fixed to the iron base-plate. A somewhat similar design of the Siemens-Schuckertwerk* is shown in Fig. 88 (*b*) with one quadrant removed. The ring core of nickel-iron with its secondary is contained within a porcelain capsule, divided in the

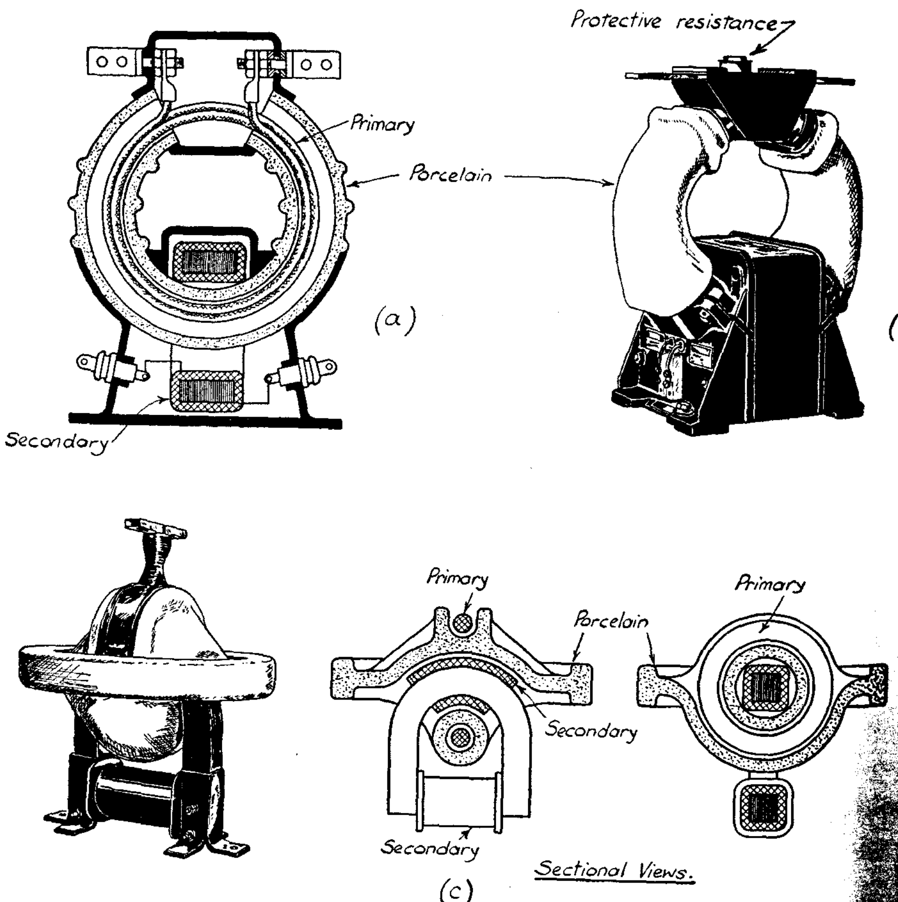


FIG. 87. VARIOUS PORCELAIN-INSULATED S.C.-PROOF TRANSFORMERS WITH CIRCULAR PRIMARIES

vertical plane of the ring, this being attached to the supporting insulator by a metal cap which also carries the primary

* "Stromwandler für einphasigen Wechselstrom, die Form A10 P1, hergestellt von den Siemens-Schuckertwerken Aktiengesellschaft in Nürnberg," *Elekt. Zeits.*, vol. 55, pp. 192–193 (1934).

terminals. The primary is wound toroidally upon the capsule. The transformer is designed for rated primary currents of 1 to 200 amperes, a secondary current of 5 amperes, and a burden of 0·6 ohm (15 VA); the primary voltage is 10 kV. Transformers on this double toroid principle are practically free from short-circuit forces.

Quite recently the Siemens & Halske A.G.* has produced a new type of transformer shown diagrammatically in Fig. 89. The magnetic circuit is open, consisting merely of a long bar-shaped iron core carrying the primary winding, the whole being

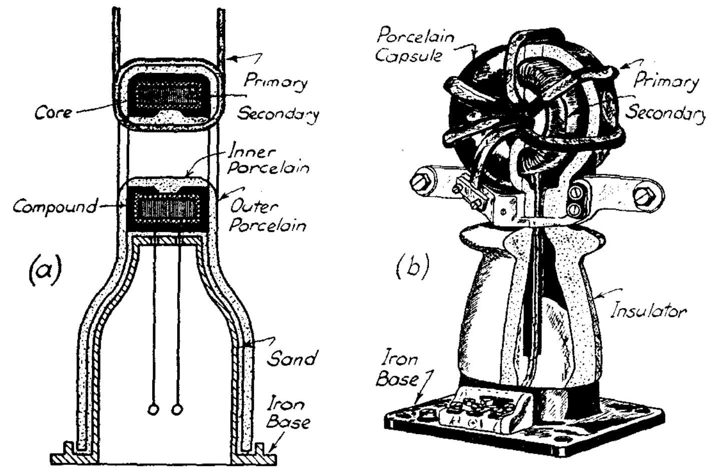


FIG. 88. CURRENT TRANSFORMERS WITH PRIMARY & SECONDARY TOROIDS

put inside a paper bushing, upon the outside of which the secondary is wound. An output of 15 VA with Class 1 accuracy can be obtained; with a lower output much higher accuracy, up to Class 0·2, is attainable; the error curves are very flat. Transformers of this type are dynamically secure up to at least 200 times the normal current amplitude and have high accuracy, security, simple construction, and ease of insulation for the very highest voltages.

24. **The insulation of current transformers.** The insulation of a current transformer consists of three main portions: (i) the insulation between the secondary winding and the core, (ii) the primary insulation, and (iii) the surrounding medium in which the transformer is immersed.

* See *Bull. Schw. Elekt. Verein*, vol. 24, p. 95 (1933).

Secondary coils are wound in a lathe or winding machine with d.c.c. or paper-covered wire, either upon a light tube which constitutes the internal insulation, or upon a former from which the coil may be removed after winding; the coils are subsequently taped up securely and vacuum impregnated with varnish or compound. Toroidal windings receive similar treatment, but the turns must be wound on the core by hand.

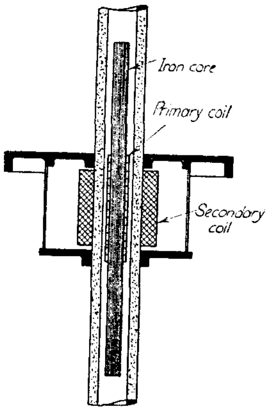


FIG. 89. CURRENT TRANSFORMER WITH OPEN MAGNETIC CIRCUIT

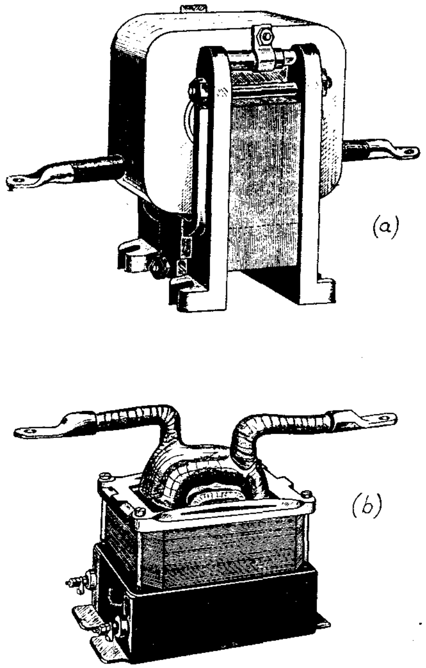


FIG. 90. CURRENT TRANSFORMERS WITH TAPED PRIMARY COILS

The primary winding is connected in the high voltage network and its insulation from the secondary and core presents, in consequence, a more difficult problem. The primary conductor has a much larger sectional area than that of the secondary winding; according to the magnitude of the current and the method of construction the conductor may consist of insulated wires in parallel, of copper bar taped and braided, of copper bar wound with the turns spaced apart, or in special instances where a flexible conductor is required (e.g. in cross-hole transformers) may be an insulated stranded cable. In the case of

bar-type transformers the primary conductor is a copper bar or rod suitably insulated in a porcelain or paper bushing, or it is a piece of high-voltage cable; numerous instances have been described in Section 22 and we shall, in consequence, devote our attention exclusively to wound primaries. For the lower working voltages, not greater than about 7 kV, the primary coil may be simply taped and impregnated in a way similar to the secondary coil; Figs. 90 (*a*) and (*b*) show respectively a

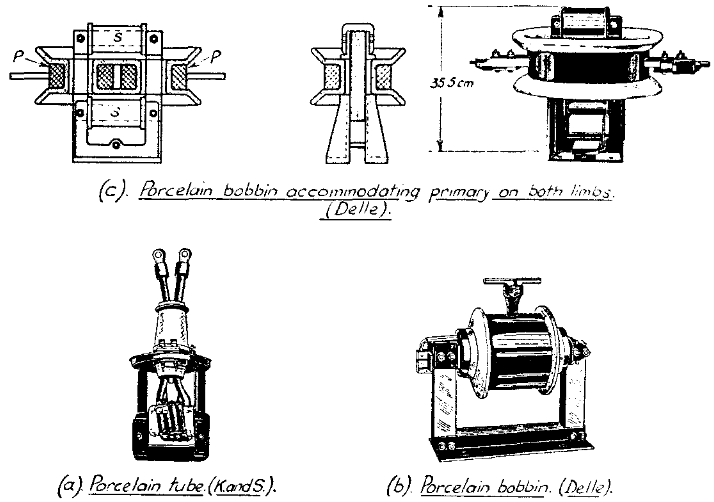


FIG. 91. CURRENT TRANSFORMERS WITH PORCELAIN PRIMARY BOBBINS

core-type (Ferranti) and a shell-type (Metropolitan-Vickers) transformer with taped primary coils. With somewhat higher voltages the primary may be wound either upon a tube or upon a flanged bobbin of bakelized paper or of porcelain, as illustrated in Fig. 91 (*a*) and (*b*). The tube is suitable if the completed transformer is to be compound-filled, since the compound holds the primary coil firmly centred upon the tube. For open-type or for oil-filled transformers the bobbin is preferable, since the flanges give the coil some axial support and at the same time enable the required creeping surface to be obtained without undue axial length; it is not practicable, however, to make very deep flanges, especially in porcelain, since these become mechanically weak. An interesting improvement on the simple porcelain bobbin is shown in Fig. 91 (*c*), which illustrates a "dry-type" transformer made by the Ateliers des Constructions Électriques de Delle. The primary consists of two coils on opposite vertical sides of the rectangular core, wound by hand upon a one-piece bobbin of peculiar form; the wide flanges provide adequate insulation up to 40 kV. The secondary coils occupy the remaining sides, and being in a plane at right-angles to the primary they are subjected to very little mechanical force; the short-circuit security is, therefore, very high. Another type of improved porcelain bobbin is found in the so-called "mussel-type" transformer of the Koch & Sterzel A.G. shown in Fig. 92; this is a "cross-hole" transformer of simplified construction with the primary placed between the

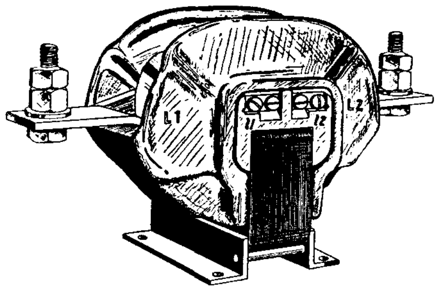


FIG. 92. THE "MUSSEL" TYPE PORCELAIN-INSULATED CURRENT TRANSFORMER (KOCH & STERZEL)

stout walls of a one-piece insulator resembling a bivalve shell, the secondary and core passing through a transverse hole. It is built for a test voltage of 26 kV (working voltage 10 kV) and is of high thermal and mechanical security.

For the highest voltages the primary insulation may consist of moulded or compressed bakelized, varnished or oil-impregnated paper, or of porcelain. Porcelain has many advantages over other insulating materials. It is easily made into any desired shape, but the forms are preferably simple with no abrupt changes in thickness if deformation and cracking during the firing process are to be avoided and high mechanical and electric strength are to be ensured. It is difficult to prepare reliable ceramic pieces of intricate form to withstand test voltages exceeding 100 kV. Porcelain-insulated transformers can be used "dry," i.e. without the addition of oil or compound filling. Since porcelain is fireproof, dry-type porcelain-insulated transformers are extensively used, particularly on the Continent, for severe short-circuit conditions, since their thermal security is very high; numerous examples have already been

described in Sections 22 and 23 and in the present section, and others will be found in Section 25. Porcelain is the only material suitable for the insulating bushings of outdoor transformers since it is non-hygroscopic, weather-resisting, and capable of maintaining high insulating properties under severe climatic conditions. On the other hand, porcelain has several disadvantages. It is brittle and easily damaged by rough treatment. Its dielectric strength falls with a rise of temperature, so that it must not be overheated by the windings. Its dielectric strength is not so high as that of oil-impregnated paper, which supersedes it, at least for indoor use, at very high voltages both for bushings and for primary insulation.

