voltage of 2 000 volts applied between them for one minute; the like is also specified for voltage transformers having their secondaries divided into separate sections.

These recommendations are the common practice of all countries with the exception of the United States, where the test voltage is 2 500 volts. The voltage must be sine-shaped and preferably of rated frequency, though most national rules tolerate any frequency from 20 to 100 cycles per sec. if more convenient; in particular, the British Rules specify 25 cycles per sec. up to double rated frequency. For testing procedure see the next section.

2. **Applied high-voltage test for primary winding.** The I.E.C. recommend that the test-voltage for the primary circuit of an instrument transformer, to be applied between the primary and secondary, core, frame and/or case, connected together, shall correspond with that laid down in the latest I.E.C. Rules contained in Publication 34, 1930. It is there stated that the test voltage is Twice Rated Voltage + 1 000 volts. Practice in the different countries varies very widely, as will now be shown.

In *Great Britain* the test-voltage for a works test is—

Rated Primary Kilovolts between Lines, V	Test-voltage in kV.
$\leqslant$ 0·660 kV	2
$>$ 0·660 kV	$2{\cdot}25V + 2$

If for any reason it is required to make an additional test after installation on a transformer that has already passed the above works test, the test voltages are to be 2 kV and $2V +$

2 kV respectively. These rules are not applicable to primary windings which are intended to be permanently and solidly connected to the case or to earth, or to both. (See Appendix IX.)

In *Germany* the requirements are much more severe than in any other country, being based on the rule $2{\cdot}2\ V + 20$ kV for line-voltages above 3 kV; the following table gives the figures tabulated in the German Rules.

Rated kV .	1	3	6	10	15	20	30	45	60	80	100	150	200	300
Test kV .	10	26	42	42	64	64	86	119	152	196	240	350	460	680

Below 750 volts the test-voltage is uniformly 3 kV. It is argued in favour of these high test-voltages that transformers withstanding them may be regarded as safe without the need of protective devices, and although power transformers are less severely tested it is pointed out that these are protected by the switchgear, whereas the voltage transformers are not.

In *Czechoslovakia* the test-voltage for transformers up to a rated voltage of 9 kV is $3\ V + 1$ kV; above 9 kV the test voltage is $2\ V + 10$ kV.

In *France* for rated voltages below 0·5 kV the test-voltage is uniformly 2 kV; above 0·5 kV the test voltage is $2\ V + 1$ kV, as the I.E.C. recommends.

In the *U.S.A.* a difference is made between current and voltage transformer primary windings. For current transformers the test voltage is $2{\cdot}25\ V + 2$ kV, like the British Rule. For voltage transformers it is $2\ V + 1$ kV like the I.E.C. Recommendation.

For comparison all these rules are plotted together in Fig. 288, logarithmic scales being used for compactness. Above a rated voltage of 50 kV all the rules give about the same result, but below about 20 kV the great severity of the German Rule in comparison with the others is apparent.

The test-voltage should be of sine wave-shape and preferably rated frequency, though if more convenient a higher or lower frequency within certain limits may be used; in Great Britain the limits are 25 cycles per sec. up to double rated frequency. The transformer is to be arranged exactly as it will be when in operation, and the h.v. test is best made after the heat run, if any. At the beginning of the test only about one-third of the prescribed voltage should be applied; the voltage is then to be raised smoothly to the prescribed value as rapidly

as is consistent with its indication on the measuring instrument. The full value is maintained for one minute, when it is rapidly reduced to about one-third of its full value before switching off. These precautions reduce the possibility of excessive surge voltages being set up in the transformer.

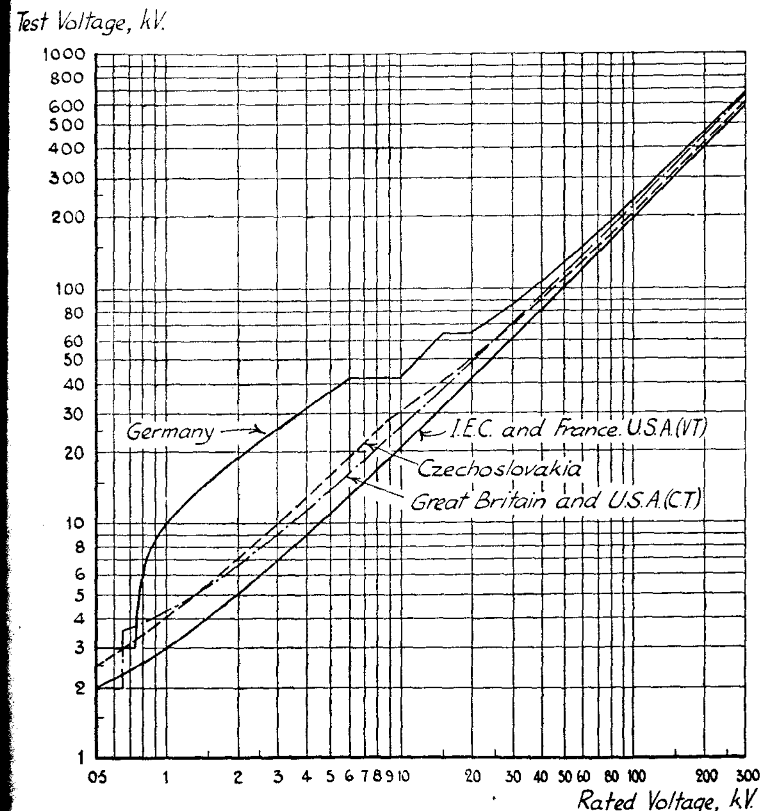


FIG. 288. COMPARISON OF TEST VOLTAGES FOR PRIMARY WINDINGS

The r.m.s. value of the voltage may be measured either by a voltmeter on the output side of the testing transformer, or by a voltmeter used in conjunction with a voltage transformer, or by a voltmeter connected to a specially calibrated voltmeter winding on the testing transformer. Alternatively, the crest value of the voltage may be found by means of a standard spark-gap, and for the purpose of the test the specified r.m.s.

test-voltage is assumed to be its crest-value divided by $\sqrt{2}$. In some rules, e.g. those of France, calibration tables for spark-gaps form an integral part of the specification.

3. **Induced high-voltage test for voltage transformers.** The British and the German Rules further prescribe that voltage transformers shall withstand, in addition to the applied high-voltage test, an induced voltage test. This has as its object subjecting the windings to a distributed voltage test from turn to turn. The British specification provides that one winding shall have applied to it an alternating voltage equal to twice the rated voltage of the winding; the test-voltage shall start at not more than one-third the prescribed value, and be increased as rapidly as is consistent with its accurate measurement. It is to be maintained for 30 seconds and then rapidly reduced to one-third of its full value before switching off. (See Appendix IX.) The German Rules prescribe the application for 5 minutes of a test-voltage of 2·5 V for transformers up to 30 kV rated voltage and 2 V for voltages above 30 kV.

To avoid the production of excessive fluxes in the core the induced voltage test is made at about double the rated frequency. It is usually more convenient to apply the test voltage to the low voltage winding, leaving the h.v. side open.

4. **Dielectric loss tests.** The usual high-voltage tests described in Sections 2 and 3, in which the transformer is subjected to a specified test-voltage for a short time and observed for breakdown or flash-over, are intended to be applied to all transformers as a normal routine. Such tests serve to discover the more radical faults in manufacture and materials but tell nothing definite about the safety of the transformer under normal working conditions. Indeed it is by no means unlikely that although a transformer may pass the high-voltage test without obvious damage, yet the insulation may be so much weakened that breakdown may easily occur with continued application of the normal working voltage. To guard against this contingency many firms impose a more severe "type-test" to be applied to a specimen transformer of a given design. For example, the Siemens & Halske A.G.* have for several years adopted as a type-test the application of the test voltage for eight hours, thereby making certain that no damage can be caused by the usual routine test with its one to five minutes duration.

It must be admitted, therefore, that the usual high voltage

* *Bull. Schw. Elect. Verein*, vol. 24, pp. 93, 96 (1933).

st is a rather rough and not very scientific test of the excellence otherwise of the transformer's dielectric. Keinath* has inted out that a much more rational procedure would be to lopt the method of the cable maker and measure the loss-gle of the dielectric by means of a Schering bridge. In a mplete investigation this quantity can be measured (i) at nstant temperature as a function of rapidly increasing voltge; (ii) at constant temperature and voltage as a function f time; (iii) as a function of temperature, or by combining with (i) s a function of voltage for different constant temperatures; finally (iv) a combination of (i) and (ii) an be used by measuring the angle s a function of voltage until the est-voltage has been reached and then as a function of time for the duration of the application of the high voltage. Such a detailed test might be justifiable in the case of important and expensive extra-high-voltage transformers but ould hardly be used for quick orkshop tests. Keinath suggests r this purpose a special loss-angle eter, similar to that used for able-testing.†

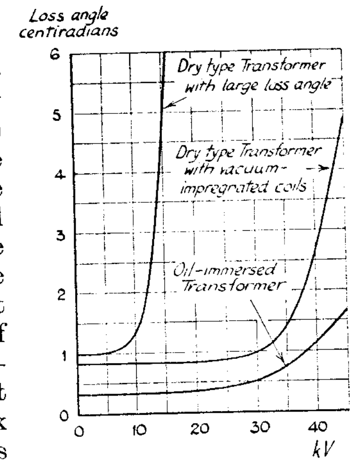


FIG. 289. VARIATION OF DIELECTRIC LOSS-ANGLE AS A FUNCTION OF VOLTAGE

The apparatus consists of two moving-coil instruments mounted with e axes of their coils in planes at right-angles; each carries a mirror, d a beam of light projected upon one mirror is reflected to the other and ence to a viewing screen where the movement of the spot of light is otographically recorded. Each instrument is supplied through a brating rectifier (p. 400). One element is arranged to measure the wer-component of the dielectric current; the other is operated by the sting voltage. Consequently the spot of light traces out the wattful-rrent/voltage curve as the voltage is raised from zero to the rated test ltage. The voltage remains constant at this rated value for a definite me and a clock-operated device gives to the voltage element a displace-ent proportional to time; a further record is traced of the loss-angle constant voltage as a function of time, thus completing the test. The pparatus is portable and easy to use.

Fig. 289 shows some typical results on three German voltage

* G. Keinath, *Arch. f. tech. Mess.*, Z37–1 (Aug., 1932); *E. u. M.*, vol. 52. 151 (1934).

† See *E. u. M.*, vol. 47, p. 160 (1929); vol. 48, p. 640 (1930).

transformers for 10 kV, for which the high-voltage test applied for one minute would be 42 kV and the induced-voltage test applied for 5 minutes 25 kV according to the German Rules. In all cases there is a definite voltage at which the loss-angle begins to increase rapidly and below which the angle is roughly constant. Oil-immersed paper insulation has the smallest loss-angle and the highest break-away point; it is the best dielectric material, as has been pointed out on p. 194, in accordance with the experience of cable makers. Next comes the dry-type transformer with vacuum-impregnated windings, and last of all the porcelain-insulated dry-type of transformer. It will be noted that the applied test-voltage of 42 kV is in all cases in the region of high loss-angle and must necessarily subject the dielectric to very severe conditions, both electric and thermal. For this reason there is a growing opinion in Germany that the standard test-voltages may be, in many cases, much too severe and act as a cause of subsequent failure under working conditions, due to permanently weakening the dielectric. The deterioration of the dielectric is partly due to the high electric stress and partly to the effects of heating by the dielectric losses. The whole subject is one of considerable complication and offers a wide field for further research.

It is probable that when more experience has been gained with these more rational methods of dielectric testing and with the interpretation of their results, that the old methods of high-voltage short-time testing will be abandoned as unscientific and unnecessarily severe. The subject is receiving attention on the Continent and in the U.S.A.* and is likely to prove interesting in the future.

* See *Elec. World*, vol. 103, pp. 68–73, 111–116, (1934).

APPENDIX I

FORCES ON STRAIGHT CONDUCTOR WITHIN A TUBULAR RETURN

The problem of the mechanical forces acting on a system consisting of a long, straight conductor carrying a current i e.m. units contained within a tube serving as the return conductor is of interest in connection with the design of coaxial terminals for current transformers, see p. 171. When the conductor passes axially down the tube the latter is

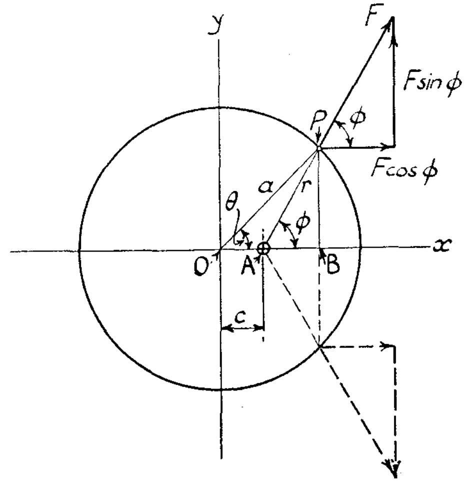


Fig. 290. Straight Conductor within Tubular Return

subjected to a uniform radial force and its material is in a state of hoop tension. It is interesting to inquire what is the system of forces when the construction is not coaxial.

In Fig. 290 let a straight thin wire carry current perpendicularly into the plane of the paper at A, at a distance c from the axis O of a thin tube carrying an equal total current out of the paper. If the current be i, then the current in the tube is assumed to be uniformly distributed, its amount per unit of periphery being $i/2\pi a$ where a is the radius of the tube.

The tube makes no magnetic field inside itself; consequently the current in the tube exerts no mechanical force on the wire.

The only force on the latter is a "pinch-effect" due to its own magnetic field.

The wire, on the other hand, acts dynamically on the tube. Consider an element at P subtending an arc $a d\theta$ at O. The force F acting upon it is $2i(d\theta/2\pi)\,(i/r) = i^2(d\theta/\pi r)$, in the outward direction of the radius vector $r = AP$ from A. This force can be resolved into two components, $F \sin \phi$ parallel to Oy and $F \cos \phi$ parallel to Ox. An element of the tube at an angle $-\theta$ is subjected to similar forces and it will be seen that the vertical components on elements at θ and $-\theta$ are equal and opposite; hence the total component of force parallel to Oy is zero for the entire tube.

The total horizontal force exerted on the tube is

$$\frac{i^2}{\pi} \int_0^{2\pi} \frac{\cos \phi \, d\theta}{r} = 2\frac{i^2}{\pi} \int_0^{\pi} \frac{\cos \phi}{r} \, d\theta,$$

since the distribution is symmetrical about Ox. Now

$$\cos \phi = AB/AP = (a \cos \theta - c)/r,$$

and

$$r^2 = a^2 + c^2 - 2ac \cos \theta;$$

hence the total horizontal force is

$$2\frac{i^2}{\pi} \int_0^{\pi} \frac{(a \cos \theta - c)}{a^2 + c^2 - 2ac \cos \theta} \, d\theta$$

$$= 2\frac{i^2}{\pi} \int_0^{\pi} \left[\frac{a \cos \theta}{a^2 + c^2 - 2ac \cos \theta} - \frac{c}{a^2 + c^2 - 2ac \cos \theta} \right] d\theta$$

It is easily shown that

$$\int_0^{\pi} \frac{\cos \theta}{1 + \cos \alpha \cos \theta} \, d\theta = \pi \frac{\sin \alpha - 1}{\sin \alpha \cos \alpha}$$

(J. Edwards, *Integral Calculus*, *I* p. 207, Macmillan & Co., 1921)

and

$$\int_0^{\pi} \frac{d\theta}{C + D \cos \theta} = \frac{\pi}{\sqrt{(C^2 - D^2)}} \text{ when } C > D \quad (\textit{ibid.}, I, \text{p. } 202.)$$

Writing $\cos \alpha = -2ac/(a^2 + c^2)$, $\sin \alpha = (a^2 - c^2)/(a^2 + c^2)$,

$$C = a^2 + c^2, \; D = -2ac,$$

the integrals can be evaluated and the total horizontal force is

$$2\frac{i^2}{\pi} \left[\frac{\pi c}{a^2 - c^2} - \frac{\pi c}{a^2 - c^2} \right] = 0.$$

Since there is no resultant horizontal force and we have seen also that there is no resultant vertical force there is no tendency for the tube to move relative to the wire. The forces exerted on the tube by the wire are equilibrated by the hoop stress set up in the tube.

The forces per unit of periphery can be expressed very simply thus—

Force F $= (i^2/\pi a)\,(1/AP) \propto 1/AP.$

Horizontal Component $= (i^2/\pi a)\,(AB/AP^2) \propto AB/AP^2.$

Vertical Component $= (i^2/\pi a)\,(PB/AP^2) \propto PB/AP^2.$

since $\cos \phi = AB/AP$ and $\sin \phi = PB/AP$.

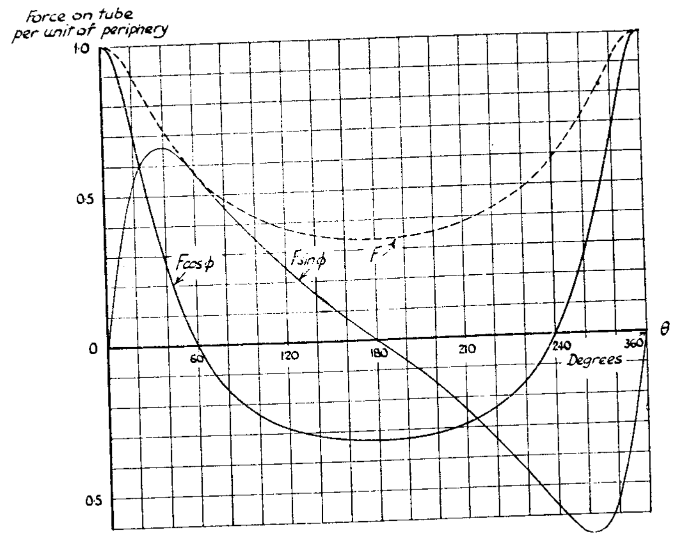


Fig. 291. Variation of Components of Force per Cm. of Periphery of Tube

These expressions are plotted in Fig. 291 for the case when the distance $c = a/2$. The areas under these curves are proportional to the total forces on the tube; the last two integrate to zero.