The medium surrounding the transformer is also of considerable importance, partly for reasons of its insulating properties and partly for its cooling influence. In the case of all dry type transformers, whether the major insulation be of porcelain or of some organic material, the external air acts merely as a cooling agent. Examples are on record, however, where air has been used for the major insulation of high-voltage transformers; the large clearances that must be maintained between the primary and the rest of the transformer results in a very bulky construction. The oustanding example is the current transformers used in 132 kV circuits at Niagara Falls,* though these would not now be accepted as good modern practice. The circular primary coil is supported by petticoat insulators and is separated by large air spaces from the core and secondary; the transformer is used in the open air and is protected from the weather by a waterproof coating of roof asphalt. Although it is not unusual at the lower voltages to use dry-type transformers, it is now modern practice, particularly at the higher voltages, to enclose the transformer in a tank or other casing and to make use of an insulating filling medium, such as bituminous compound or oil. In smaller sizes the tank is of cast iron; in the larger sizes steel boiler-plate tanks with welded joints are used, exactly as in switchgear practice. The primary leads pass into the transformer through insulating bushings mounted on the lid of the tank. Fig. 93 illustrates the appearance of several types of compound- or oil-filled transformers for various voltages. In bar-type transformers it is usual to impregnate the secondary with compound and to enclose it

* L. C. Nicholson, "High voltage current transformers developed at Niagara," *Elec. World*, vol. 87, pp. 868–869 (1926); *Elekt. Zeits.*, vol. 48, p. 1042 (1927).

ght sheet-metal casing; sometimes a cast-
ded and the whole is filled with compound.
ound is extensively used, but has been
from the standpoint of fire hazard under
ons (see Section 20); again, the dielectric
mpounds falls considerably with rise of
ases are known where breakdown has
al voltage after an extended overload has
the compound to reduce its insulating
are now produced in which these defects
ayed, resulting in greater reliability and
ts are entirely absent from a filling of
ed by certain German manufacturers.
rticularly on the Continent, tends to the
ersion for current transformers in the way
proved successful for power transformers;
excellent insulator but it is also an admir-
. Dr. Keinath* has expressed the opinion
llulose paper is the most reliable insulating
oltage measuring transformers. There is
eplace the oil by non-inflammable liquids
chloro-hydrocarbon type.

ormers for very high voltages (cascade
insulation design of current transformers
high voltages that are now common in
es presents several difficult problems,
e of transformers for use in the open air,
lation is essential. Some manufacturers,†
U.S.A., have overcome the difficulties by
ormer within the tank of the oil-break
taking advantage of the highly developed
insulation of this apparatus has attained.
curity, and ease of inspection and replace-
ore usual for the current transformers in
to be separate oil-immersed units. Below
e type of transformer is common; above
the crossed-coil types are preferred on
ater electrical and mechanical symmetry
ofness. These types are diagrammatically

lations de mesure pour très hautes tensions," *Rev.*
584–585 (1933).
ion of wound type current transformers installed in
eaker tanks," *Journal Amer. I.E.E.*, vol. 47, pp. 872–

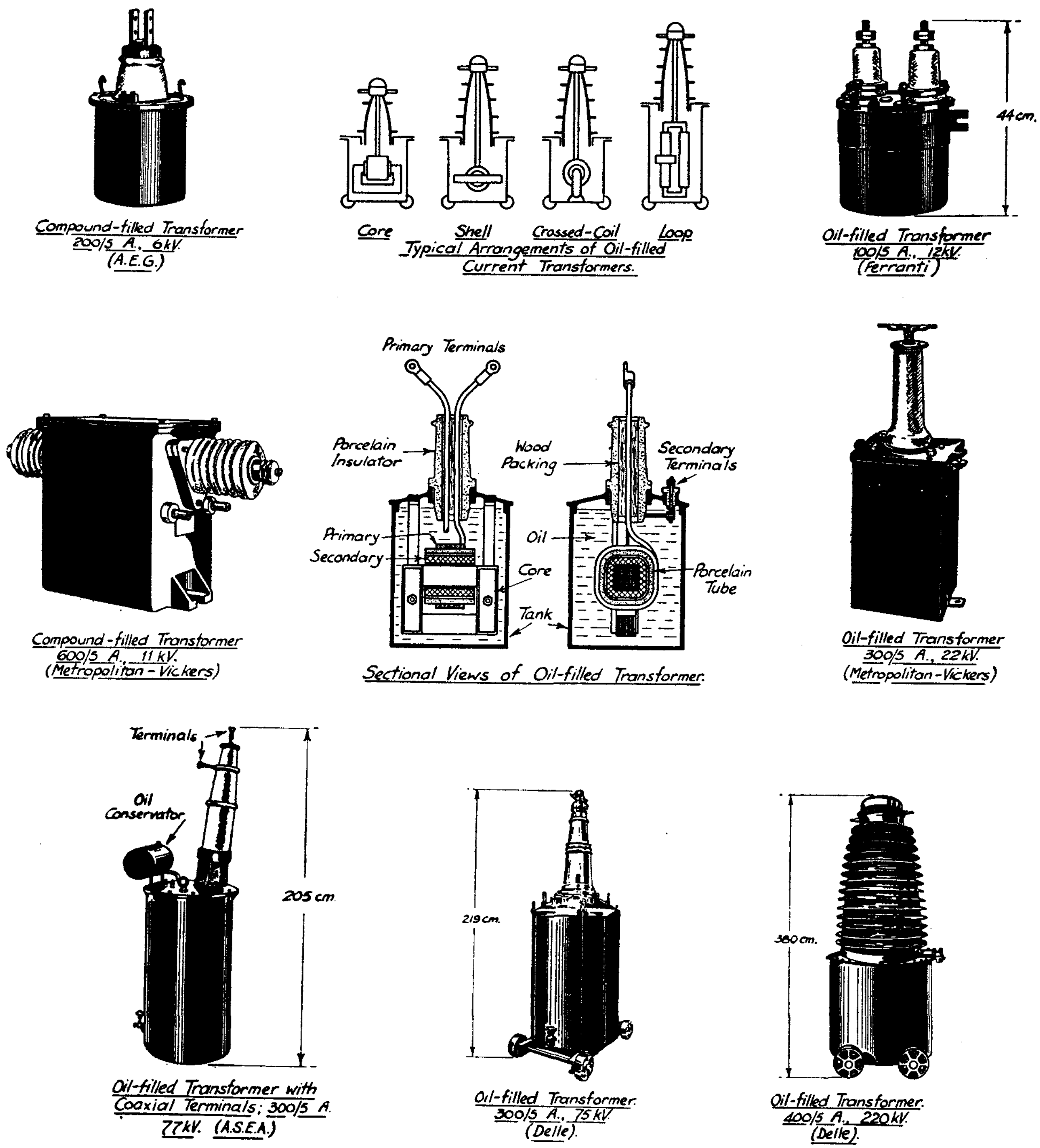


FIG. 93. COMPOUND-FILLED AND OIL-IMMERSED H.V. CURRENT TRANSFORMERS

depicted in Fig. 93. For the highest voltages oil-filled terminals with expansion heads or conservators are employed, exactly as in modern e.h.v. oil-switch design.

High-voltage current transformers of the normal construction are necessarily bulky and heavy; for example, a transformer made by the G.E.C. of America* for outdoor use at 115 kV, is 14 ft. 3 in. high, weighs 4 800 lb. and contains 225 gallons of oil! It is not surprising, therefore, that considerable attention has been given to the reduction of their bulk and weight without impairing either their security or accuracy;

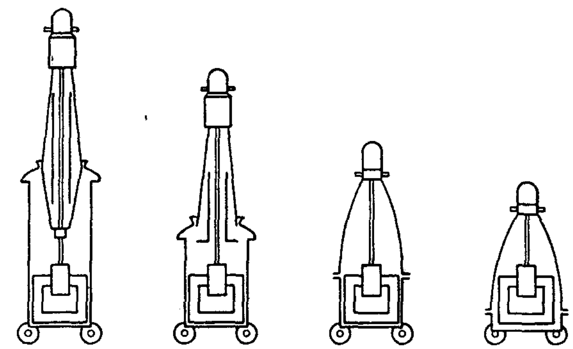


FIG. 94. EVOLUTION OF THE OIL-FILLED, PORCELAIN-CASED CURRENT TRANSFORMER

Fig. 94 shows† in a striking way the evolution of the modern design from the much more bulky early type. Fig. 94 (*a*) shows a transformer in which the active parts are immersed in oil contained in a steel tank, through the cover of which passes an oil-filled terminal; there is no connection between the oil in the tank and that in the terminal. If the joint between the tank and cover is made oil-tight it is possible to suppress the lower portion of the terminal insulator, so that the terminal and tank form a common oil space; this results in a reduction of height and weight that is quite important, as Fig. 94 (*b*) indicates. We may, however, proceed further, as in Fig. 94 (*c*), by reducing the tank to the height of the core

* I. H. Sclater, "Oil-immersed current transformers," *Gen. Elec. Rev.*, vol. 33, pp. 658–659 (1930).

† G. Courvoisier, "Messwandler. Brown-Boveri Spannungs-und Stromwandlern," *Bull. Schw. Elekt. Verein*, vol. 24, pp. 88–93 (1933).

and increasing the diameter of the insulator to that of the tank. Finally, it is a simple step to enclose the whole transformer within the oil-filled insulator, the tank becoming a mere base plate, as in Fig. 94 (*d*). Transformers on this principle are made by Brown-Boveri & Co. and other makers, but the most remarkable success has been obtained by the Siemens & Halske A.G. with crossed-coil transformers assembled within a porcelain insulator. Fig. 95 shows to the same scale* two S. & H. transformers for 150 kV (test voltage 350 kV), the one of normal tank construction and the other with the insulated casing; both deliver the same output and have the same accuracy. The saving in height is considerable and there is an even more striking reduction in weight; the larger transformer weighs about 3 000 kg. and the smaller only 900 kg. Similar transformers have also been constructed† for a working voltage of 220 kV. This design has Class 0·5 accuracy with a burden of 1 200 VA, weighs 1 500 kg. and successfully withstands the test voltage of 460 kV for eight hours instead of the regulation one minute. In the most up-to-date installations these crossed-coil transformers are now being built into the insulators of expansion-type circuit-breakers with great success.

The transformers just described provide a satisfactory solution of the problem of h.v. current transformer design by putting the entire insulation which separates the h.v. side from the earthed core upon the primary winding and immersing the whole in oil. In view of the possible fire hazard attending the use of oil, transformers have been developed for lower voltages (see pp. 185–189) in which the major insulation is porcelain and the windings are maintained "dry." Unfortunately, it does not seem possible to prepare satisfactory single ceramic pieces suitable for test voltages much over 100 kV, so that single-unit dry-type transformers for very high voltages are not at present a practicable proposition. The difficulty has been overcome on the Continent by using the "cascade" principle,‡ in which the major insulation is subdivided into stages in a way analogous to the insulation of a transmission line by an insulator chain. The principle is illustrated diagrammatically in Fig. 96 for

* G. Keinath, *Elekt. Zeits.*, vol. 52, pp. 284–285 and p. 1597 (1931).

† G. Keinath, *Bull. Schw. Elekt. Verein*, vol. 24, p. 95 (1933); also "Stützer-Stromwandler Freiluftausführung für 220 kV. Betriebsspannung," *Arch. f. tech. Mess.*, Z283–2 (1932).

‡ For excellent discussions of the cascade principle, see F. J. Fischer, "Kaskaden-Transformatoren," *K.u.S. Mitt.*, No. T.16, pp. 1–47 (1929), and W. Reiche, "Kaskaden-Stromwandler," *Arch. f. tech. Mess.*, Z287–1 (1931).

a two-unit transformer in which the primary winding P in the h.v. network is put on core 2 and the secondary S upon core 1. The two cores are connected by the intermediate windings, which may carry any convenient current, usually 20 to 50 amperes; the lower core and one secondary terminal are earthed, while the upper core must be insulated for half the rated voltage to earth. It will be clear that the principle can be extended to any number of units, the total insulation between the h.v. line and the earth being subdivided among

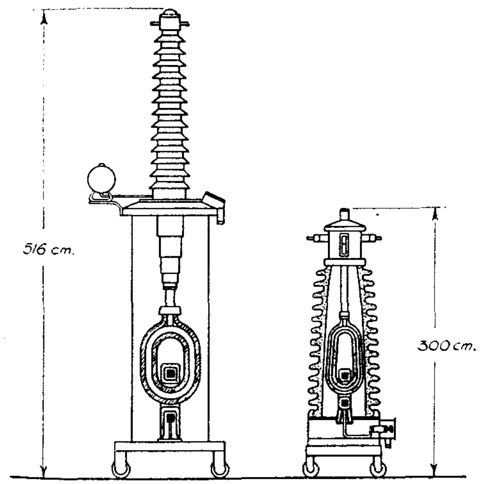


Fig. 95. Comparison of Tank Type and Insulator Type Oil-filled Transformers for 150 kV

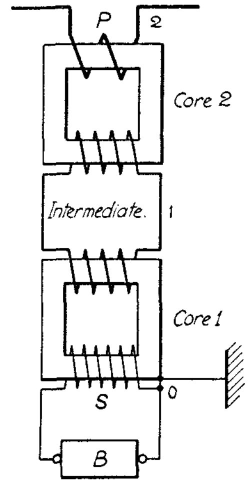


Fig. 96. Diagrammatic Arrangement of Cascade Current Transformer

the several units. Since the upper unit has to supply not only the burden B but also the magnetization for and the losses in the other units, the overall ratio error and phase-angle is the sum of those in the several units. To reduce the errors as much as possible it is usual to provide suitable error-compensating devices of the types described in connection with individual transformers in Sections 6 and 8.

The subdivision of the voltage from line to earth among the various elements of the cascade is determined by the intercapacitances between the windings on the several cores and the earth-capacitances of these windings. Consider the two-unit arrangement of Fig. 96, having three separate circuits, namely, the primary, intermediate, and secondary respectively, and let none be earthed. Then Fig. 97 (*a*) shows the two intercapacitances between (i) the secondary 0 and intermediate 1 and

(ii) between the intermediate 1 and primary 2; these intercapacitances are about equal. There is, in addition, a much smaller intercapacitance between 0 and 2, and the three earth-capacitances, all of which are unequal. If 0 is now earthed, as in the actual transformer, the arrangement becomes equivalent to Fig. 97 (*b*). Consider next a three-unit cascade having the arrangement of capacitances shown in Fig. 97 (*c*); upon earthing the lowest conductor the equivalent system of condensers is shown in Fig. 97 (*d*). Converting the mesh *abc* into its equivalent star we arrive finally at the grouping of condensers given in Fig. 97 (*e*). A precisely similar analysis of the capacitances for a cascade with still more units leads to the following conclusion: That the equivalent

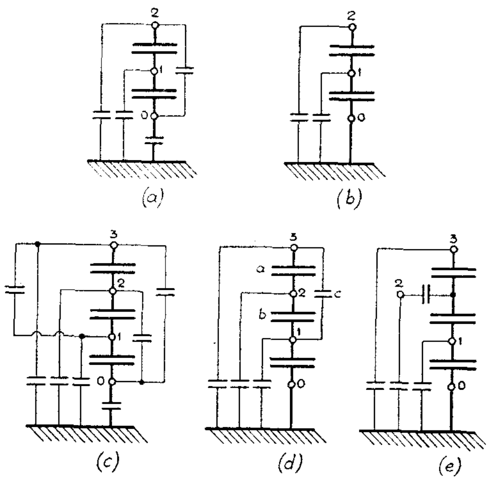


FIG. 97. INTER- AND EARTH-CAPACITANCES IN CASCADE-CONNECTED TRANSFORMERS

network for an n-unit cascade consists of n unequal "intercapacitances" and n unequal, but much smaller, "earth-capacitances" joining to earth the points of junction of the intercapacitances.