The total radial force acting on the tube in the direction OP is

$$2\frac{i^2}{\pi} \int_0^{\pi} \frac{\cos (\phi - \theta)}{r} \, d\theta = 2\frac{i^2}{\pi} \int_0^{\pi} \frac{a - c \cos \theta}{a^2 + c^2 - 2ac \cos \theta} \, d\theta,$$

which can readily be evaluated in terms of the preceding integrals and gives

$$2\frac{i^2}{\pi}\left[\frac{a\pi}{a^2 - c^2} - \frac{c^2\pi}{a(a^2 - c^2)}\right] = \frac{2i^2}{a}.$$

This is exactly the same total radial force, tending to burst the tube, that is produced with the wire at the axis. The maximum hoop stress occurs at the places where the tube cuts the axis of x, and is consequently exactly the same whether the wire is axial or not.

APPENDIX II

TABLES FOR PHASE-ANGLE CORRECTION FACTORS IN POWER MEASUREMENTS

APPENDIX II

TABLES FOR PHASE-ANGLE CORRECTION-FACTORS IN POWER MEASUREMENTS

TABLE I

For use with {lagging / leading} current when δ is {positive / negative}

Angle δ	Apparent Power-Factor (Cos ϕ') 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
[illegible]	[illegible]	[illegible]	[illegible]	0·6586	0·7191	0·7965	0·8452	0·8800	0·9073	0·9308	0·9540	0·9675	0·9838	0·9962
[illegible]	[illegible]	[illegible]	[illegible]	0·6472	0·7096	0·7896	0·8400	0·8759	0·9041	0·9284	0·9523	0·9663	0·9831	0·9959
[illegible]	[illegible]	[illegible]	[illegible]	0·6357	0·7001	0·7827	0·8347	0·8717	0·9008	0·9260	0·9507	0·9651	[illegible]	0·9957

TABLE II

For use with {lagging / leading} current when δ is {negative / positive}

Angle δ	Apparent Power-Factor (Cos ϕ') 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	0·0108	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	1·0492	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

The theory of these tables is given on p. 304, where it is shown that

$$True\ power = \frac{F_v F_c}{\cos \alpha} \cdot \frac{\cos \phi}{\cos \phi'} W,$$

where

W = wattmeter reading corrected for scale error;
$F_v = K_v/K_{nv}$, the ratio-factor for the voltage transformer;
$F_c = K_c/K_{nc}$, the ratio-factor for the current transformer;
$\cos \phi$ = true power-factor of the circuit; ϕ is positive when the voltage leads on the current, i.e. with inductive load;
$\cos \phi'$ = apparent power-factor = $W/(volts \times amperes)$. The volts are read on a voltmeter in parallel with the wattmeter voltage coil on the voltage transformer secondary; the amperes are obtained from an ammeter in series with the wattmeter current coil in the secondary circuit of the current transformer;
$\phi' = \phi - \delta$;
$\delta = \alpha + \beta - \gamma$,

where

α = phase-angle of wattmeter voltage circuit, which rarely exceeds 5 minutes and is usually positive, i.e. the voltage across the voltage circuit leads on the current through it;
β = phase-angle of current transformer, usually positive, i.e. the reversed secondary current leads on the primary current;
γ = phase-angle of voltage transformer, which is positive if the reversed secondary voltage leads on the primary voltage.

The values of F_v, F_c, γ and β are found from the calibration curves of the transformers. The tables give the factor $\cos \phi/\cos \phi'$ as a function of δ for various constant values of $\cos \phi'$, Table I being used when ϕ is $\pm$ with δ $\pm$, while Table II is applicable when ϕ is $\pm$ but δ is $\mp$. Linear interpolation may be made without error for intermediate values of δ, but there will be certain interpolation errors for intermediate values of $\cos \phi'$. Interpolation for correction-factors, $\cos \phi/\cos \phi'$, corresponding to values of $\cos \phi'$ lying between the tabulated entries may be made without exceeding an error of 0·0010 in the sections of the tables between the heavy lines; outside these sections and in all cases where adjacent values of $\cos \phi'$ are separated by a heavy line the maximum error in interpolation will exceed 0·0010.

EXAMPLE. The readings of the voltmeter, ammeter and wattmeter corrected for scale errors are, in primary units, 22 400 volts, 490 amperes, and 5 120 kW respectively when measuring an inductive load. The following data are found from the calibration of the transformers—

$$K_{nv} = 200, \quad K_v = 199{\cdot}2, \quad F_v = 0{\cdot}9960;$$
$$K_{nc} = 100, \quad K_c = 99{\cdot}7, \quad F_c = 0{\cdot}9970.$$

$\alpha = +3'$, $\beta = +6'$, $\gamma = +3'$, so that $\cos \alpha$ is unity to a higher degree of precision than the table. From these, $\alpha + \beta - \gamma = \delta = +3 + 6 - 3 = 6'$; $\cos \phi' = 5120 \times 10^3/(22{\cdot}4 \times 4{\cdot}9 \times 10^5) = 0{\cdot}4665$. The value of $\cos \phi/\cos \phi'$ is found by proportion from Table I thus—

For $\cos \phi'$	0·4	0·5
$\delta = 5'$	0·9967	0·9975
$\delta = 10'$	0·9933	0·9950
∴ for $\delta = 6'$	0·9960	0·9970

∴ 0·9967 for $\cos \phi' = 0{\cdot}4665$

Collecting the various factors,

$$True\ power = \frac{F_v F_c}{\cos \alpha} \cdot \frac{\cos \phi}{\cos \phi'} W = 0{\cdot}9960 \times 0{\cdot}9970 \times 0{\cdot}9967 W$$
$$= 0{\cdot}9930 \times 0{\cdot}9967 W = 0{\cdot}9897 W = 0{\cdot}9897 \times 5120$$
$$= 5067 \text{ kW}.$$

APPENDIX III

USE OF VOLTAGE TRANSFORMER WITH ELECTROSTATIC VOLTMETER FOR PRECISE MEASUREMENTS OF CURRENT AND VOLTAGE

MANY years' experience at the National Physical Laboratory has shown that a carefully-designed reflecting electrostatic voltmeter is an excellent instrument for the precise measurement of current, voltage and power. By using a long, suitably curved scale at a considerable distance from the mirror very high precision can be obtained; for example, the N.P.L. instrument at the top of its scale can be read to 1 in 10 000, the voltage being about 100 volts. Lower voltages can be measured with comparable accuracy by stepping them up to 100 volts with a voltage transformer of appropriate ratio. Currents can be measured by passing them through suitable four-terminal resistors, the p.d. across the voltage terminals being then stepped up to 100 volts by means of a voltage transformer.

The idea of using a voltage transformer with a reflecting electrostatic voltmeter is due to Campbell,* who in 1901 described an arrangement capable of measuring voltages from 0·1 volt upwards and large currents. His transformer consisted of a laminated core of soft iron rings weighing about 1·5 kg. provided with two toroidal windings, a primary of 100 turns and a secondary of 10 000 turns. The apparatus for current measurement is shown in Fig. 292 (*b*). Campbell has shown that to get a constant ratio of V_s/I, independently of frequency and wave-form, the primary of the transformer should have a high ratio of inductance to resistance, i.e. a large time-constant; and the effective impedance of the winding should be much greater than the resistance R across which it is joined. This second condition is equivalent to stating that the exciting current taken by the transformer with the capacitive load provided by the voltmeter on its secondary side, must be negligible in comparison with the current flowing in R. In this early transformer the error in V_s/I was − 1·9 per cent at

* A. Campbell, "On test-room methods of alternate current measurement," *Journal I.E.E.*, vol. 30, pp. 889–908 (1901).

40 cycles per sec. and − 0·8 per cent at 86 cycles per sec.; at a given constant frequency the error can be compensated by an adjustment of the turns-ratio, but even then there will be possible wave-form error.

About 1911 the performance was greatly improved by making a core of silicon-iron (Stalloy) plates. With 2 volts applied to the primary the exciting current was 20 mA, corresponding with an impedance of 100 ohms, which is large compared with the resistance of any usual four-terminal resistor. This result was obtained by a large number of primary turns, namely,

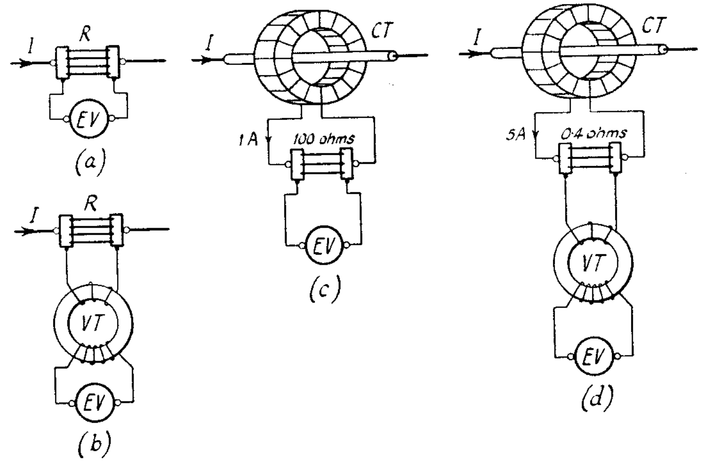


FIG. 292. METHODS FOR MEASURING SMALL VOLTAGES WITH ELECTROSTATIC VOLTMETER AND VOLTAGE TRANSFORMER

340, but an unforeseen consequence was that the self-capacitance of the winding was so much increased that partial resonance occurred at power frequencies. The voltage ratio increased with frequency and there was appreciable wave-form error; the change of V_s over a range of 25 to 100 cycles per sec. amounted to 0·47 per cent. It was found that shunting a resistance of 143 000 ohms across the secondary terminals made the ratio independent of frequency but increased the primary current to 140 mA, so that the advantage of a large number of turns giving a low exciting current was largely lost.

Recently* the adoption of nickel-iron cores has made a

* A. H. M. Arnold, "A voltage transformer for use in the measurement of small voltages," *Journal I.E.E.*, vol. 69, pp. 156–163 (1931).

further marked improvement and the use of a shield has enabled capacitance troubles to be abolished. A ring core of mumetal is wound with a uniformly-distributed tertiary coil of 4 000 turns, its mid-point being joined to that of the secondary and brought out to a terminal; this tertiary acts as a shield. Over it is wound the secondary winding in twenty sections of 200 turns each. Over this again is the primary in four sections of twenty turns; by series, series-parallel or parallel connection of its sections ratios of 2/100, 1/100 or 0·5/100 can be provided. The change of ratio with frequency, whether on open-circuit or with the electrostatic voltmeter connected, is not greater than 1 in 10 000 over a range of 25 to 500 cycles per sec. The phase-angle on the 2/100 range is less than 2 minutes. The exciting current is 30 mA at 25 cycles per sec. and 8 mA at 500 cycles per sec. The transformer was made by Everett, Edgecumbe & Co.

The modifications of Campbell's method used at the National Physical Laboratory for various currents are shown in Fig. 292. For currents under 20 amperes the electrostatic voltmeter is joined directly to a resistor giving a drop of 100 volts, as in Fig. 292 (*a*). From 20 to 2 000 amperes a resistor dropping 2 volts and the above mumetal transformer on its 2/100 range are used, as in Fig. 292 (*b*). In an alternative method, Fig. 292 (*c*), the primary resistors and voltage transformer are replaced by a special nickel-iron cored current transformer made by Elliott Bros.* The ring core has a toroidal coil of 2 000 turns suitable for 1 ampere and with a single primary turn gives a ratio of 2 000/1, which is constant within 3 parts in 10 000 of the nominal value for all frequencies from 25 to 100 cycles per sec. and for primary currents down to 1/10 of full current. The secondary is closed through a 100 ohm resistor giving a drop of 100 volts for application to the voltmeter. Currents below 2 000 amperes are measured by looping a suitable number of turns of the primary conductor through the transformer. For currents above 2 000 amperes the arrangement of Fig. 292 (*d*) is used. A suitable mumetal-cored current transformer steps the primary current down to 5 amperes, which is passed through a 0.4 ohm resistor, the 2 volts drop across which is raised by the above voltage transformer to 100 volts across the voltmeter. Full details of the apparatus and its calibration are given by Arnold in the papers cited.

* A. H. M. Arnold, "Precision measurements of alternating currents up to 2 000 amperes," *Journal Sci. Insts.*, vol. 8, pp. 154–155 (1931).

Although the method has been fully developed at the N.P.L. it has also been occasionally used elsewhere. The Siemens-Schuckert A.G. have used a 70/1 transformer in conjunction with a 70 volts Kelvin multicellular voltmeter, details being given by Gewecke* in 1919.

* H. Gewecke, "Messinstrumente für kleine Wechselspannungen," *Arch. f. Elekt.*, vol. 7, pp. 203–209 (1919).

APPENDIX IV

CAPACITOR METHODS FOR MEASURING HIGH VOLTAGES

THE use of coupling capacitors to connect small loads to h.v. transmission lines* has received some application, both in Europe and America, particularly in rural areas where the load is so small that the investment of capital in distribution transformers would be unremunerative. The much lower cost of h.v. condensers suitable for this purpose makes the connection of such loads through capacitors a much more reasonable economic proposition. There have recently been some attempts to use such capacitors instead of voltage transformers to supply the protective apparatus in h.v. systems.

It has been pointed out in Chapter V that the design of a voltage transformer for very high voltages is a somewhat difficult matter; quite apart from the attainment of adequate accuracy, it is also necessary to provide means of protection against internal faults and particularly against surges and voltage rises. These requirements are successfully met in a number of special designs described in detail on pp. 245 to 263. Nevertheless, there is an opinion held by some American and British engineers that a voltage transformer is to be regarded as a somewhat weak link in the system, though it must be pointed out that this opinion is not shared by other engineers in France and Germany, where the modern voltage transformer has been largely developed. Consequently, there has been some trend in America and Great Britain towards the replacement of voltage transformers in h.v. networks by coupling capacitors, resembling those already used for load tapping. They are entirely free from surge troubles and by attention to their proper design it is possible to obtain an output and accuracy quite adequate for the operation of protective gear. In view of their use in the 132 kV section of the Grid

* H. Brooks, "With the high voltage capacitor small loads can be [illegible]omically connected to high tension lines," *Elect. J.*, vol. 26, pp. 477–[illegible] (1929). C. Dannatt and S. E. Goodall, "Capacity coupling to transm[illegible] lines," *World Power*, vol. 17, pp. 173–179 (1932), gives the theory of [illegible] apparatus on the 132 kV section of the Grid. P. Hochhaüsler, "Die [illegible]trahmek leiner Leistung aus Hochspannungsnetzen," *Arch. f. Elekt.*, vo[illegible] pp. 302–310 (1934).

it is thought that a few notes on the various types of capacitor devices used for measuring high voltages will be appropriate in this Appendix.

The original idea appears to be due to Keinath,* who first described the method known as "C-Messung." In its simplest form a condenser C is joined in series with an ammeter between the h.v. line and earth, the current being proportional to the voltage; see Fig. 293 (*a*). As Fig. 293 (*b*) further shows, C may be the capacitance to earth of a simple through bushing; in this form the method would be suitable for relatively low

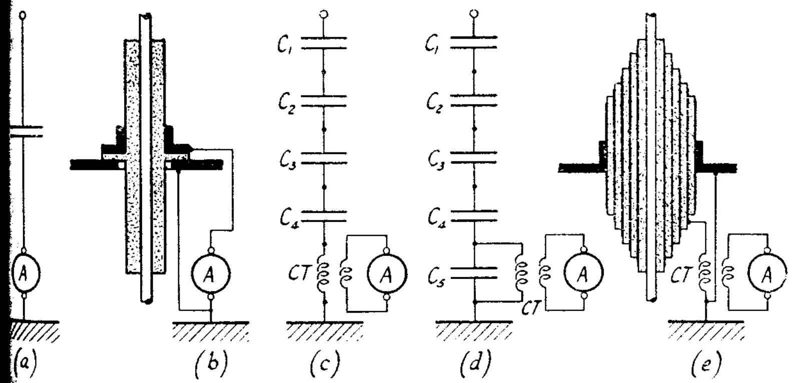


FIG. 293. CONDENSER METHODS FOR HIGH-VOLTAGE MEASUREMENTS

voltages where the charging current of the bushing is fairly large. For high voltages condenser bushings with intersheaths are used and the capacity current is much smaller. To make the measurement easier the current is stepped up to 0·1–0·5 ampere by a small current transformer, as in Fig. 293 (*c*). In this diagram C_1, C_2, C_3, C_4 represent either the capacitance of the various layers of the condenser bushing, or alternatively they may be individual coupling condensers joined in series.