The general case is somewhat cumbrous to handle and does not readily lead to useful conclusions; interesting results can be obtained from the simpler assumption of n equal intercapacitances and only $n - 1$ equal but smaller earth-capacitances, since the earth-capacitance from the high-voltage conductor has no influence upon the potential distribution among the elements of the cascade. Following Fig. 98, let C be the intercapacitance between the pairs of windings on a core, C_e the earth capacitance, both being assumed loss-free; let V_1, V_2, V_3, V_4 be the potentials of the higher potential windings on each unit, and Q_1, Q_2, Q_3, Q_4 the charges in the intercapacitances. Then, for each unit,

$$Q_1 = CV_1 = CV_{10},$$
$$Q_2 = C(V_2 - V_1) = CV_{21} = Q_1 + C_eV_1 = CV_{10} + C_eV_{10},$$
$$Q_3 = C(V_3 - V_2) = CV_{32} = Q_2 + C_eV_2 = CV_{10} + C_eV_{10} + C_eV_2,$$
$$Q_4 = C(V_4 - V_3) = CV_{43} = Q_3 + C_eV_3 = CV_{10} + C_eV_{10} + C_eV_2 + C_eV_3.$$

Solving for the voltages across the units, V_{21}, V_{32}, V_{43}, in terms of that over the first stage, put $\alpha = C_e/C$, then

$$V_{21} = (1 + \alpha)V_{10},$$
$$V_{32} = (1 + 3\alpha + \alpha^2)V_{10},$$
$$V_{43} = (1 + 6\alpha + 5\alpha^2 + \alpha^3)V_{10}.$$

The total voltage across the whole arrangement will be

$(2 + \alpha)V_{10}$ with two units,

$(3 + 4\alpha + \alpha^2)V_{10}$ with three units,

and $(4 + 10\alpha + 6\alpha^2 + \alpha^3)V_{10}$ with four units.

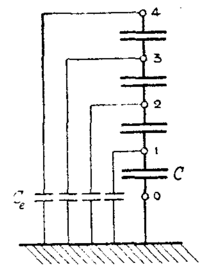


FIG. 98. SIMPLIFIED CAPACITANCES FOR A FOUR-STAGE CASCADE

Hence the fraction of the total voltage sustained by the individual units will be, reckoning from the lowest unit upward,

$1/(2 + \alpha)$ and $(1 + \alpha)/(2 + \alpha)$ with two units;

$1/(3 + 4\alpha + \alpha^2)$, $(1 + \alpha)/(3 + 4\alpha + \alpha^2)$ and
$(1 + 3\alpha + \alpha^2)/(3 + 4\alpha + \alpha^2)$ with three units;

$1/(4 + 10\alpha + 6\alpha^2 + \alpha^3)$, $(1 + \alpha)/(4 + 10\alpha + 6\alpha^2 + \alpha^3)$,
$(1 + 3\alpha + \alpha^2)/(4 + 10\alpha + 6\alpha^2 + \alpha^3)$ and
$(1 + 6\alpha + 5\alpha^2 + \alpha^3)/(4 + 10\alpha + 6\alpha^2 + \alpha^3)$ with four units.

These expressions are plotted as functions of α in Fig. 99 for two-unit and three-unit transformers. It will be noticed (i) that the voltages across the individual units will be equal only when the earth-capacitances are zero; and (ii) that the upper unit supports too great and the lower unit too small a share of the total voltage, the inequality in potential distribution becoming more marked as the proportion of earth-capacitance grows larger. To maintain a reasonably uniform potential distribution it is essential, therefore, that the inter-capacitance between the two windings on each of the several cores should be large in comparison with the earth-capacitances; this close coupling can be very satisfactorily attained by the porcelain-insulated, cross-hole construction with sand filling illustrated in Figs. 84 and 85.

The first installations of cascade current transformers were described by Pfiffner* in 1926, but the present-day cross-hole

* E. Pfiffner, "Kaskaden-Erdungsspulen und- Messwandler," *Elekt. Zeits.*, vol. 47, pp. 44–46 (1926).

type is the product of the firm of Koch & Sterzel.* Fig. 100 shows sectional views of a two-unit transformer for indoor use at a working voltage of 60 kV, in which the lower porcelain is mounted in a cast-iron base-plate and carries the windings for the lower stage. The upper part of this insulator is expanded to form a socket to receive the insulator of the second unit, the iron core of which rests upon the top of the lower porcelain; both units are filled with graphited sand and are entirely fireproof.

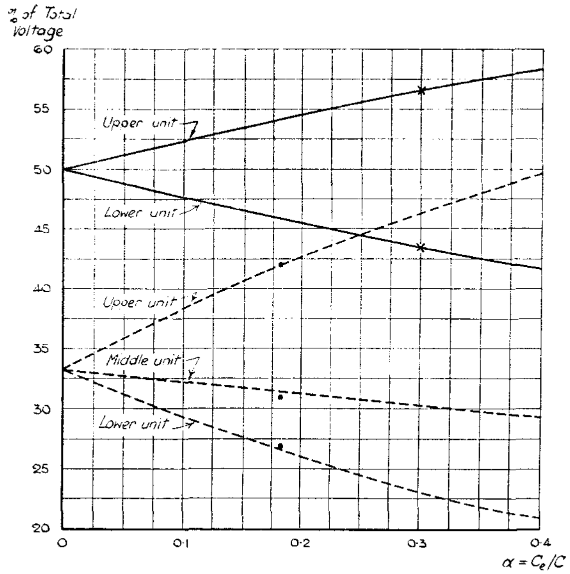


FIG. 99. VARIATION OF P.D. OVER THE STAGES OF A CASCADE TRANSFORMER

The cap contains the primary terminals and surge-protective resistance; the secondary terminals are mounted on the base-plate. Measurements of the voltage subdivision shows that 56·5 per cent is borne by the upper unit and 43·5 per cent by the lower; these figures are represented by the crosses in Fig. 99. For a working voltage of 110 kV (240 kV test voltage) a three-unit cascade is used, composed of two units like the lower

* K. Grundig, "Fortschritte im Bau von Kaskaden-Messwandlern," *Elekt. Wirts.*, vol. 29, pp. 576–579 (1930). "Kaskaden-Messwandler," *E.u.M.*, vol. 48, pp. 633–636 (1930); *Elekt. Zeits.*, vol. 53, pp. 341–342 (1932). A. Mathias, "Die heutigen Probleme der Hochspannungs-Kraftübertragung," *Elekt. Zeits.*, vol. 52, p. 1497 (1931). Also see G. Keinath, *Elekt. Zeits.*, vol. 52, pp. 1597–1598 (1931).

one in Fig. 100 placed one above the other and surmounted by a third upper unit; the division of voltages across the upper, middle and lower units is 42 per cent, 31 per cent and 27 per cent, shown by the dots in Fig. 99. For outdoor use the cap and the iron casings between the stages are provided with metal rain shields, serving also as arcing rings. The figure 42 per cent for the upper unit in the three-stage transformer brings the test-voltage across that unit rather too near the

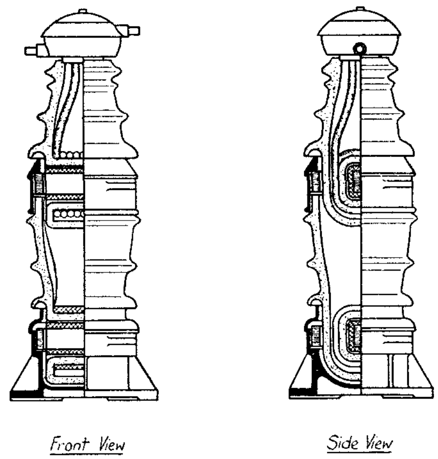


FIG. 100. SECTIONAL VIEWS OF TWO-UNIT CASCADE CURRENT TRANSFORMER FOR 60 kV (KOCH & STERZEL)

limit of 100 kV for which such cross-hole porcelains can be satisfactorily manufactured. Again, increasing the number of similar units from two to three greatly reduces the accuracy of the transformer; for example, Class 0·5 accuracy is given with two units for an output of 60 VA, but with only 20 VA when there are three units, in consequence of the great magnetizing load put on the uppermost unit. Also, the overload figure—the multiple of normal primary current up to which the secondary current remains proportional to the primary current—is considerably decreased. These defects have been overcome by the Koch & Sterzel A.G. in the three-unit transformer shown in Fig. 101. By radical changes in the design, especially of the upper unit, almost equal division of voltage among the stages is secured; measurement and relay cores are provided, the former with a Class 0·5 output of at least 30 VA and the latter with an overload figure of 10. The transformer is suitable for open-air use at 110 kV working voltage.

A further interesting application of the cascade principle is due to Iliovici* of the Compagnie des Compteurs, known as the "Type Φ" transformer from its fancied resemblance to the form of that Greek letter. As shown diagrammatically in Fig. 102, it is a two-unit arrangement in which each unit is a toroidally-wound ring core and the insulation is provided by

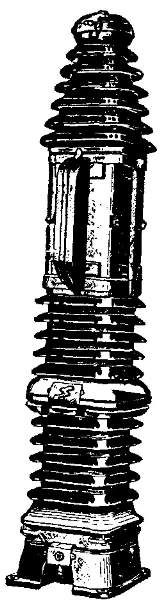


FIG. 101. THREE-UNIT CASCADE CURRENT TRANSFORMER FOR 110 KV (KOCH & STERZEL)

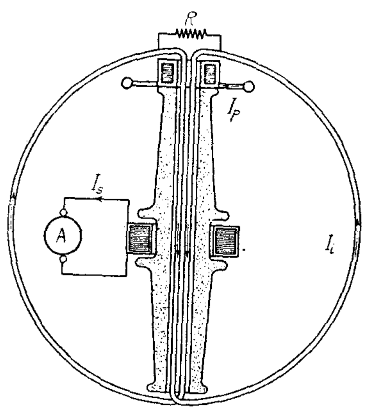


FIG. 102. THE "Φ-TYPE" CASCADE CURRENT TRANSFORMER (COMPAGNIE DES COMPTEURS)

a paper or porcelain through-bushing. The primary is ring-wound on the upper core, supported within a suitable cover upon the top of the bushing; its secondary is formed by the intermediate winding consisting of one or more turns of copper tube. The ratio in this stage is chosen in such a way that I_t has a large value which can be used as the primary current

* A. Iliovici, "Tendences actuelles dans la construction et l'utilisation des transformateurs de mesure," *Bull. Soc. Franç. des Élecns.*, vol. 10, 4th series, pp. 1191–1215 (1930); "Transformateurs de mesure. Progrès constructifs récents. Discussion des Règles de Normalisation," *ibid.*, vol. 2, 5th series, pp. 1117–1131 (1932); "Perfectionnements aux transformateurs de mesure pour circuits haute tension," *Rév. Gén. de l'Él.*, vol. 34, pp. 585–586 (1933).

of the second stage to give a highly accurate bar-type transformer. The resistance R serves to compensate the phase-angle between I_p and I_s; Class 0·5 accuracy is readily obtainable. The transformer is manufactured for open-air use up to 220 kV.

26. **Voltage rises and surge phenomena.** We have hitherto considered the insulation of a current transformer in regard to its safety under normal working conditions with a steady voltage. It is well known, however, that considerable voltage-rises may occur during switching or other transient conditions and it should be the aim of satisfactory design to ensure the security of the transformer in these circumstances. Two classes of phenomena should be distinguished (i) due to saturation of the core when the secondary circuit is opened; (ii) due to the effect of travelling waves set up in the primary network by switching, sudden short-circuits, arcing earths, lightning strokes and other such transient conditions, of which lightning is responsible for by far the most dangerous over-voltages.

On p. 124 it has been shown that if the secondary circuit of a current transformer be opened while the primary is carrying its normal current, the flux in the core will increase to several times its rated value, in consequence of the large magnetizing ampere-turns to which the core is subjected. The wave-shape of the primary current is determined by the load on the primary network, and not by the current transformer. Supposing the primary current to be sinusoidal, Fig. 103 shows that the flux wave will have steep sides and a flat top; consequently, the voltage induced in the secondary winding will have a very pronounced peak, although the average and the r.m.s. values of the wave have quite moderate values. These facts are readily demonstrated with an oscillograph and measurements of the voltage have been made by several observers.* The r.m.s. value is obtained with an electrostatic voltmeter; the average value, with a thermionic or other rectifier in conjunction with a moving-coil voltmeter; and the peak value, with a thermionic crest voltmeter† or with a synchronous contact-maker. Fig. 104, which is plotted from results given by Edgcumbe and

* W. R. Woodward, "Characteristics of current transformers on open circuit," *Elect. J.*, vol. 15, pp. 48–50 (1918). R. Brown, "Effects of opening the secondaries of current transformers," *Power*, vol. 58, p. 843 (1923); "Abnormal current transformer secondary voltages," *ibid.*, vol. 60, p. 130 (1924).

† See for example, A. C. Bartlett, *Journal Sci. Insts.*, vol. 1, p. 281 (1924); L. G. A. Sims, *ibid.*, vol. 10, p. 344 (1933).

Ockenden (loc. cit. *ante.*, p. 585) for a transformer having a normal rating of 960 primary ampere-turns and a silicon-iron core, shows the average, r.m.s. and peak voltages across the open secondary up to $2\frac{1}{2}$ times the rated primary current. It

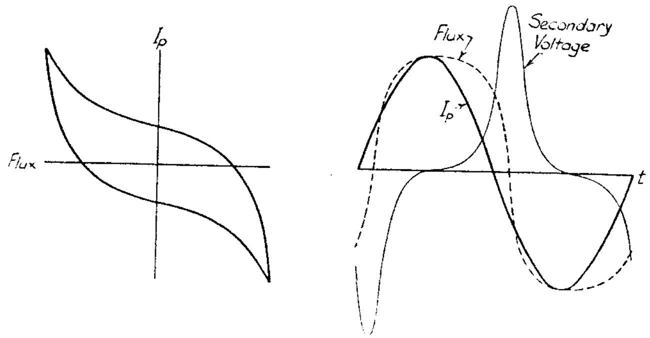


FIG. 103. CURRENT, FLUX AND SECONDARY VOLTAGE IN A TRANSFORMER WITH OPEN SECONDARY

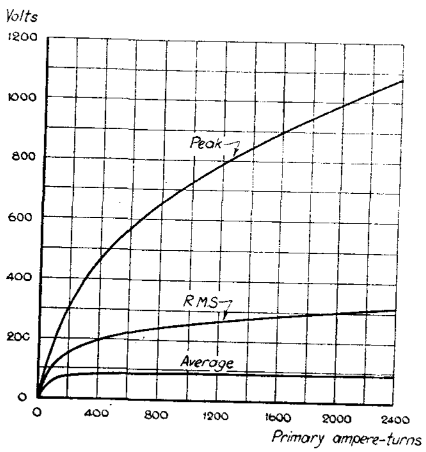


FIG. 104. AVERAGE, R.M.S. AND PEAK VALUES OF OPEN-CIRCUIT SECONDARY VOLTAGE

will be seen that the average voltage is practically constant for all fluxes, the r.m.s. value rises slowly and later becomes constant, while the peak value continues to rise steeply with increasing saturation, and is several times greater than the r.m.s. For example, with rated ampere-turns the r.m.s. is 250 volts and the peak over 700 volts. From this it is clear

that the great danger from an open-circuited secondary lies in the high peak voltage, which may easily be sufficient to break down the insulation of the winding and to give serious, even fatal, shocks to a person coming in contact with the terminals. Some of the National Standard Rules demand that current transformers shall be capable of operation for a specified time with full rated primary current and opened secondary, and it is usual for the insulation of modern transformers to be quite safe under this condition; even so, the possibility of dangerous shock must not be overlooked.