The assumption that the capacitance current in Figs. 293 (*a*), (*b*), and (*c*) is proportional to the voltage is by no means true. If the harmonics in the voltage are v_3, v_5, v_7, etc., expressed as a percentage of the fundamental, the voltage will be proportional to

$$\sqrt{(100^2 + v_3^2 + v_5^2 + v_7^2 + \ . \ . \ . \ .)},$$

* G. Keinath, *Die Technik Elektrische Messgerate*, vol. 2, pp. 17–34 (1928). Also see *German Patent* No. 336563 and "Messung von Wechselspannungen mit Kondensatoren ("Kapazitive Spannungswandler")," *Archiv. f. tech. Mess.*, V 3333-3 (Sept., 1934).

while the capacitance current will be proportional to

$$\sqrt{(100^2 + 3^2 v_3^2 + 5^2 v_5^2 + 7^2 v_7^2 + \ldots)}.$$

Consequently changes of voltage wave-form may produce very considerable error in the ammeter reading. By connecting the current transformer in parallel with the last condenser or the outer layer of the bushing, as in Fig. 293 (*c*), it is easy to show that if the effective impedance of the transformer is high compared with that of the condenser across which it is joined, the reading of the ammeter is proportional to the voltage independently of frequency and wave-form. Temperature effects may, however, cause some error since the capacitance-temperature coefficient may be considerable, of the order of 0·05 per cent per ° C. It will be realized that the simple methods of Fig. 293 are the capacitance analogues of the resistor and inductor methods shown in Figs. 125, 126, and 127. Capacitor arrangements on these principles, using condenser bushings as in Fig. 293 (*e*), are described and illustrated in Keinath's papers cited above, some being of German and some of Swedish manufacture. Several devices using coupling-capacitor units in series have been described in the technical press; to some of these we shall now briefly give attention. Bushing methods have the disadvantage that the available output is small, at 66 kV being about 7 VA and at 220 kV about 60 VA; with condensers an output of 100 VA or more is easily obtained and a higher precision is also possible.

The Westinghouse Co. of Pittsburg* make a coupling-capacitor consisting of paper-foil condensers embedded in a paraffin compound within a ribbed porcelain container, 22 cm. diameter inside and 43 cm. outside, the whole being closed by metal caps. A single unit is intended for use between line and earth on a three-phase system with line voltage of 44 kV. The caps are arranged so that units may be stacked one above the other and joined in series to suit voltages up to 220 kV between lines. Fig. 294 shows diagrammatically the arrangement for 132 kV circuits. The small transformer in the b[illegible] is tuned to resonance with the rated frequency, and [illegible] offers a very high impedance to harmonic currents: the wave-form error is thus very small. The output is 100 VA. Fig. 29[illegible] gives curves of ε_v and γ for the apparatus, with rated bur[illegible] connected to the secondary terminals; at rated voltage b[illegible]

* P. O. Langguth, "Capacitor potential devices," *Elect. J.*, vol. 31[illegible] 107–109, 112 (1934).

errors are zero and for all other voltages the accuracy falls within the limits of Class 1. This result has been obtained by proper choice of the constituent capacitances. A somewhat similar device is in use on the network of the Southern California Edison Co.,* supplying current to the protective system.

The apparatus used on the 132 kV section of the Grid† is

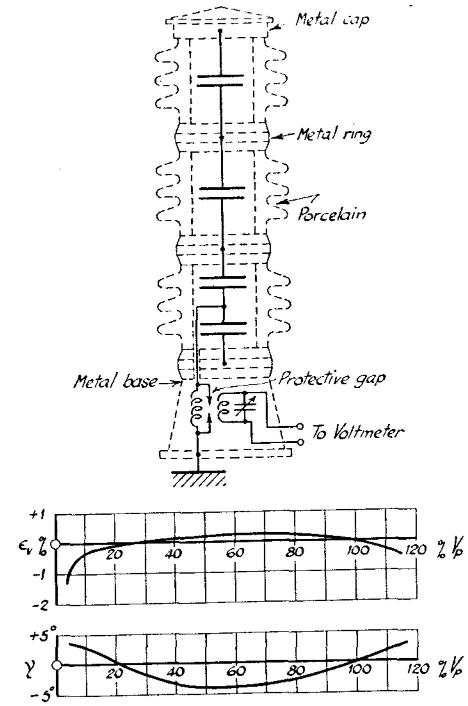


Fig. 294. Coupling Capacitor for High-voltage Measurements (Westinghouse)

somewhat similar but differs in certain details. Referring to the simple circuit of Fig. 295 (*a*), the small transformer T is tapped across a section of the h.v. condenser, its secondary supplying a condenser C and inductor L which are tuned to resonate at the supply frequency. Consequently, the transformer offers a very low impedance to the fundamental and

* F. B. Doolittle, "For a better use of investment in coupling capacitors," *Elec. World*, vol. 103, pp. 256–257 (1934).

† *British Patents* 354 236 (1930) and 365 194 (1931) granted to A. Reyrolle & Co. and H. Leben. H. W. Clothier, *Journal I.E.E.*, vol. 71, p. 299 (1932).

a very high impedance to harmonics, acting as an efficient filter and suppressing wave-form errors. Since the effective impedance of the transformer is very low compared with that of C_2 the current I_p is almost equal to I; the current I_s is, therefore, also nearly proportional to I and in phase with it. The p.d. V_s over L will lead on I_s by nearly $\pi/2$ and since I

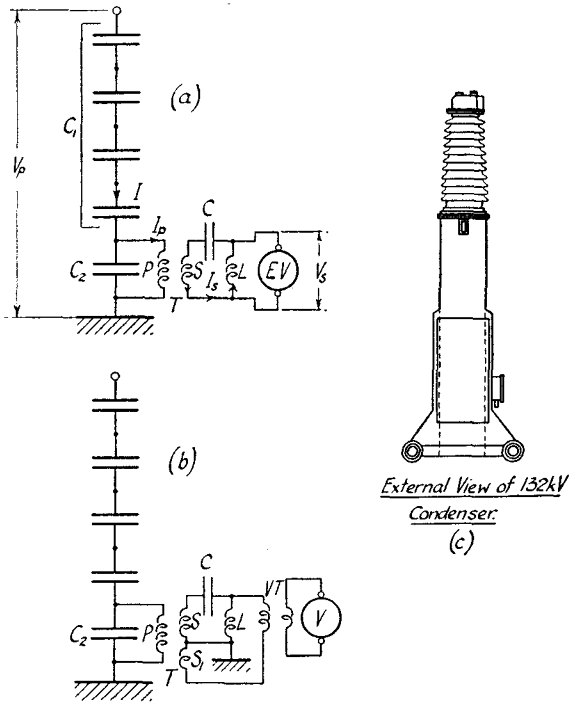


FIG. 295. COUPLING CAPACITOR FOR HIGH-VOLTAGE MEASUREMENTS (REYROLLE)

leads on V_p by nearly $\pi/2$, it follows that V_s is practically in phase with V_p and proportional to it. This will be true when the voltmeter tapped across L takes no appreciable current.

When the burden takes an appreciable current the voltage V_s falls considerably and is no longer in phase with V_p; the effect of the load is to add losses to the resonant branch, blunting its resonance peak. Compensation can be effected by adding a tertiary winding S_1 to the transformer T, as in Fig. 295 (b), this injecting a voltage with makes up for the dissonance set up by the burden. A considerable burden can then

be supplied without seriously disturbing the proportionality of the low and high voltages or introducing an appreciable phase-displacement between them. As a rule the voltage so obtained is too high for direct application to standard instruments and a small voltage transformer VT is interposed.

The whole equipment, condensers and transformers, is contained in an oil-filled steel tank provided with a porcelain lead-in bushing suitable for open air use. The condensers are of bakelized paper. For burdens up to 100 VA and for voltages between 10 per cent and 100 per cent of the rated value ε_v lies between limits of $\pm$ 7·5 per cent and γ of $\pm$ 360 min., which considering the complexity of the circuit is not a very high degree of precision.* The whole weighs 1 300 kg. and contains 130 gal. of oil; the external appearance of the capacitor is shown in Fig. 295 (c).

* Keinath points out that a modern voltage transformer of reliable design gives 400 VA with Class 1 accuracy and weight only 1 100 kg.