It is of interest to note two devices for limiting the voltage rise at the secondary terminals, which may be useful in certain troublesome cases. Pfiffner* describes a transformer in which the core has a constricted section which, in the event of an opened secondary, rapidly saturates and prevents the flux in the main part of the core from increasing very seriously. Schunck† suggests that the secondary winding should be shunted by a rejector circuit tuned to reject the fundamental and accept the harmonics in the secondary voltage wave. When the transformer operates normally the secondary voltage is practically sinusoidal and the rejector acts only as a small additional burden. When the secondary is opened and the voltage is rich in harmonics, these harmonics drive currents through the rejector, leaving a rise at the terminals of the transformer dependent on the fundamental alone. In an actual case the voltage rose with the rejector in place to 5–17 times the normal value, according to the degree of saturation, compared with 50 times without the rejector.

The insulation of the primary may be damaged by the over-voltages that are set up when travelling electromagnetic waves propagated in the primary network impinge upon the winding. Such waves or surges are produced by transient disturbances such as switching on or off some portion of the network, the incidence of short-circuits or of earth faults, and, in the most dangerous cases, by lightning strokes. The effects are of an impulsive or "hammer-blow" character and can be seriously destructive, the more so as the wave-front becomes steeper. Again, the frequency of the wave may be high enough to resonate with the oscillatory circuit composed of the transformer and the capacitance of some portion of the network, still further increasing the voltage rise. It is not our purpose

* E. Pfiffner, "Stromwandler mit kleiner induzierter Spannung bei offenem Sekundärstromkreis," *E.u.M.*, vol. 33, pp. 289–291 (1915). See p. 192.

† H. Schunck, "Spannungsanstieg beim Unterbrechen der Sekundärseite eines Stromwandlers," *Elekt. Zeits.*, vol. 53, pp. 1129–1130 (1932).

here to discuss the theory and general properties of surges* but rather to summarize their effects on current transformers and the methods of protection against their destructive influences.

The general nature of the problem may be illustrated by a simple hydraulic analogy. In Fig. 105 (*a*) the transformer primary is represented by inductive turns, the capacitance of the inter-turn insulation being indicated by the condensers. In the analogous hydraulic arrangement of Fig. 105 (*b*), the inductances of the individual turns are replaced by the inertia of the pistons P_1, P_2, P_3; the insulation is represented by the elastic diaphragms D_1, D_2, D_3. If the piston P be moved regularly and smoothly, P_1, P_2, P_3 and the diaphragms D_1, D_2, D_3 take up a regular motion. On the other hand, if P is given a sudden jerk the inertia of the lower pistons prevents the immediate passage of the impulse by that path; the impact is concentrated upon the diaphragms, particularly on D_1, which will yield or, if the movement of P is sufficiently sudden, rupture. In a similar way, the incidence of a surge upon the coil results in a concentration of voltage upon the inter-turn insulation, particularly on that of the end turns, and may result in breakdown. In power transformers the trouble is overcome by reinforcing the insulation of the end turns; this is not usual in current transformers since the number of turns is small and it is more general to insulate all the turns similarly to withstand specified surge conditions. See p. 279 for a fuller discussion.

Complete investigations of surge phenomena in current transformers have been made by Berger† and by Reimann‡ who have made measurements of the voltage rise and its distribution over the transformer windings in relation to the height of the wave, its frequency and the steepness of its front and rear; the effect of the position of the transformer in the network is also investigated with reference to the production of resonant conditions. From the data obtained the factors are established which must be taken into account in designing a surge-proof transformer and in comparing the efficacy of the various methods of surge protection. Wirz§

* See W. Petersen, "Überspannungen und Überspannungsschutz," *Elekt. Zeits.*, vol. 34, pp. 167–170, 204–207, 237–241, 267–272 (1913). Consult also the standard treatise of R. Rüdenberg, *Elektrische Schaltvorgänge*, for a complete treatment; the *J. & P. Transformer Book* also contains an excellent discussion of the subject.

† K. Berger, "Ueber das Verhalten der Stromwandler bei Hochfrequenz und den Schutzwert von Parallelwiderständen gegen Ueberspannungen," *Bull. Schw. Elekt. Verein*, vol. 18, pp. 657–692 (1927).

‡ E. Reimann, "Sprungwellenbeanspruchungen von Stromwandler mit und ohne Schutzapparat," *Wiss. Veröff. Siemens Konz.*, vol. 8, pt. 3, pp. 1–49 (1930).

§ E. Wirz, "Ueberspannungserscheinungen bei Stromwandlern," *Bull. Schw. Elekt. Verein*, vol. 6, pp. 121–127 (1915).

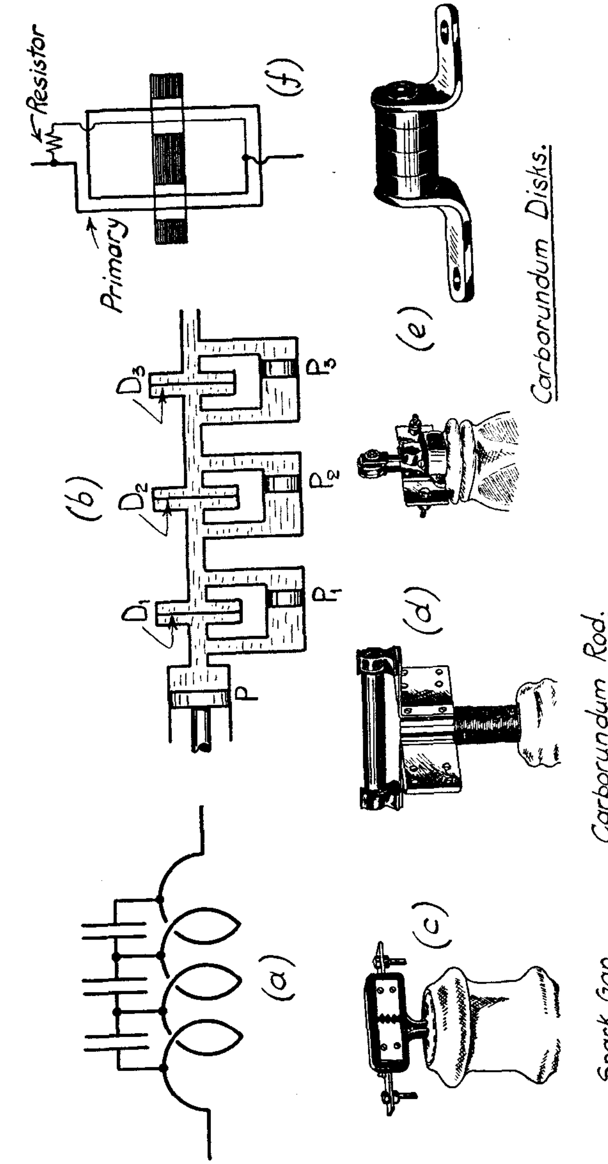


FIG. 105. TRANSIENT VOLTAGE CONCENTRATION OVER END TURNS OF PRIMARY: PROTECTIVE RESISTANCES

has made some interesting tests upon the effect of the shape of the primary coil on the voltage rise. He finds that a circular turn gives a smaller rise than a rectangular turn of the same length; also the rise is less in a loop of any shape if the leads to it are spaced apart rather than close together. The section of the primary conductor is also important; edge-wound coils of rectangular strip are more liable to breakdown than are flat-wound coils.

The bar-type transformer has the highest inherent security against the effects of transients, since the bar has usually a short length and the leads to it are not close together. The greatest trouble is experienced in tank-type transformers with the leads contained in a single bushing and in loop-primary transformers of the types sketched in Figs. 81 (*b*) and (*c*), the former on account of the closeness of the leads and the latter because of the large area of the loop. The cross-hole type, Fig. 81 (*e*), is inherently good since the coil has a small area. In many cases it is usual not merely to rely on the inherent safety of the transformer, but to add some form of protective device.

A current transformer may be protected against voltage rises in three ways*: (i) By flattening the wave-front of the surge before its incidence upon the transformer; (ii) by absorbing the energy of the wave and converting it into heat; and (iii) by providing an alternative path for the surge in parallel with the transformer. The first method consists in the addition of suitable reactances in the line leading to the transformer, in order to attenuate the wave-front. In the third method a suitable circuit is shunted across the primary terminals. The addition of resistances in either of these methods will fulfil the second condition. The commonest method of protection is the third and the shunt is either a spark-gap, a resistor, or a discharge tube. Of these the spark-gap is least satisfactory, on account of the time-lag between the application of the voltage and the breakdown of the gap; for an example see Fig. 105 (*c*). A shunt resistor must have certain peculiar properties: under normal working conditions it should have a high resistance, so that it has little effect on the precision of the transformer (see p. 80), but with rise of voltage its resistance should fall rapidly so that it presents a low impedance path to the surge. These conditions are approximately met in "Silit,"

* V. Karapetoff, "Insuring protection of current transformers," *Elec. World*, vol. 73, pp. 473–474 (1919).

an electric furnace product of the carborundum (silicon-carbide) type, introduced by Dr. Egly.* Under normal conditions a silit resistor has a resistance of 100 to 1 000 times the transformer impedance; with a high transient voltage the impedance of the transformer increases, while the resistance of the silit falls to $\frac{1}{5}$ or so of its original value. The G.E.C. of America use "Thyrite" resistors in a similar way. Such resistors are used in the form of rods, Fig. 105 (*d*), or disks, Fig. 105 (*e*); they are frequently incorporated in the construction of the primary terminals, particularly in transformers of continental make. In bushing-type, loop-primary transformers and in those of the cross-hole type the resistor is fixed to one of the terminal caps, as indicated diagrammatically in Fig. 105 (*f*); actual examples will be seen in Figs. 83, 84 and 87 (*b*). In all cases where a protective resistor is used, it must be in position when the transformer is tested for ratio and phase-angle.

Wirz† has objected that the use of such materials as silit introduce variable errors into the operation of the transformer long before the resistance has fallen low enough to be regarded as "protective." He also points out that surges may cause a permanent change of ratio, as with d.c. magnetization (see p. 127). He suggests that the best method of protection is to omit the shunt and to add an iron-cored choking coil in series with the primary; or a metallic resistance may be put in parallel with the transformer together with an air-cored choke in series with the combination. Other workers‡ have objected to Wirz's conclusions and have shown that silit resistors will operate satisfactorily if properly designed.

Another method of protection is a discharge tube filled with one of the rare gases. Such a tube presents almost infinite resistance to normal voltages and has no influence on the transformer's accuracy, but breaks down almost instantaneously when subjected to a voltage in excess of a certain critical value. A resistor in series with the tube converts the energy of the surge into heat, and the combination constitutes an ideal protective device.

* K. Perelwitz, "Silit, ein neues elektrische Widerstandsmaterial," *Elekt. Zeits.*, vol. 34, pp. 263–267 (1913). Egly, "Silit as a resistance material," *Helios*, vol. 20, pp. 257–261, 381–386 (1914).

† E. Wirz, "Überspannungsschutz bei Stromwandlern," *Elekt. Zeits.*, vol. 36, pp. 450–452, 467–470 (1915).

‡ H. Gewecke, "Überspannungsschutz bei Stromwandlern," *Elekt. Zeits.*, vol. 35, pp. 386–389 (1914). Also see *Elekt. Zeits.*, vol. 37, pp. 69–70 (1916).

CHAPTER IV

THEORY OF THE VOLTAGE TRANSFORMER

1. **Vector diagram of the voltage transformer.** The theory of the voltage transformer* is considerably simpler than that of the current transformer, and is easily developed from the vector diagram. In the current transformer the primary current, and hence the voltage applied at the primary terminals, is varied over a wide range, with the effects upon the ratio and phase-angle that have been discussed in Chapters II and III. In the voltage transformer, however, the primary voltage is practically constant under normal conditions; interest centres, therefore, upon the way in which the characteristics vary with the nature of the secondary load and the output delivered to it. The problem is similar to that presented by the power transformer, but with certain differences that will be noted as we proceed.

The vector diagram is shown in Fig. 106. Starting with the main flux in the core, linking both the primary and the secondary windings, a voltage E_s will be induced in the secondary, E_s lagging by a quarter period behind the flux. This voltage will cause a current I_s to circulate in the closed secondary circuit, the magnitude and phase of the current depending upon the resistance and reactance of the whole circuit, composed of the secondary winding and the external burden with which the transformer is loaded. Deducting from E_s the resistance and leakage-reactance drops in the secondary winding, $R_{ws}I_s$ and $X_{ws}I_s$, gives the p.d. V_s at the terminals of the burden. The main flux will induce a voltage in the primary winding,

* For details the reader should consult: C. V. Drysdale, "The use of shunts and transformers with alternating current measuring instruments," *Phil. Mag.*, 6th series, vol. 16, pp. 136–153 (1908). L. T. Robinson, "Electrical measurements on circuits requiring current and potential transformers," *Trans. Amer. I.E.E.*, vol. 28, pp. 1005–1039 (1910). M. G. Lloyd and P. G. Agnew, "The regulation of potential transformers and the magnetizing current," *Bull. Bur. Stds.*, vol. 6, pp. 273–280 (1910). P. G. Agnew and F. B. Silsbee, "Accuracy of the formulas for the ratio, regulation and phase-angle of transformers," *Bull. Bur. Stds.*, vol. 10, pp. 279–293 (1914). E. Wirz, "Theorie und Berechnung der Spannungswandler," *Bull. Schw. Elekt. Verein*, vol. 5, pp. 303–320, 347–355, 360–368, 388–400 (1914). A. Iliovici, "Methode d'essai des transformateurs de mesure de tension," *Lum. Élect.*, vol. 33, pp. 276–277 (1916); *Soc. Int. des Elecns.*, vol. 6, pp. 155–187 (1916).