APPENDIX V

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APPENDIX VII

PERIODICAL LITERATURE

In the course of preparing this book a considerable amount of periodical literature has been examined, some facts in connection therewith being of general interest. Some seventy-three publications have been consulted, distributed geographically as follows: Germany, 25; U.S.A., 17; Great Britain, 12;

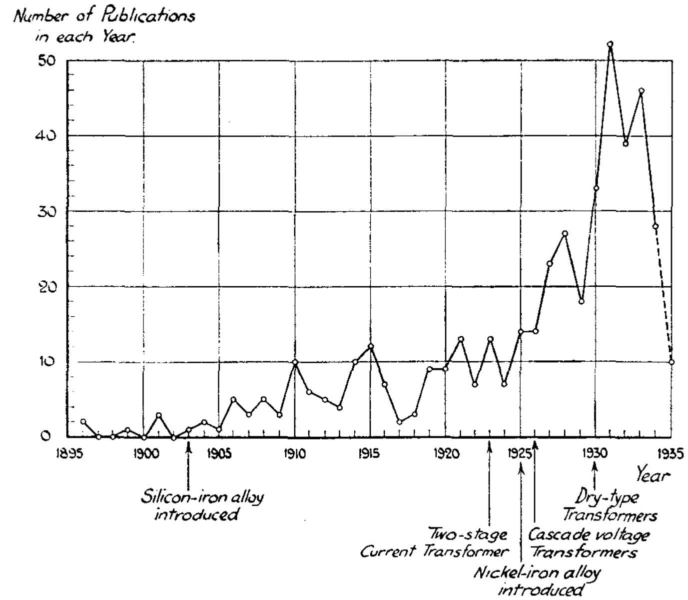

Fig. 296. Annual Output of Periodical Literature on Instrument Transformers

France, 6; Switzerland, 5; Belgium, Italy and Japan, 2 each; Austria, Canada, Holland and South Africa, 1 each.

Omitting from consideration all articles not dealing in the main with instrument transformers 447 articles dated prior to July 1935 have been referred to. To these must be added a considerable number of articles dealing with ancillary questions, e.g. the metallurgy of nickel-iron alloys, the design of resistors, condensers, and other apparatus, etc. Fig. 296

shows the allocation of these 447 articles to each year of publication, beginning with Campbell's pioneer work of 1896 and ending with the contribution of the first six months of 1935.*

The graph presents several points of interest. Up to the beginning of the World War there is a steady increase in the annual output of papers dealing with instrument transformers, due no doubt to the development then taking place in the electrical supply industry with its demand for more accurate measurement and also to the improvement in transformers arising from the introduction of silicon-iron alloys about 1903. After the complete stagnation of the war period followed an intensive development in the transmission and distribution of energy at high voltages. With the advent of the super-power system came special problems in the design, construction and testing of current and voltage transformers for high voltages. At the same time enormous improvements were made in the accuracy of current transformers by the introduction of nickel-iron alloys about 1925. These things are reflected in a phenomenal increase in the annual number of publications dealing with instrument transformers, rising to a peak about 1931–33 and then rapidly declining when the various problems have, for the present, been satisfactorily solved. The modern instrument transformer is now a piece of apparatus of such high perfection that it seems hardly probable that it can be much further improved; consequently, we may reasonably expect the output of technical literature on the subject during the next few years to be lower than it has been during the recent past. This is borne out by the rapid decline in publications since 1933.

* To these must now be added 7 articles published during the second half of 1935 and 10 articles contributed by the first four months of 1936. These bring the grand total of references dealing mainly with instrument transformers to 464.

APPENDIX VIII

NOTE ON THEORY OF NEUTRAL-POINT DISPLACEMENT IN SINGLE-PHASE CIRCUIT

On page 287 and in Fig. 153 a simple physical explanation of the phenomenon known as neutral-point displacement or inversion has been given. The following note gives a mathematical treatment of the basic circuit involved in the problem and further stresses some of its interesting properties.

In Fig. 297 a circuit consisting of two equal capacitances, C, C, one of which is shunted by an inductance L, is shown; all are assumed to be free from losses. The impedance operators for the sections AN and NB are

$$\frac{j}{(1/\omega L) - \omega C} \text{ and } -\frac{j}{\omega C}$$

respectively, while that for the whole circuit AB is

$$z = j\left[-\frac{1}{\omega C} + \frac{1}{(1/\omega L) - \omega C}\right] = j\,\frac{2\omega C - (1/\omega L)}{\omega C[(1/\omega L) - \omega C]}$$

If $\mathbf{v}$ is the harmonic vector of voltage applied to AB, the current is

$$\mathbf{i} = -j\,\frac{\omega C[(1/\omega L) - \omega C]}{2\omega C - (1/\omega L)}\,\mathbf{v},$$

which is in quadrature with the voltage and has a r.m.s. value of

$$I = \frac{\omega C[(1/\omega L) - \omega C]}{2\omega C - (1/\omega L)}\,V,$$

V being the r.m.s. value of the voltage. When this fraction is positive the current lags on the voltage, and when negative it leads.

Suppose now that the pulsatance ω and the capacitances are fixed while the admittance $1/\omega L$ of the coil is varied from zero to infinity, i.e. the current through the coil changes progressively from zero to infinity. When $1/\omega L$ is zero the current becomes $-\omega CV/2$, i.e. that through two equal condensers in series. As $1/\omega L$ increases, the leading current falls until, when $(1/\omega L) = \omega C$, the branch AN comes into parallel resonance; its impedance is infinite and the current becomes zero. Further increase in $1/\omega L$ causes the current to increase and to lag on the voltage. When $2\omega C = (1/\omega L)$, i.e. when the lagging current taken by the coil is twice the leading current in the capacitance shunted across it, the branch AN has an effective inductive reactance equal to the capacitive reactance of NB. The circuit is then in series resonance, its impedance is zero

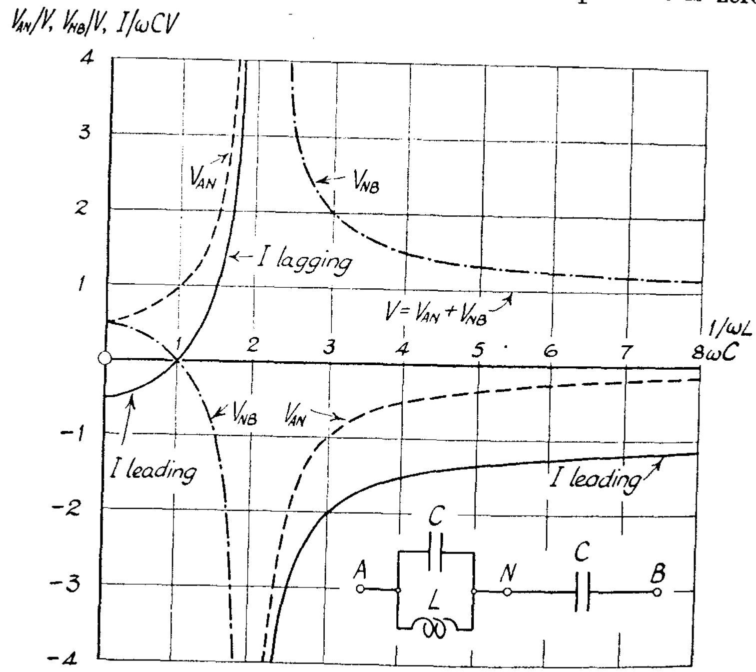

FIG. 297. THEORY OF NEUTRAL-POINT DISPLACEMENT IN SINGLE-PHASE CIRCUIT

and the current approaches positive infinity. As $1/\omega L$ is still further increased, the current swings over to a lead and gradually falls from negative infinity asymptotically to $-\omega CV$ as $1/\omega L$ tends towards infinity, i.e. as the condenser in AN is short-circuited. The variation of I (in terms of ωCV) with the admittance $1/\omega L$ (in terms of ωC) is plotted in the full curves of Fig. 297.

Turning now to the distribution of voltage over the parts of the circuit, that over AN is

$$v_{AN} = \frac{\omega C}{2\omega C - (1/\omega L)} v;$$

and that over NB is

$$v_{NB} = -\frac{(1/\omega L) - \omega C}{2\omega C - (1/\omega L)} v.$$

Hence the p.d.'s are in phase with v, which is equal to their arithmetical sum.

When $1/\omega L = 0$, $V_{AN} = V_{NB} = V/2$, so that N is midway in potential between A and B. As $1/\omega L$ increases V_{AN} grows and V_{NB} falls until, at the parallel-resonance point ($1/\omega L = \omega C$), $V_{AN} = V$ and $V_{AB} = 0$, i.e. N and B coincide in potential. When this point is passed V_{AN} increases and remains positive while V_{NB} changes sign and increases negatively; in these conditions the potential of N relative to A is greater, by an amount depending on the value of $1/\omega L$, than the applied voltage V and is positive, while the potential of B relative to N is negative by a similar amount. At the series-resonance point ($1/\omega L = 2\omega C$) $V_{AN} \to +\infty$ and $V_{NB} \to -\infty$ with a residual sum of V. On passing through this point, V_{AN} becomes negative and falling towards zero, i.e. N is below A in potential; V_{NB} becomes positive and falling toward V, i.e. B is above the potential of N. When $1/\omega L \to \infty$ the whole voltage is borne over NB.

These voltage variations are plotted in Fig. 297, V_{AN} being shown dotted and V_{NB} chain-dotted to enable them to be easily identified. Further illustration is provided in Figs. 153 (c) to (h), page 288. In this diagram potentials are shown relative to N, which is earthed.