E_p, in phase with E_s and such that $E_p/E_s = T_p/T_s$; in opposition to this the primary applied voltage must contain a component $-E_p$. The primary current is composed of two principal components I_0 and I_p'. The former, I_0, is the exciting current which provides a component I_m in phase with and responsible for the production of the main flux, and an iron-loss component I_w in phase with $-E_p$ accounting for the power dissipated in the iron core by hysteresis and eddy currents. The component I_p' is required to balance the secondary ampere-turns, is opposite in phase to I_s and of such magnitude that $I_p'T_p = I_sT_s$. The primary current I_p is the vector sum of I_0 and I_p'. To obtain the voltage V_p that must be applied to the terminals of the primary winding, it is necessary to add to $-E_p$ the resistance drop $R_{wp}I_p$ and the leakage-reactance drop $X_{wp}I_p$ in that winding, as shown in the diagram. The ratio of the transformer is then $K_v = V_p/V_s$ and its phase-angle is γ, the angle between V_s and $-V_p$.

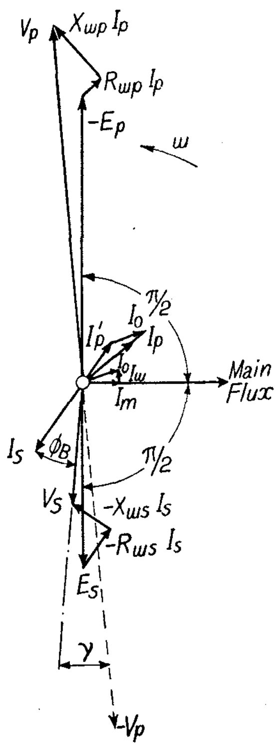


FIG. 106. VECTOR DIAGRAM OF THE VOLTAGE TRANSFORMER

The resistance and reactance drops shown in this and in subsequent vector diagrams are, for ease of draughtsmanship, considerably exaggerated; hence $E_s \doteqdot V_s$ and $E_p \doteqdot V_p$ very nearly. Since the primary winding is connected to a system in which the voltage is constant, and the drops of voltage are small, it follows that the main flux is practically constant no matter what may be the secondary load; consequently, the exciting current I_0 is almost unchanged from no-load to full-load and it would be expected, therefore, that the change of ratio with secondary burden would be practically independent of I_0 and would depend almost entirely upon the resistances and leakage-reactances of the transformer. Since the leakages are easily kept small by interleaving the primary and secondary coils or by the use of a properly designed concentric construction, the variation of ratio and phase-angle with the primary voltage or frequency will be slight. It is to be expected, therefore, that the voltage transformer is a piece of apparatus of high perfection, as is fully substantiated both by theory and by experiment. In very good transformers the change of ratio from no-load to full-load may be as low as 0·3 per cent and in ordinary cases seldom exceeds 1 per cent. The phase-angle is seldom more than 10 minutes (0·3 centi-radian) and is frequently negligible.

It must not be assumed, however, that because the characteristics are practically independent of the exciting current that this quantity can be disregarded. In a power transformer the regulation is determined by the change of secondary voltage between no-load and full-load when the primary voltage, and hence the main flux and exciting current, are all constant; the regulation is, therefore, independent of the value of the exciting current. In a voltage transformer, on the other hand, we are concerned with the ratio of the primary to the secondary voltage, so that it is essential to take the exciting current into account and to allow for the drop of voltage it causes in the primary winding. To ensure that its influence on the ratio and phase-angle shall be small it is essential, just as in current transformers, to reduce I_0 to a minimum by the use of a short magnetic circuit made of good quality silicon-steel with high permeability and low iron losses (see further, Chapter V, Section 2).

2. **Expressions for ratio and phase-angle.** The expressions for the voltage ratio K_v and the phase angle γ of a voltage transformer are rather more complicated than those deduced for the values of K_c and β in a current transformer. They are, nevertheless, of some interest since they lead to a simple graphical construction from which the characteristics are easily obtained.

Referring to Fig. 106, we may write the following vector equations,

$$\boldsymbol{v}_p - (R_{wp} + jX_{wp})(\boldsymbol{i}_0 + \boldsymbol{i}_p') = -\boldsymbol{e}_p = -(T_p/T_s)\boldsymbol{e}_s = -K_T'\boldsymbol{e}_s;$$

$$\boldsymbol{v}_s + (R_{ws} + jX_{ws})\boldsymbol{i}_s = \boldsymbol{e}_s;$$

$$T_p\boldsymbol{i}_p' = -T_s\boldsymbol{i}_s.$$

Substituting the second and third in the first

$$\boldsymbol{v}_p - (R_{wp} + jX_{wp})(\boldsymbol{i}_0 + \boldsymbol{i}_p') = -K_T'\boldsymbol{v}_s + K_T'^2(R_{ws} + jX_{ws})\boldsymbol{i}_p';$$

or

$$\boldsymbol{v}_p - (R_{wp} + jX_{wp})\boldsymbol{i}_0 = -K_T'\boldsymbol{v}_s + [(R_{wp} + K_T'^2R_{ws}) + j(X_{wp} + K_T'^2X_{ws})]\boldsymbol{i}_p'.$$

Now write

$$R = R_{wp} + K_T'^2R_{ws},$$
$$X \doteq X_{wp} + K_T'^2X_{ws},$$

as the "equivalent resistance and reactance" of the transformer referred to the primary side, then

$$\boldsymbol{v}_p = -K_T'\boldsymbol{v}_s + (R + jX)\boldsymbol{i}_p' + (R_{wp} + jX_{wp})\boldsymbol{i}_0,$$

in which the first term balances the secondary terminal voltage, the second term is the total referred impedance drop in the

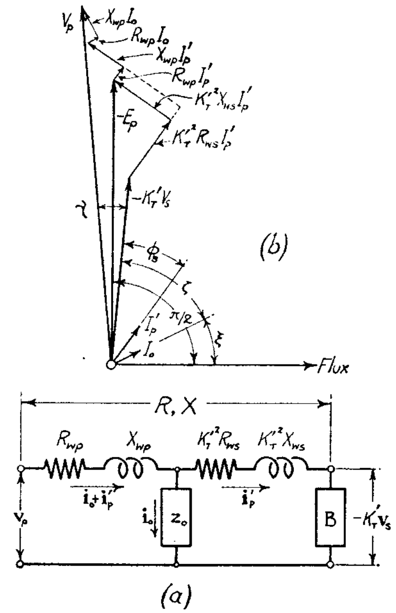


FIG. 107. EQUIVALENT CIRCUIT FOR THE VOLTAGE TRANSFORMER

transformer windings due to the load current, and the third term the drop due to the exciting current in the primary winding. This equation corresponds with the equivalent circuit* shown in Fig. 107 (*a*), where B is the "equivalent burden" referred to the primary side and $1/z_0$ is the "excitation admittance." The magnitudes and directions of the various harmonic vectors are shown in Fig. 107 (*b*), the impedance drops being exaggerated in comparison with the induced and terminal voltages.

* For certain modifications that may be important at very high voltages, see B. G. Gates, "The Equivalent Circuit of Transformers," *World Power*, vol. 19, pp. 366–372 (1933).

Taking ζ as the angle between the reversed secondary terminal voltage and the exciting current, and ϕ_B as the phase-angle of the burden, resolve V_p upon and perpendicular to $-K_T'V_s$; then numerically

$$V_p \cos\gamma = K_T'V_s + I_p'(R\cos\phi_B + X\sin\phi_B) + I_0(R_{wp}\cos\zeta + X_{wp}\sin\zeta),$$

$$V_p \sin\gamma = I_p'(R\sin\phi_B - X\cos\phi_B) + I_0(R_{wp}\sin\zeta - X_{wp}\cos\zeta).$$

Since γ is very small, $\cos\gamma$ may be taken as unity and the first relation gives

$$K_v = \frac{V_p}{V_s} \doteq K_T' + \frac{I_p'(R\cos\phi_B + X\sin\phi_B) + I_0(R_{wp}\cos\zeta + X_{wp}\sin\zeta)}{V_s}$$

Dividing the second relation by the first,

$$\tan\gamma \doteq \gamma = \frac{I_p'(R\sin\phi_B - X\cos\phi_B) + I_0(R_{wp}\sin\zeta - X_{wp}\cos\zeta).}{K_T'V_s + I_p'(R\cos\phi_B + X\sin\phi_B) + I_0(R_{wp}\cos\zeta + X_{wp}\sin\zeta)}$$

Since γ is small it is clear from the diagram that $\zeta \doteq \pi/2 - \xi$; remembering that $I_0\cos\xi \doteq I_0\sin\zeta = I_m$, and $I_0\sin\xi \doteq I_0\cos\zeta = I_w$, and neglecting the primary drops in comparison with $K_T'V_s \doteq V_p$,

$$K_v \doteq K_T' + \frac{I_p'(R\cos\phi_B + X\sin\phi_B) + (R_{wp}I_w + X_{wp}I_m),}{V_s}$$

$$\tan\gamma \doteq \gamma \doteq \frac{I'_p(R\sin\phi_B - X\cos\phi_B) + (R_{wp}I_m - X_{wp}I_w)}{K_T'V_s}$$

from which the ratio and phase-angle are calculable. It is simpler, however, to develop from these expressions a graphical construction based on the fact that, since V_p, K_TV_s, and E_s are all practically equal and the value of I_0 is almost independent of the secondary load, arithmetical processes may be substituted for vector processes.

3. The diagram of Möllinger and Gewecke. The construction of the diagram due to Möllinger and Gewecke* follows closely that already described on p. 50 for current transformers; it will be unnecessary, therefore, to trace out in detail the development of the diagram, which the reader will recognize as a simple modification of the well-known Kapp regulation diagram adapted to our special purpose.

The range of primary voltages encountered in practice is very wide; the secondary voltage, on the other hand, is standardized in all countries at a value between 100 and 125 volts. There is some advantage, therefore, in drawing the vector diagram with all quantities referred to the secondary side, since the scale used will then be independent of the magnitude of the primary voltage and practically the same for all transformers. Taking the vector equation on p. 213, multiply by $K_T = 1/K_T'$ and substitute $\boldsymbol{i}_p' = K_T\boldsymbol{i}_s$; then,

$$K_T\boldsymbol{v}_p = -\boldsymbol{v}_s + K_T^2(R + jX)\boldsymbol{i}_s + K_T(R_{wp} + jX_{wp})\boldsymbol{i}_0$$
$$= -\boldsymbol{v}_s + [(R_{us} + K_T^2R_{wp}) + j(X_{ws} + K_T^2X_{wp})]\boldsymbol{i}_s + K_T(R_{wp} + jX_{wp})\boldsymbol{i}_0;$$

$$\frac{\boldsymbol{v}_p}{\boldsymbol{v}_s} = K_T'\left\{-1 + [(R_{ws} + K_T^2R_{wp}) + j(X_{ws} + K_T^2X_{wp})]\frac{\boldsymbol{i}_s}{\boldsymbol{v}_s} + K_T(R_{wp} + jX_{wp})\frac{\boldsymbol{i}_0}{\boldsymbol{v}_s}\right\}.$$

In these equations the second term is the vector drop due to load current in the effective impedance of the transformer windings as viewed from the secondary side, and the third term is the primary excitation drop similarly referred to the secondary; in the vector ratio equation these drops are expressed in terms of the secondary terminal voltage which, for the purpose of our diagram, we shall assume to be constant. In particular, if the rated secondary voltage is 100, then the percentage volt-drops may be drawn to the same scale as the voltage, i.e. 1 per cent drop is 1 volt.

Referring now to Fig. 108, the horizontal line represents the direction of the core-flux vector; the vertical will then be the direction of the voltage induced in the secondary. Since all drops are small the vertical line is also, without serious error, the direction of the secondary terminal voltage. When the secondary is unloaded, the exciting current I_0 will flow in the primary and will be denoted by a vector lying in a direction inclined to the flux vector by the angle of lead ξ. The primary resistance and reactance drops lie along and perpendicular to I_0 respectively, and have the secondary equivalent values

* J. Möllinger and H. Gewecke, "Zum Diagramm des Spannungswandlers," *Elekt. Zeits.*, vol. 32, p. 922 (1911). H. Gewecke, "Einfaches Diagramm des Drehstrom-Spannungswandler," *Elekt. Zeits.*, vol. 36, pp. 253–256 (1915). Also see J. Vassilliére-Arlhac, *Bull. Soc. Franç. des Elecns.*, vol. 7, pp. 1330–1347 (1927), and E. Dünner, *Bull. Schw. Elekt. Verein*, vol. 24, pp 85–8[illegible] (1933).

$K_T R_{wp} I_0$ and $K_T X_{wp} I_0$, which can be drawn in the diagram as percentages of the assumed constant value of V_s; the total equivalent secondary drop is OA_0. Now set off a distance O_1O to represent 100 per cent of V_s reversed; then the primary voltage to the secondary scale is O_1A_0. As in the current transformer diagram the approximate value of the percentage ratio

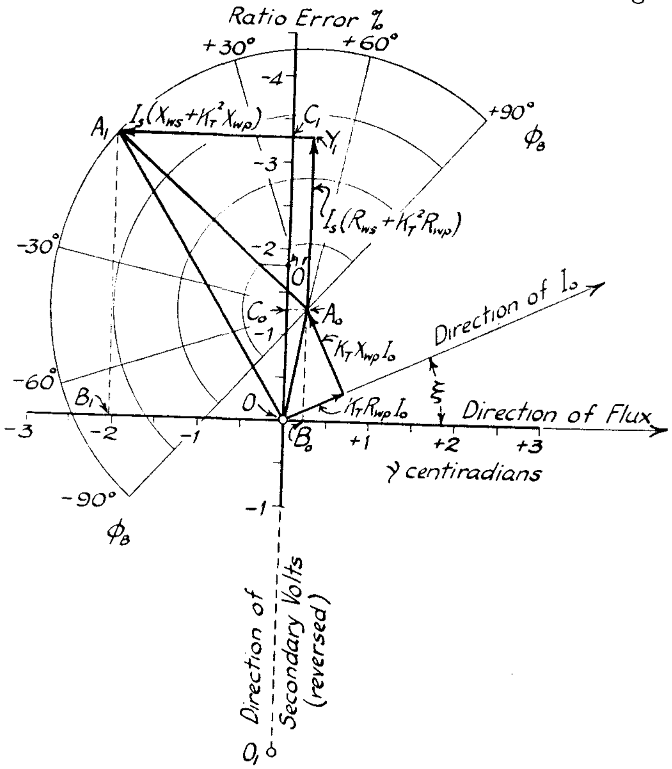


FIG. 108. MÖLLINGER AND GEWECKE'S VECTOR DIAGRAM FOR A VOLTAGE TRANSFORMER

error with respect to the turns ratio K'_T will be OC_0, and the approximate phase-angle OB_0; a scale of centiradians may be marked off along the horizontal so that the angle can also be read directly from the diagram.