In an actual case the presence of losses in C or L will prevent the occurrence of the infinite peaks in the current and voltage graphs of Fig. 297; but as the losses are usually small, very considerable voltage-rises may still be experienced.

APPENDIX IX

REVISION OF BRITISH STANDARD SPECIFICATION FOR INSTRUMENT TRANSFORMERS

On page 16 the provisions of the *British Standard Specification for Instrument Transformers*, No. 81—1927, have been explained. It is stated there that this Specification was under revision but, at the time the text of this book went to Press, details of the proposed changes were not available. The new Specification B.S.S. No. 81—1936 has, however, recently reached the stage of first proof and by kind permission of the British Standards Institution* it is now possible to include in this Appendix some description of the new requirements. Since this account has been prepared from a proof it may be regarded as correct in its general provisions; slight changes of detail may, however, be found when the Specification is officially published.

The new Specification has 42 pages, 25 numbered sections, and 10 appendices. It applies primarily to instrument transformers used with measuring instruments and divides them into classes according to their degree of accuracy; it is also applicable to transformers operating protective devices, but then does not deal with accuracy requirements or special characteristics. The general definitions are practically unchanged but there have been added (i) definitions of ratio error and phase-angle (the term *phase-displacement* being used) similar to those used in this book; (ii) a definition of overcurrent factor, of which particulars will be given later.

Current Transformers. The old requirements for current transformers are given on p. 17. The rated secondary current is still 5 amperes except when (i) T_s is too small to enable the ratio to be adjusted to the required value by adding or removing a single turn; (ii) when the secondary leads are excessively long. In such cases 1 ampere or 0·5 ampere may be used. The rated primary currents follow the values tabulated on p. 17 with the following changes: 80 and 250 amperes are omitted and 75, 1 200 (for Classes AL and BL only), and 6 000 amperes are added.

In place of the original four classes there are now nine classes, due to the addition of two classes for transformers of the highest precision for laboratory use and three classes for metering transformers. A letter notation is still adopted.

* Official copies will be obtainable after publication from the British Standards Institution, 28 Victoria Street, London, S.W.1.

The following table gives the limits of error for transformers used with measuring instruments for laboratory use (AL and BL) or general use (A, B, C, and D).

Class	Use	Rated Burden at 50 cycles per sec. and unity power-factor	Percentage of rated primary current	ε_c ± %	β ± min.
AL	For precision laboratory testing, and as substandard for testing laboratory current transformers	7·5 VA	120 to 60 Below 60 to 20 Below 20 to 10	0·15 0·15 0·15	3 4 6
BL	For work in conjunction with (*a*) substandard instruments, (*b*) highest grades of integrating meters, (*c*) wattmeters of special accuracy. Also as substandard for testing industrial current transformers	7·5 VA	120 to 60 Below 60 to 20 Below 20 to 10	0·3 0·4 0·5	10 15 20
A	For use with substandard indicating wattmeters	2·5, 5, or 15 VA	120 to 60 Below 60 to 20 Below 20 to 10	0·5 0·5 1·0	35 35 50
B	For use with first-grade indicating and graphic wattmeters	2·5, 5, or 15 VA	120 to 60 Below 60 to 20 Below 20 to 10	1·0 1·0 1·5	60 60 90
C	For use with first-grade and graphic indicating ammeters	2·5, 5, or 15 VA	120 to 60 Below 60 to 20 Below 20 to 10	1·0 1·0 2·0	120 120 180
D	For purposes where ratio is of less importance than in above	2·5, 5 or 15 VA	120 to 20	5·0	—

The new classes AL and BL give a specification for the most precise transformers now available since the introduction of nickel-iron cores. Classes A, B, C, and D are similar to the old specification (p. 18) with the following exceptions: (*a*) Their uses are more exactly defined. (*b*) The limits of error are specified up to 120 per cent of rated current. (*c*) The ratio error below 20 per cent of rated current has been reduced from 2 per cent to 1·5 per cent in Class B. (*d*) The rated burdens are changed.

The remaining classes, AM, BM, and CM are modifications of Classes A, B, and C for various grades of industrial metering.

Class	Use	Rated Burden at 50 cycles per sec. and unity power-factor	Percentage of rated primary current	ε_c ± %	β ± min.
AM	For precision industrial metering	2·5, 5 15 or 30 VA	120 to 20 Below 20 to 10	1 1	30 30
BM	For industrial metering of substandard grade according to B.S.S. 37	2·5, 5 15 or 30 VA	120 to 20 Below 20 to 10	1 1·5	35 50
CM	For general industrial metering of commercial grade according to B.S.S. 37	1·5, 5 or 15 VA	120 to 20 Below 20 to 10	1 2	90 120

In addition, the following variations in ratio error and phase-angle are permissible over the whole range from 120 to 10 per cent of rated primary current—

Class	AM	BM	CM
Variation in ε % .	0·5	1·0	1·5
,, ,, β, min.	15	25	60

Omitting Class D, the limits of ratio error and phase-angle for the new classification are plotted in Fig. 298 along with Classes 0·5 and 1 of the I.E.C. Recommendations; it should be compared with Fig. 5.

An entirely new feature is the specification for current transformers of an over-current factor defined by the relation

$$\frac{\textit{Rated primary over-current}}{(\textit{R.m.s over rated time})} = \frac{\textit{Rated primary current}}{(\textit{R.m.s.})} \times \frac{\textit{Over-current factor}}{(\textit{O.c.f.})}$$

When this rated over-current is passed through the primary for the rated time, the secondary being connected to its rated burden, the temperature

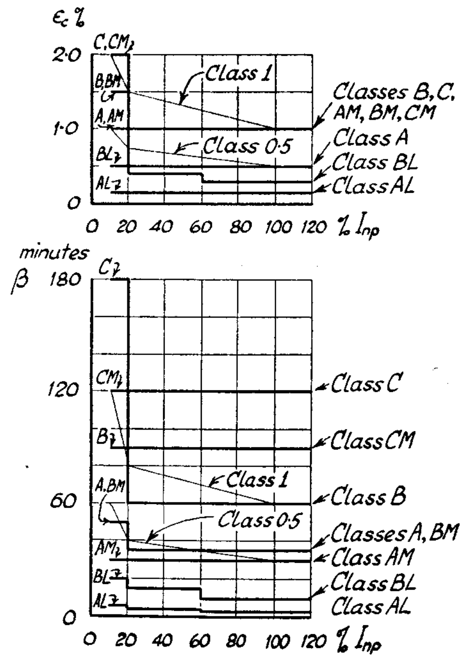

Fig. 298. Revised Limits of Error for Current Transformers Great Britain

rise at any part shall not exceed 200° C. With the usual ambient temperature of 40° this corresponds with a greater temperature of 240° C. (see p. 159).

Reference to p. 159 will also show that the o.c.f. corresponds with the thermal overload factor, k_{ss}, plotted in Fig. 65 for a rather higher temperature (250° C.). A transformer is considered to have complied with the over-current requirements if (i) the primary winding has a conductivity in accordance with B.S.S. 128; (ii) the current density in the winding at the rated r.m.s. over-current does not exceed the following values.

Rated time, seconds	0·5	1·0	2·0	5·0	10
Current density, A./sq. in.	150 000	106 500	75 000	48 000	33 0
,, ,, A./sq. mm.	221	157	116	71	4

ith current densities of of 1·5, 2 and 2·5 A./sq. mm. the ½ second rating rresponds with an o.c.f. of 148, 110, and 88 respectively; these figures check ite reasonably with Fig. 65, allowing for difference in initial assumptions. is explained in the Specification that a commercial grade of transformer ay, without special design, have an o.c.f. of 50 to 100 (½ sec. rating); with asonable commercial facility 200 to 400 may be attained. If 400 is to be ceeded, a bar-type transformer is practically a necessity.

In addition, the transformer shall stand without electrical or mechanical amage an initial peak 2½ times the rated r.m.s. over-current. This factor is e product of $\sqrt{2}$, the peak-factor of a sine wave, and 1·8, the maximum obable displacement of the first half-wave of an asymmetrical over-current.

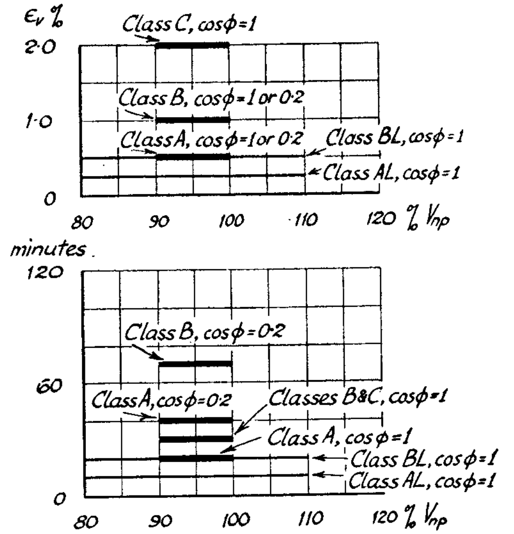

Fig. 299. Revised Limits of Error for Voltage Transformers Great Britain

e factor 2½ (o.c.f.) corresponds with the mechanical overload factor worked on pp. 166–169, but gives a considerable factor of safety, making quite e that the elastic limit of copper is not nearly reached.