Now let the secondary be closed on a non-inductive burden; then since all drops are small and the core-flux in consequence remains practically unaltered, the drop due to the exciting current is unchanged and, with high accuracy, is represented

by OA_0. The secondary current I_s makes an equivalent secondary resistance drop $I_sK_T^2R = I_s(R_{ws} + K_T^2R_{wp})$ parallel to the current and represented by A_0Y_1, and an equivalent secondary reactance drop $I_sK_T^2X = I_s(X_{ws} + K_T^2X_{wp})$ perpendicular to the current and represented by Y_1A_1. The total drop is now OA_1, the referred primary voltage is O_1A_1, the percentage ratio error OC_1 and the phase-angle OB_1. The vectors O_1O, A_0A_1, OA_0 represent graphically the three terms in the preceding vector equations.

If I_s remains constant so also will A_0A_1; if the power-factor of the burden be altered from unity to any desired value all that is necessary is to rotate A_0A_1 about A_0 through the appropriate phase-angle ϕ_B and to read off the new values of the projections of A_1 upon the axes. If the secondary current be changed this merely involves the proportionate alteration in the length of A_0A_1. A series of circles drawn from A_0 give the loci of A_1 for various constant values of I_s. Since V_s has been supposed constant, each circle will correspond with a definite constant value of the volt-amperes in the secondary burden. It will be seen, therefore, that it is easy to read off from the diagram the characteristics of the transformer for any conditions of operation.

4. **Numerical example.** The general behaviour of a voltage transformer under various conditions can be illustrated by an example taken from Möllinger and Geweckes' paper.

The transformer has the following particulars: $K_{nv} = 10\,000/100$; $K_T' = T_p/T_s = 100$; $K_T = T_s/T_p = 1/100$; $R_{wp} = 8000$ ohms; $R_{ws} = 1{\cdot}2$ ohms; an open-circuit test at normal primary voltage gave $I_0 = 0{\cdot}0096$ A, $I_w = 0{\cdot}00405$ A, and $\xi = 25°$; the normal full-load rating is 100 VA. Further, a short-circuit test showed that 300 V applied to the primary winding caused 0·01 A to flow in it, corresponding with full-load current of 1 A in the shorted secondary winding. The equivalent impedance referred to the primary is $Z = 300/0{\cdot}01 = 30\,000$ ohms, and to the secondary is $K_T^2Z = 30\,000/100 \times 100 = 3$ ohms. The equivalent secondary resistance is $1{\cdot}2 + (8000/100 \times 100) = 2$ ohms $= K_T^2R$ and the equivalent reactance K_T^2X is $\sqrt{(9 - 4)} = 2{\cdot}235$ ohms. Hence the no-load resistance drop referred to the secondary is $8\,000 \times 0{\cdot}0096/100 = 0{\cdot}768$ V. To obtain the no-load reactance drop assume, as is usually done in the case of power transformers, that the equivalent reactance of the transformer is equally divided between the primary and secondary windings; hence the no-load reactance drop is $2{\cdot}235 \times 0{\cdot}0096 \times 100/2 = 1{\cdot}075$ V. These values are set out in Fig. 108 to obtain A_0. With a load of 100 VA, i.e. 1 A at 100 V in the secondary, the drop $K_T^2RI_s = 2$ V and $K_T^2XI_s = 2{\cdot}235$ V, which locate the point A_1. Since the rated secondary voltage is 100, a distance representing a ratio error of 1 per cent corresponds with 1 V, and an equal distance along the horizontal represents a phase-angle of 1 centiradian or 34·38 minutes. The actual value of the errors in this triansformer is rather large, since it is of an early and imperfect type.

We see, therefore, that the Möllinger and Gewecke diagram may be constructed if we measure (i) the magnitude and phase of the exciting current by means of an "open circuit test"; (ii) the equivalent impedance of the transformer by means of a "short-circuit test" at rated secondary current; (iii) the resistances of the primary and secondary windings. In addition it is necessary to know the turns ratio and to make an assumption as to the proportion in which the total leakage reactance is divided between the primary and secondary windings.

It is further to be noted that as the ratio error is positive when the actual ratio is less than the nominal (or turns ratio), errors are counted as negative in the diagram when measured upwards from O.

5. **Variation of K_v and γ with secondary power-factor.** The diagram in Fig. 108 enables the variation of K_v and γ with the phase-angle of the secondary burden to be easily found.* Since the nominal ratio and the turns ratio are identical in the example of Section 4, errors read off the diagram from O will also give the values with respect to the nominal ratio, i.e.

$$\varepsilon_v = [(K_{nv}/K_v) - 1]\ 100 \text{ per cent.}$$

Taking the case of rated secondary current, i.e. an output of 100 VA, the following results are obtained—

Phase angle of burden, deg.	+ 90	+ 60	+ 30	0	− 30	− 60	− 90
ε_v per cent	− 3·50	− 4·25	− 4·15	− 3·30	− 1·90	− 0·35	+ 0·95
γ centiradians	+ 2·20	+ 0·85	− 0·70	− 2·05	− 2·72	− 2·65	− 1·80
γ minutes	+ 75·6	+ 29·2	− 24·1	− 70·5	− 93·5	− 91·1	− 61·9
K_v/K_{nv}	1·036	1·045	1·042	1·034	1·019	$1·003_5$	$0·990_5$

These figures are plotted in Fig. 109 and show characteristic features similar to the corresponding curves for current transformers, Fig. 15. It will be seen that there is a certain inductive burden for which γ vanishes and K_v is practically a maximum. For burdens more inductive than this, γ is positive, i.e. $-V_s$

* See E. G. Reed, "Voltage transformers," *Elect. J.*, vol. 18, pp. 323–329 (1921).

leads on V_p; for burdens less inductive, non-reactive and capacitive γ is always negative. These variations of γ are important when a voltage transformer is used with a wattmeter, see p. 311. Also, when $K_T' = K_{nv}$ the actual ratio K_v is in excess of the nominal, except for highly capacitive burdens; there may be some advantage, therefore, in making K_T' somewhat less than K_{nv}, as indicated by the equation on p. 214.

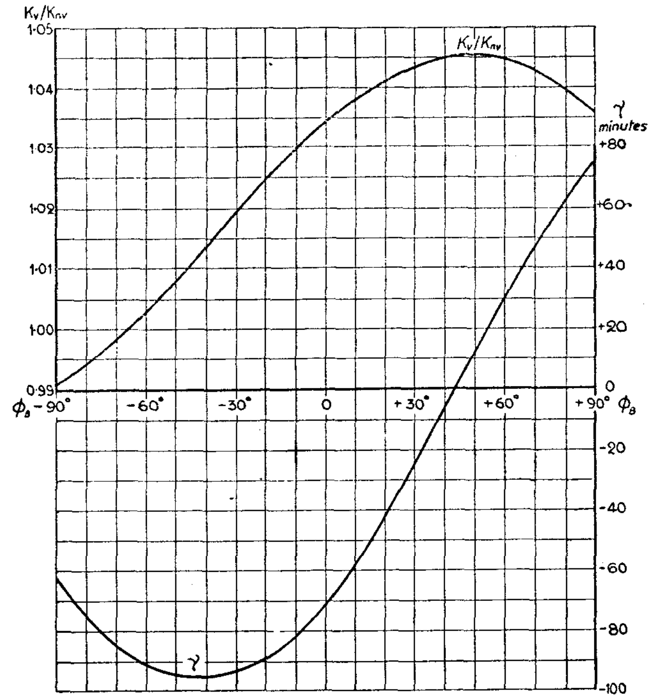


FIG. 109. K_v AND γ AS FUNCTIONS OF ϕ_B; OUTPUT 100 VOLT-AMPERES

6. **Variation of K_v and γ with secondary output.** Consider the transformer of Section 4 when the secondary burden consists of a non-reactive resistance which can be varied from 100 ohms to infinity, i.e. when the secondary volt-amperes are altered from the full-rated value of 100 down to zero. At no-load the ratio error is given by OC_0 and the phase-angle by OB_0; at full-load with unity power-factor the corresponding quantities are OC_1 and OB_1. Since the triangle $A_0A_1Y_1$ is unaltered in shape and varies in size proportionally to the secondary current,

it follows that the ratio error and phase-angle vary linearly between these limits as the secondary volt-amperes are changed from zero to full-load of 100. The table gives figures taken from the diagram.

Load in volt-amperes	0	50	100
ε_v per cent	$-1{\cdot}3$	$-2{\cdot}3$	$-3{\cdot}3$
γ centiradians	$+0{\cdot}20$	$-0{\cdot}92$	$-2{\cdot}05$
γ minutes	$+6{\cdot}9$	$-31{\cdot}8$	$-70{\cdot}5$
K_v/K_{nv}	1·0131	1·0235	1·0340

These are plotted in Fig. 110, from which it may be seen that (i) except at low loads γ is a lagging angle, i.e. $-V_s$ is behind V_p; and (ii) when the turns ratio K_T' is equal to the nominal ratio K_{nv}, as in the present transformer, the ratio K_v is always in excess of K_{nv}. It is possible, however, to make the ratio equal to the nominal value for one particular secondary output by the simple device of adjusting K_T' to be less than K_{nv}. For example, if we desire to compensate the ratio at one quarter of full-load, this is equivalent to the use of the origin O' in Fig. 108. Then $O'O$ is the deviation of the turns ratio K_T' from the nominal ratio,

$$\varepsilon_T' = [(K_{nv}/K_T') - 1]\ 100 \text{ per cent};$$

in this example $\varepsilon_T' = +1{\cdot}75$ per cent, so that $K_T' = 0{\cdot}983K_{nv} = 98{\cdot}3 = T_p/T_s$. The appropriate adjustment is most easily made by the *addition* of about 2 per cent to the number of secondary turns. When so compensated the following results are obtained by reading the errors from O'—

Load in volt-amperes	0	50	100
ε_v per cent	$+0{\cdot}45$	$-0{\cdot}55$	$-1{\cdot}55$
K_v/K_{nv}	0·9955	1·0055	1·0157

This is also plotted in Fig. 110. These results and those of Section 5 are fully verified by experiment, as Chapter V will show, with the exception that the magnitudes of the ratio error and the phase-angle are much less in modern transformers than in this illustrative example.

7. Determination of leakage reactances and turns ratio. The

diagram can be used in an inverse sense to find the leakage reactances and turns-ratio from a knowledge of ε_v and γ, as has been shown independently by Schunck* and by Berghahn.

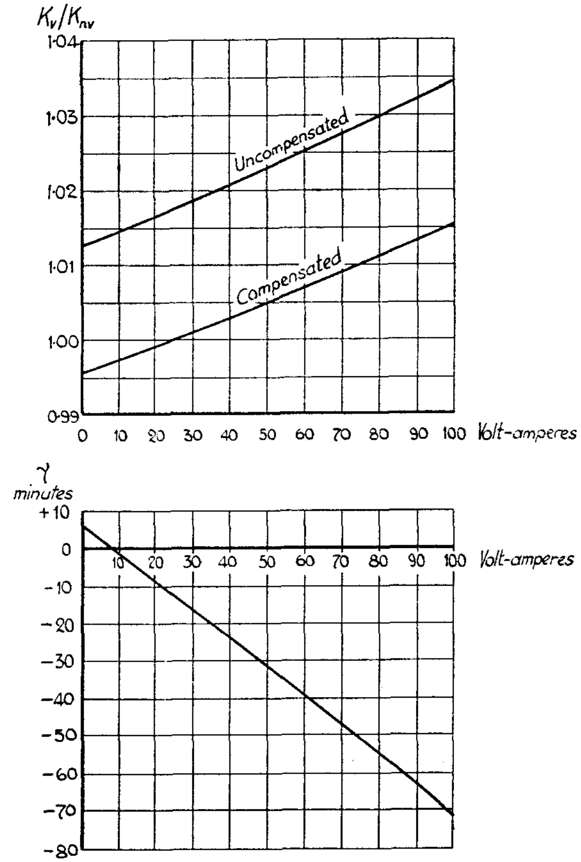


FIG. 110. K_v AND γ AS FUNCTIONS OF SECONDARY BURDEN IN VOLT-AMPERES

In the method due to Schunck the values of ε_v and γ are measured with the secondary on open-circuit, i.e. $I_p' = 0$. From Fig. 107 and the equations on p. 214, the no-load value of γ in radians is approximately

$$\fallingdotseq I\gamma_0(R_{wp}\sin\zeta - X_{wp}\cos\zeta)/V_p;$$

* H. Schunck, "Ermittlung der Streureaktanzen aus der Fehlermessungen des Spannungswandler," *Elekt. Zeits.*, vol. 54, pp. 1236–1237 (1933).

hence if the no-load current be measured in magnitude I_0 and phase ζ for a given applied voltage V_p, and the resistance R_{wp} is found by a bridge or other suitable method, X_{wp} can be calculated. Again, the no-load voltage ratio is

$$K_{v0} = K_T'\left(1 + \frac{I_0(R_{wp}\cos\zeta + X_{wp}\sin\zeta)}{V_p}\right) \equiv K_T'(1 + \alpha) \text{ say,}$$

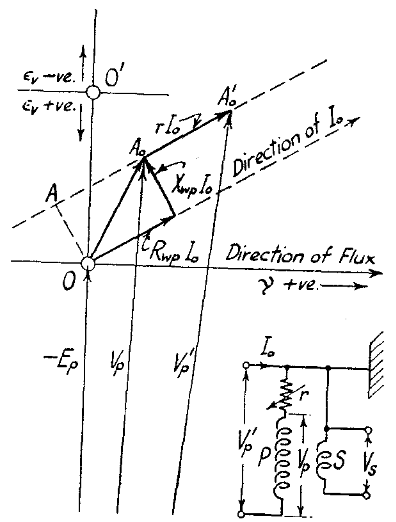


FIG. 111. DIAGRAM FOR DETERMINATION OF LEAKAGE REACTANCES AND TURNS RATIO

where α can now be calculated. Now if ε_{v0} is the measured no-load percentage ratio error and ε_T' the deviation of K_T' in per cent from the nominal ratio K_{nv},

$$\varepsilon_{v0}/100 = (K_{nv}/K_{v0}) - 1, \text{ and } \varepsilon_T'/100 = (K_{nv}/K_T') - 1.$$

Eliminating K_{v0} and K_T' and neglecting the products of small quantities,

$$\varepsilon_T'/100 = (\varepsilon_{v0}/100) + \alpha$$

which determines the turns ratio K_T'. By repeating the test on the secondary winding X_{ws} is similarly found and a check on the value of ε_T' is provided.