Voltage Transformers. The old requirements for voltage transformers are en on p. 19. The rated secondary voltage is still 110 when the primary connected between the lines but is now stated as $110/\sqrt{3}$ when the primary joined between line and neutral. The rated primary line voltages are as ted on p. 19 with the exception that 1 100 and 49 500 are omitted and 000, 55 000, 88 000, 165 000, and 220 000 are added. When the primary connected to line and neutral, rated primary voltage is the standard line ltage divided by $\sqrt{3}$.

In place of the original four classes there are now six classes namely AL, L, A, B, C, and D. Of these, AL and BL are highly-accurate portable transmers, while A and B are transformers for use with integrating meter equipent. The following tables give the limits of error measured at the primary d secondary terminals excluding any fuses or protective resistors; when asured at the end of the leads remote from the transformer these limits ll be exceeded.

The uses of Classes AL and BL are similar to those of the corresponding current transformers. The limits are as follows—

Class	Rated Burden at 50 cycles per sec. and unity power-factor Single-phase only	Percentage of rated Primary voltage	ε_v ± %	γ ± min.
AL	10 VA	From 110 down to and including 80	0·25	10
BL	10 VA	From 110 down to and including 80	0·5	20

The uses of the Classes A, B, C, and D are similar to those of the corresponding current transformers. In addition Classes A or B are intended to work in conjunction with current transformers of Class AM, while Class B is to be used with current transformers of Classes BM and CM. The limits of error are as follows—

Class	Rated Burden at 50 cycles per sec. and unity power-factor		From 90 to 100% of rated voltage with 25 to 100% of rated burden and unity power-factor		From 90 to 100% of rated voltage with 10 to 50% of rated burden and 0·2 power-factor	
	Single-phase VA	Three-phase VA per phase	ε_v ± %	γ ± minutes	ε_v ± %	γ ± minutes
A	50, 100, 200	50, 100, 200	0·5	20	0·5	40
B	15, 50, 100, 200	25, 50 100, 200	1·0	30	1·0	70
C	15, 50, 100, 200	25, 50, 100, 200	2·0	30	—	—
D	No Standard	No Standard	5·0	—	—	—

The limits given in these two tables are plotted in Fig. 299, which shou[illegible] compared with Fig. 6. Classes A, B, C, and D differ from those of [illegible] specification in the following particulars: (*a*) Their uses are more [illegible] defined. (*b*) The limits of error with a unity power-factor burden are [illegible] from 90 to 100 per cent of rated voltage. (*c*) Under these conditions the [illegible] for Classes A, B, and D remain unchanged, but Class C has double th[illegible] error and half the phase-angle laid down in B.S.S. 81—1927. (*d*) Lim[illegible] given for Classes A and B with a burden of 0·2 power-factor. (*e*) Th[illegible] single-phase burden for Class A is changed; three-phase burdens [illegible] specified for this class and 200 VA per phase is added to Classes B and [illegible]

Terminal Marking. The specification for terminal marking has und[illegible] minor changes. For *current transformers* the notation given on p[illegible] appears, but as an alternative it is provided that the primary may be [illegible] T_1, T_2 with the same letters within circles for the secondary terminal[illegible] vision is also made for transformers with tapped secondary or [illegible] secondary windings. *For single-phase voltage transformers* it is no[illegible] mended that the primary be lettered V_1, V_2 and the secondary [illegible]

same letters in circles, superseding the arrangement shown on p. 584. If the windings are tapped, the terminal notation is to be V_1, V_2, V_3, etc. For *three-phase voltage transformers* the new specification is the same as the old, see p. 585.

Temperature-rise. The specification given on p. 591 is superseded by the I.E.C. recommendations given on p. 590. In addition it is provided that the temperature-rise for the windings of compound-filled transformers shall not exceed 50° C. whether with Class A or Class B insulation. Methods of measuring the temperature, ambient and barometric conditions, etc., accord in general with the I.E.C. recommendation.

Dielectric Tests. The new dielectric tests for primary windings are entirely different from the old. Two systems of test voltages are specified; a low system (symbol *L*) applicable when all the lines of a circuit are insulated and a high system (symbol *H*) for use when one line is earthed. It is understood that system *L* will usually apply. The detailed recommendations are—

System L—

Three-phase: Neutral point directly earthed or through a resistor.
Neutral point insulated or earthed through a reactor.
Single-phase: Normally insulated or mid-point directly earthed.

System H—

Three-phase: One line permanently earthed.
Two-phase: Three-wire system with common terminal directly earthed.
Single-phase: One line directly earthed.

The two systems of test voltages are as follows—

Rated kilovolts between lines, *V*	System L, kV	System H, kV
Not exceeding 0·440 kV	2	2
Exceeding 0·440 kV and up to and including 0·660 kV	2·25 *V* + 1	3·90 *V* + 1
Exceeding 0·660 kV and up to and including 220 kV	2·25 *V* + 2	3·90 *V* + 2

It will be seen on reference to p. 595 that System L above 0·66 kV agrees with the old specification, but that otherwise the rules are new.

Windings of current and voltage transformers fully-insulated for connection between lines are to be given an applied-voltage test, System L or H as the case may be, with a duration of 1 minute. Corrections are specified for tests lasting longer than 1 minute and for frequencies exceeding twice the rated value. If subsequent applied-voltage tests are to be made after installation of the transformer, the voltage must not exceed 90 per cent of the tabulated value. In addition to the applied-voltage test made at the maker's works voltage transformers are also to be given an induced voltage test at 2·5 *V* for a similar duration.

Voltage transformers for voltages $>$ *0·660 kV with one end of the primary directly earthed* cannot usually be given an applied-voltage test. Its place is taken, therefore, by an induced voltage test of System L or H, as may be appropriate; the duration of the test is as before.

The following table gives for convenient reference the values of the test voltages for some standard rated primary voltages.

Line kV V	0·44	0·66	3·3	6·6	11	22	33	44	55	66	88	110	132	165	220
System L, kV	2·0	2·5	9·5	17	27	52	76	101	126	150	200	250	299	374	498
System H, kV	2·0	3·6	15	28	45	88	131	174	216	260	345	431	517	645	860
$2{\cdot}5V$, kV	1·1	1·65	8·3	16·5	27·5	55	83	110	138	165	220	275	330	413	555

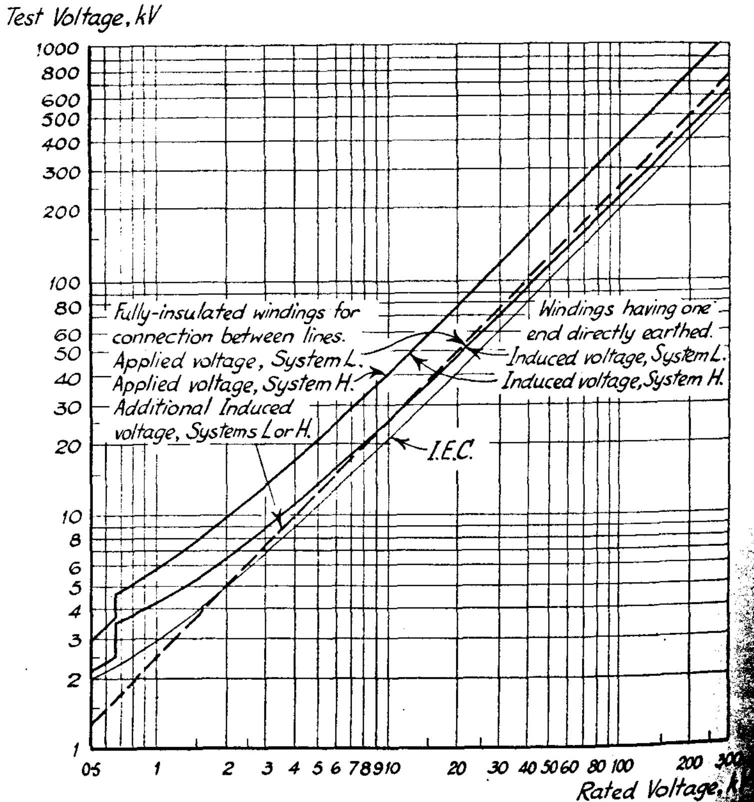

FIG. 300. REVISED TEST VOLTAGES FOR PRIMARY WINDINGS GREAT BRITAIN

These figures are plotted in double-logarithmic co-ordinates in Fig. 30 and should be compared with Fig. 288. It is interesting to note that fo transformers working above 10 kV the System H test voltages are the mo severe specified by any national standard rules.

AUTHOR INDEX

SUBJECT INDEX

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