Berghahn's* method is more convenient in practice. Fig. 111 shows the essential parts of Figs. 106 and 108, relative to the primary side, together with a diagram of connections for the test. A variable resistor, r, having a maximum value about equal to the resistance of the winding, is included in series with the primary winding. With $r = 0$ and rated primary voltage V_p, measurement is made of ε_v and γ with the secondary on open circuit; these values in centesimal measure locate the point A_0 in the Möllinger and Gewecke diagram with reference to the origin O'. Similar measurements of ε_v and γ are then made with several known values of r, keeping I_0 constant by slight adjustment of the applied voltage to V_p'; these values are the co-ordinates of points such as A_0', the locus of these points being a straight line A'_0A_0A parallel to $R_{wp}I_0$. Since all the drop vectors are proportional to I_o, they may be scaled in ohms; thus, $A'_0A_0 \propto r$ and $A_0A \propto R_{wp}$, R_{wp} being known from a bridge or other test. From A draw a perpendicular to cut the axis of ε_v in O; then $AO \propto X_{wp}$ and $O'O = \varepsilon_T'$. By repeating the test using the secondary winding, X_{ws} can be found and a check made on ε_T'. Suitable methods for the measurement of ε_v and γ are given in Part 4, see particularly p. 553.

* A. Berghahn, "Ein neues Leerlaufverfahren zur Ermittlung der Streureaktanzen und der Windungsabweichung des Eisentransformators," *Elekt. Zeits.*, vol. 55, pp. 667–669 (1934).

CHAPTER V

CHARACTERISTICS OF THE VOLTAGE TRANSFORMER

1. **Introductory.** In its main features of design and construction the normal type of voltage transformer resembles the power transformer, but a closer examination reveals several important differences. Three main considerations influence the design of a voltage transformer: (1) the maintenance of an accurate ratio and a small phase-angle; (ii) the provision of a high factor of safety in the insulation of the high voltage winding from the low voltage winding and earth; and (iii) such economy of material that the transformer is produced at a reasonable cost. Efficiency is of very little importance in a voltage transformer; the output is never very great and the heat generated is never sufficient to be a serious factor in the design. Consequently cooling arrangements are of a very simple character, oil immersion in a plain tank being quite adequate even for transformers with an output of a few thousand volt-amperes; as the usual output is not more than a few hundred volt-amperes, oil immersion is resorted to more for reasons of insulation than for purposes of cooling. In this respect a voltage transformer is in sharp contrast to a power transformer, where the considerable heating is an important factor in fixing the dimensions of the transformer and in necessitating more or less elaborate systems of cooling. The conditions for small ratio-error and phase-angle are somewhat analogous to those determining the volt-drop or regulation of a power transformer, and will be examined in Section 2.

In the case of power transformers, those of the smaller outputs usually operate at the lower voltages and those of the larger outputs at the higher voltages; hence the dimensions of the transformers are determined by the output, so far as the proportions of copper and iron are concerned, and by the space required for the insulation appropriate to the voltage. On the other hand, in a voltage transformer the output is so small that it has practically no influence in settling the size of the transformer; the decisive factor is, therefore, the provision of adequate space for the insulation of the high-voltage winding. The primary voltage fixes the number of turns in the winding

for a given safe value of volts per turn, and hence the flux and core section; the cross-section of the primary conductor, especially at high voltages, is chosen so that the wire can be conveniently manipulated, since a section derived from heating considerations alone is usually so small that great difficulty will be experienced in winding the primary coils with such a thin and weak conductor. Summarizing, the most important factor fixing the dimensions of a voltage transformer is the primary voltage.

The economic design of power transformers has proved an attractive subject for many writers, technical literature providing numerous papers examining the proportions that will fulfil certain technical conditions with a minimum cost of material in the coils and core; there is, however, little published material relating to the cognate problem of the voltage transformer. Some interesting conclusions have been stated by Krüzner* and are summarized here. Since the voltage is $E_p = 4{\cdot}44\, f A_i B_{max} T_p\, 10^{-8}$, with a given flux density $A_i \propto 1/T_p$. If the mean length of iron path is fixed, the weight of the core is proportional to A_i and the price of the core can be written as

$$P_i = K/T_p.$$

The cost of the thin wire coils of the high-voltage winding is much greater than that of the secondary winding composed of much fewer turns of thicker wire; we can, therefore, neglect the cost of the secondary or, if we desire, account for it by a small increase in the cost per unit weight of the primary. Now the weight of primary copper can be written as

$$W_c = T_p l_c \gamma_{cp}$$

where l_c = mean length of primary turn and γ_{cp} = weight per unit length of the primary conductor. Again l_c is proportional to the perimeter of the circle circumscribing the core section; thus we may put

$$l_c \propto \sqrt{(A_i)} \propto 1/\sqrt{T_p}$$

With an increased value of T_p the open-circuit current falls and with it the cross-section of the conductor and weight per unit length; thus, provided the voltage is not too high and the wire does not become unmanageably thin we can write, $\gamma_{cp} \propto 1/T_p$ and

$$W_c \propto 1/\sqrt{T_p}.$$

* H. Krüzner, "Zur Theorie des Aufbaues der Spannungswandler," *E.u.M.*, vol. 43, pp. 309–314 (1925).

The price per kilogramme of a wire increases with diminishing size; assuming the increase to be linear, i.e. proportional to T_p, the total cost of primary copper becomes

$$P_c = CT_p^{\frac{1}{2}},$$

and the cost of active material

$$P_c + P_i = CT_p^{\frac{1}{2}} + KT_p^{-1},$$

where C and K are constants. In the usual theory of a power transformer the cost of active material is a minimum when the cost of copper is equal to the cost of iron; with the expressions just deduced this would imply

$$T_p = (K/C)^{\frac{2}{3}}.$$

Actually, minimum cost occurs when

$$(d/dT_p)\,(P_c + P_i) = 0 \equiv \tfrac{1}{2}\,CT_p^{-\frac{1}{2}} - KT_p^{-2}$$

or
$$T_p = (2K/C)^{\frac{2}{3}} = 1{\cdot}585\,(K/C)^{\frac{2}{3}},$$

whence,
$$P_c = 1{\cdot}259\; C^{\frac{2}{3}}K^{\frac{1}{3}} \text{ and } P_i = 0{\cdot}630\; C^{\frac{2}{3}}K^{\frac{1}{3}}.$$

Thus the minimum cost of active material in a voltage transformer occurs when the copper costs about double the iron.

In practice numerous conditions serve to make this rule inapplicable in the strict sense, e.g. the necessity for keeping the exciting current, the leakage-reactances and the winding resistances as low as possible so that ε_v and γ may not exceed the specified limits for a given accuracy; or the modification in proportions necessitated at high voltages by the large share of space occupied by insulation; or by the fact that beyond a certain voltage the size of wire is not further diminished below about 0·1 mm. diameter, for purely mechanical reasons. Nevertheless, the rule does serve to emphasize the difference between power and voltage transformers. A further modification is introduced by the fact that voltage transformers are, for economy in manufacture, arranged in a "line" or series of graduated sizes each for a different voltage, but of similar type and accuracy. Laubinger* has considered this problem and has pointed out that the methods used for the design of a line of power transformers are not strictly applicable on account of the greater proportion of space filled by insulation, and the additional fact that the accuracy depends largely on the leakage

* G. Laubinger, "Über die Entwicklung einer Spannungswandlerreihe," *Elekt. Zeits.*, vol. 55, pp. 186–188 (1934).

reactances, i.e. on the clearances between the coils. Assuming the same accuracy throughout and minimum cost of active material, he gives curves showing core diameter, coil clearances, window proportions and the ratio of iron and copper weights for a line of transformers covering a range from 10 to 150 kilovolts; the interested reader should consult the original.

Voltage transformers are of two principal kinds. *Laboratory transformers* are usually portable, oil-immersed units of high accuracy, Class 0·5 or better, intended for substandard measurement of voltage. *Switchboard transformers* serve for industrial measurements and range in accuracy from the precision transformers required for energy metering to the less accurate types required for voltage relay operation. They may be of the "dry" type, porcelain insulated; or they may be compound-filled or oil-immersed. The type of construction depends largely on the value of the voltage and whether the transformers are for indoor or outdoor use. Numerous illustrative examples of the various types and their properties will be found in following sections.

2. **Methods for reducing ratio error and phase-angle.** The equations on p. 214 for the voltage ratio and phase-angle may be written

$$K_v \doteq K_T' + \frac{(R_{wp}I_w + X_{wp}I_m)}{V_s} + \frac{I_p'(R\cos\phi_B + X\sin\phi_B)}{V_s},$$

$$\gamma \doteq \frac{(R_{wp}I_m - X_{wp}I_w)}{V_p} + \frac{I_p'\,(R\sin\phi_B - X\cos\phi_B)}{V_p}.$$

The deviation of the actual ratio from the turns ratio, $K_v - K_T'$, and the phase-angle γ each consist of two parts. The first depends on the drop of voltage due to the exciting current I_0 flowing in the resistance and leakage-reactance of the primary winding only; while the second depends on the load current I_p', determined by the secondary burden, flowing in the equivalent impedance of the whole transformer, looked at from the primary side.

Consider first the case of no load, $I_p' = 0$; then it is clear that the actual ratio will exceed the turns ratio by an amount $(R_{wp}I_w + X_{wp}I_m)/V_s$. If therefore K_T' had been equal to the nominal ratio K_{nv}, then $K_v > K_{nv}$. It is easy, however, to make the ratio K_v equal to K_{nv} at no-load by slightly reducing the turns ratio $K_T' = T_p/T_s$ by the amount of the above excess. When the transformer is on load a further deviation occurs due to the load current drop of voltage; if ϕ_B is positive, as with an inductive burden, the deviation is in the same sense as that due to the no-load current and for a given value of the burden can be compensated by a further reduction in turns-ratio, as in Fig. 110. It will be clear, therefore, that the actual ratio can be made equal to the nominal ratio for one particular burden; and provided that I_0 and the resistances and leakage-reactances are small, the change in K_v for other burdens will be slight.

The appropriate reduction of K_T' can be made with the least alteration to the coils by *adding* the appropriate number of turns to the secondary winding, i.e. by increasing T_s. Frequently this is not convenient, as for example in core-type transformers where the secondary is inside the primary and is inaccessible. In such cases a considerably greater number of turns must be *removed* from the primary winding to effect the same percentage change. Adjustment of the primary has the disadvantage of increasing the flux and consequently making I_0 greater, so that alteration of the secondary turns is to be preferred if possible.

Modification of the turns ratio only succeeds in compensating the ratio and has no influence on the phase-angle. To make γ small and to render variation of the ratio from its nominal value as slight as possible, it is essential to reduce the exciting current, the resistances and the leakage-reactances as far as possible. The resistances are reduced by keeping down the mean length of turn and providing adequate section of copper. The reactances are reduced sufficiently in practice by the coaxial arrangement of the primary and secondary coils and the reduction of leakage flux spaces to the minimum consistent with good insulation of the windings from one another.

A small enough value of the exciting current can only be secured by providing a short iron path, using good quality paper-insulated silicon-iron plates working at a density much lower than that used in power transformers. With 3·5 per cent silicon-iron plates 0·5 mm. thick, the density at 50 cycles per sec. lies between 7 000 and 9 000. All burrs must be removed after punching, the plates being annealed before assembly; the corner joints are now almost always interleaved even in the largest sizes. Even with all these precautions it is not unusual for I_0 to be of the same order as I_p', and it is frequently much larger.

In discussing the no-load conditions we have assumed the

no-load current to be the exciting current required for the iron core, compounded of the magnetizing component I_m in lagging quadrature with the induced voltage and the iron loss component I_w in phase with this voltage. This is true in the lower voltage transformers, but above 66 kV a third component becomes important, namely, the charging current flowing into the self- and earth-capacitances of the transformer windings. Fig. 112 shows some results given by Wiggins* from tests on a series of transformers rated at 200 VA for various voltages. The total no-load current, the vector sum of the magnetizing, iron-loss and capacitance components, varies linearly with the voltage rating; it will be seen that above about 40 kV the no-load current exceeds the load current. As pointed out above, the no-load current is constant at constant primary voltage, and the ratio error due to it can be compensated by turns adjustment, leaving as the outstanding ratio error that due to the burden only. The effect on the phase-angle γ may, however, be serious, and this graph serves to emphasize the care that is needed to reduce the no-load current when γ is to be confined within narrow limits; the means for doing this have already been indicated.

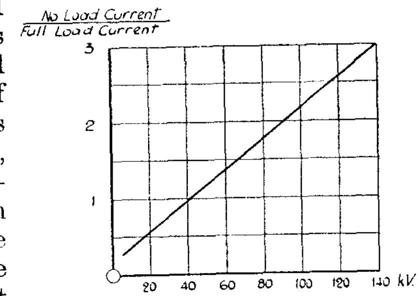


FIG. 112. VARIATION OF NO-LOAD CURRENT/FULL-LOAD CURRENT WITH VOLTAGE RATING

3. **The effects of frequency.** A reduction in frequency causes an increase in flux for a constant primary voltage, thereby increasing I_m and I_w, but at different rates. Fig. 113 shows the results of tests made by Agnew and Fitch† upon a transformer having a rated non-reactive burden of 50 VA and a nominal ratio $K_{nv} = 2\ 200/100$. In agreement with the equations on p. 214, the reduced frequency, with consequently increased I_0, causes the ratio to increase slightly for all values of the secondary load. The effect on γ is, however, a little more complex and much more important. With $\sin \phi_B = 0$ and $\cos \phi_B = 1$ the burden alone would tend to make γ negative if the exciting current were absent. The effect of I_0, however, is to cause γ to become

* A. M. Wiggins, "Potential transformer exciting current," *Elect. J.*, vol. 26, p. 139 (1929).

† P. G. Agnew and T. T. Fitch, *Bull. Bur. Stds.*, vol. 6, pp. 281–299 (1910).

positive with low burdens and negative with larger burdens, when the influence of I_p' becomes more important than that of I_0. Reducing the frequency lifts up the whole curve, making the angle more positive for low burdens and less negative for the high values; this is due to the fact that I_m initially grows at a more rapid rate than I_w with rising flux densities, so that although I_m and I_w are both greater at the lower frequency, the

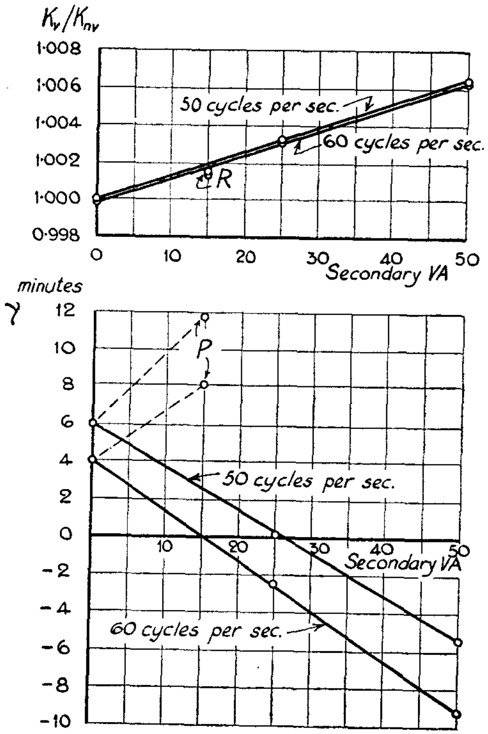


FIG. 113. VARIATION OF K_v/K_{nv} AND γ WITH BURDEN AND FREQUENCY

difference $(R_{wp}I_m - X_{wp}I_w)$ is positive and larger than before the reduction of frequency was made. The change of frequency is such as might occur in the use of a standard transformer in the laboratory. The variation of frequency on switchboard transformers is much less and the alteration of ratio with the usual changes is quite negligible; the change in phase-angle, though much smaller than is here illustrated, is still important in some cases.

4. **The effect of wave-form.** Lloyd* has shown that the effect of wave-form is relatively unimportant in practice since the deviation of practical voltage waves from the sine shape is usually slight. With a third harmonic as large as 30 per cent of the fundamental, the ratio changes by less than 0·1 per cent from the values found with a sine wave; a peaked wave lowers the ratio and a dimpled wave increases it. Since such a harmonic content would be quite exceptional in practice, it may safely be assumed that the characteristics of a voltage transformer are not appreciably changed by altering the shape of the primary voltage wave. Oscillograph tests also show that the secondary voltage wave is an exact copy of the primary wave, indicating a negligible distortion.

5. **The effect of secondary burden.** If the voltage is constant I_0 is fixed; if now the phase-angle ϕ_B of the burden is maintained constant while its magnitude in ohms is varied, both K_v and γ vary linearly with the load current I_p', i.e. with the secondary volt-amperes. This is verified by reference to the equations on p. 214 and by the theoretical and experimental results plotted in Figs. 110 and 113. The slopes of the lines depend on the power-factor of the burden; the initial starting points of the lines depend on the components of I_0. With non-inductive or inductive burdens, which are the usual practical cases, the slope of the ratio curve is positive, i.e. the ratio increases with the volt-amperes; under the same conditions, the slope of the phase-angle curve is usually negative. The points R and P in Fig. 113 show, for two frequencies, the values of ratio and phase-angle at 15 volt-amperes when the burden is an inductive load of very low power factor, $\cos \phi_B \to 0$. It will be seen that the change of ratio is small but the effect on the phase-angle is very considerable; the slope of the phase-angle line in this extreme case actually becomes positive, as indicated by the dotted lines.

It is to be understood that the total burden with which a voltage transformer is loaded includes not only the secondary instruments but also the leads connecting them to the transformer terminals. Collins† has pointed out that failure to observe this condition may result in considerable addition to the phase-angle. With a load of two watt-hour meters a run of 300 feet of connecting leads may add 15 to 20 minutes to the

* M. G. Lloyd, *Elec. World*, vol. 52, p. 845 (1908).
† G. A. Collins, "Errors from potential transformer leads," *Elec. World*, vol. 91, pp. 1013–1014 (1928).

phase-angle as determined with the meters directly connected across the terminals of the secondary. If, therefore, the figures obtained for the calibration of a transformer are to have real practical value it is essential (i) that the rated burden includes both apparatus *and* leads; (ii) that the resistance and reactance of the burden are both specified, a mere statement of volt-amperes alone being worthless. These facts are recognized in the national specifications, detailed particulars of rated

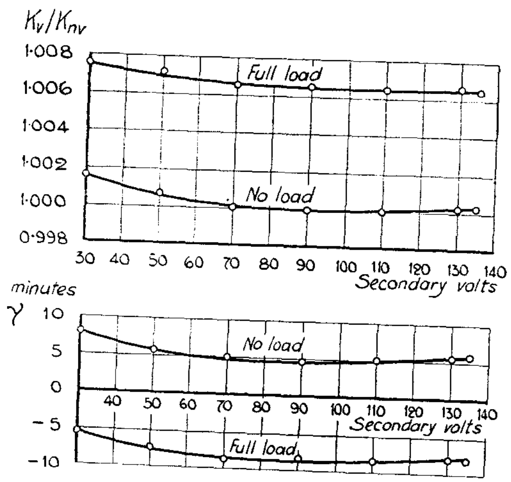


Fig. 114. Variation of K_v/K_{nv} and γ with Secondary Voltage

burdens, power-factors, etc., being given in Sections 6 and 7 of Chapter I.

6. **The effect of primary voltage.** The variation of ratio and phase-angle with primary (or secondary) voltage is only of importance in laboratory transformers where a high precision is to be maintained over a wide range of voltage; in all other cases the working voltage is practically constant. Fig. 114 shows the variation of K_v and γ over a wide range of voltage from the rated value of 110 at a fixed frequency, both at no-load and at full-load, for the transformer tested by Agnew and Fitch (loc. cit. *ante.*). Variation of voltage changes the core-flux and with it the values of I_m and I_w, with the general effect shown in the diagram. The general tendency of a reduction of voltage from the rated value is to increase both K_v and γ, though the increase is usually small, even for quite considerable changes of voltage.

7. **Construction and insulation of normal types of voltage transformer.** The normal type of construction for voltage transformers designed for use at lower voltages, less than about 50 kV, resembles in many respects the type now regarded as usual for power transformers. A similar construction has also been used at 100 kV or higher voltages, but is uneconomic and by no means the best for the purpose; this case will be argued in Section 9, so that the considerations of the present section are limited in their application to lower voltages. Although they are similar to power transformers in their general constructional features, voltage transformers differ in some important particulars. For example, the output seldom exceeds a few hundred volt-amperes; consequently, as has been pointed out on p. 224, the dimensions of the transformer are determined more by the space required to accommodate the insulation of the primary coil than by the amount of copper in its cross-section. Again, the core is proportioned to secure the desired precision of ratio and phase-angle, since the question of output is a secondary one. Some distinction is also made between transformers for indoor and those for outdoor use. The former must be, as far as possible, explosion- and fire-proof when subjected to internal fault, but this security is less essential in outdoor transformers where fire hazard is not serious; this factor affects the construction in some ways, particularly as regard the method of insulating the transformer.

The shell-type core is used only in the smallest transformers for low voltages; an example is given in Fig. 115 (*a*), suitable for an output of 50 VA at primary voltages up to 3 300. For all larger sizes it is usual to adopt the core-type construction since this is easier to assemble and gives greater accommodation for insulation at higher voltages. The windings may be put entirely on one limb, as in Fig. 115 (*b*), or they may be divided into two equal groups put on two parallel limbs, as shown in Fig. 115 (*c*) for a transformer suitable up to 6 600 volts. The two-coil arrangement has a smaller mean length of turn than the single coil design, with the advantage of a rather smaller amount of copper, but this is offset by the fact that more insulation is required, since there are four winding ends to be insulated instead of two; consequently, there is very little difference, from the point of view of economy of material, between the two designs. The primary and secondary coils are usually coaxial, one within the other, to reduce leakage to the minimum. The secondary or l.v. coil is usually the

17—(T.5722)

inside member and nearest to the iron core; occasionally the secondary is put outside, as in Fig. 115 (*d*), a position which has some advantage when turns adjustment is to be made on the secondary coil, see p. 228.

The coils are usually former-wound and of circular cylindrical shape. Secondary coils are composed of cotton- or paper-insulated

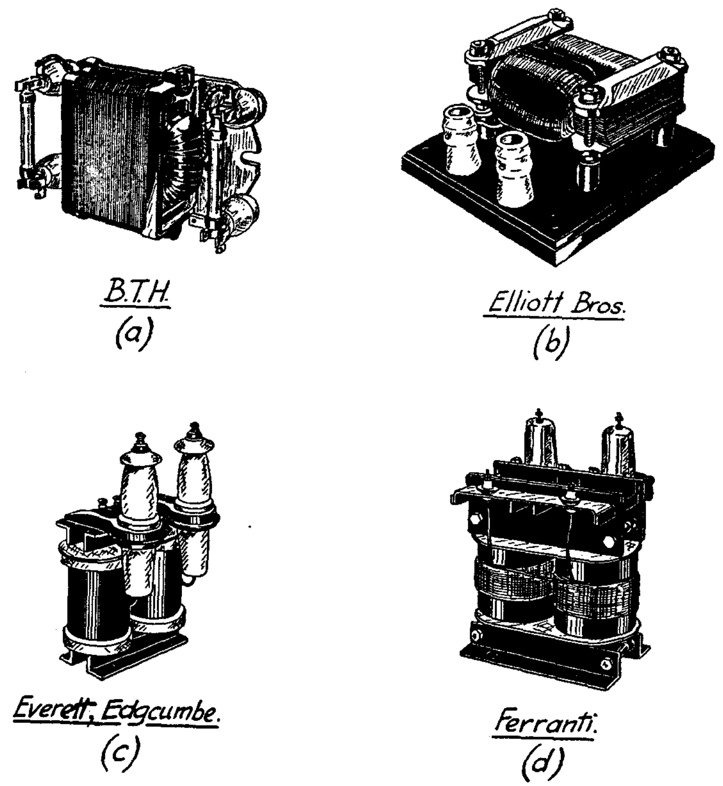


FIG. 115. AIR-INSULATED VOLTAGE TRANSFORMERS

wire and after taping are dried, baked and vacuum-impregnated with oil or compound to exclude moisture. Primary coils for low voltage transformers are made in a somewhat similar way. For higher voltages the primary winding is composed of a number of separate coils connected in series, exactly as in h.v. power-transformer practice. To save space it may be necessary to use specially fine cotton, paper or silk covering for the wires and

silk tape for the inter-layer insulation. It is not usual to reinforce the end turns only, but to carry an adequate amount of insulation to withstand surge-voltage stress right through the entire winding. In transformers working with one terminal earthed, some economy may be gained by grading the quantity of insulation between windings and core from the line to the earthed end of the primary; most manufacturers prefer to sacrifice economy for security by insulating such windings uniformly from end to end.

The safety of a voltage transformer in operation depends entirely upon the security of its insulation.* Raising the test-voltages prescribed in the national standard specifications, and especially the specification of surge tests, has led makers to concentrate upon the improvement of voltage transformer insulation, the elimination of defective features from the design, the more scientific and economical utilization of insulating materials, and to put less reliance upon protective devices to save the transformer from dangerous transient conditions. With more secure transformers the protective arrangements become simpler and the whole equipment is cheaper. For lower voltages up to 3 000 volts the open-type transformer in air, with taped and impregnated coils, proves satisfactory. At higher voltages the modern material for coil insulation is paper, developed to a high degree of perfection in cable technology; but on account of the hygroscopic character of this material, coils insulated with it must be vacuum-impregnated with compound or with oil. Two courses are then open; either to enclose the transformer in a compound- or oil-filled tank, or to eliminate these completely by the use of an all-porcelain construction. The porcelain-insulated transformer is a modern type, largely called into being by the recent development of oil-less switchgear for open-air use, and warrants separate discussion in Section 8. The combination of oil-impregnated, paper-insulated coils with oil immersion constitutes the modern transformer. The oil fills the finest spaces and excludes air; it has a high dielectric strength, and it satisfactorily cools the core and windings. Consequently higher current- and flux-densities can be used than in open-type transformers, with resulting reduction in size and cost of the transformer. Fig. 116 illustrates some typical designs of oil-insulated transformers. The greatest disadvantage of oil

* G. Keinath, "Isolierung von Spannungswandlern," *Arch. f. tech. Mess.*, Z37–1 (Aug., 1932); *Bull. Schw. Elekt. Verein*, vol. 24, pp. 93–97 (1933).

insulation is the danger of explosion and fire if internal faults should occur; this can be avoided by the use of "Pyranol." Compound filling is far less likely to fill up all the interstices and eliminate air pockets, so that the insulation is much less satisfactory than with oil. Again, since the material is solid or at best very viscous, cooling conditions are very poor. Experience has also shown that compound-filled transformers are not less dangerous than oil-filled transformers from the explosion and fire hazard points of view. Fig. 116 gives in addition some designs of transformers with compound filling.

Voltage transformers for switchboard or other industrial uses are made with a single ratio; transformers for laboratory purposes are usually required to cover a fairly extensive range of primary voltages and thus to have a variety of ratios. Series-parallel grouping of sections of the primary winding enables ratios in the proportion of 1 to 2, using a primary divided into two equal parts, or in the sequence 1 : 2 : 4 by the use of four equal parts, to be easily obtained. Fig. 117 (*a*) shows a dry-type transformer for 600 volt circuits mounted in a wooden case and provided with terminals and links for two ratios 600/100 and 300/100; Fig. 117 (*b*) illustrates a two-ratio oil-filled transformer for ratios of 4 000, 2 000/100. The ratio may be changed in any desired series of steps, equal or unequal, by tappings on the primary winding; the Koch & Sterzel A.G. make a transformer, shown in Fig. 117 (*c*), on this principle giving 16 steps of 1 000 volts each. Series-parallel connection of the secondary is applicable in the same way as the corresponding primary connection. Tapping the secondary is useful when an intermediate ratio, not otherwise attainable by series-parallel grouping of the primary alone, is desired; Fig. 117 (*d*) shows how, by tapping the secondary at a point three-quarters of its total number of turns, ratios in the proportion 1 : 2 : 3 : 4 can be obtained with a four-section primary winding. Secondary tapping is also resorted to, even in industrial transformers, to provide both 110 and 100 volts on the secondary side to suit non-standard voltmeters or wattmeters.

8. **"Dry type" voltage transformers.** The desire to reduce the risk of fire in power stations, and the increasing use of open-air switching- and sub-stations requiring the minimum of attention, has led in the past few years to striking advances in the design of oil-free switchgear and apparatus. Although the relative advantages of oil-filled and dry apparatus are still the subject of some discussion, there is no doubt that expansion circuit-breakers and porcelain-insulated, sand-filled current transformers have definitely established for themselves an important position in modern switching plant design. Until quite recently the only remaining oil-filled component in a modern substation, apart from the power transformer itself, was the voltage transformer. About four years ago, however,

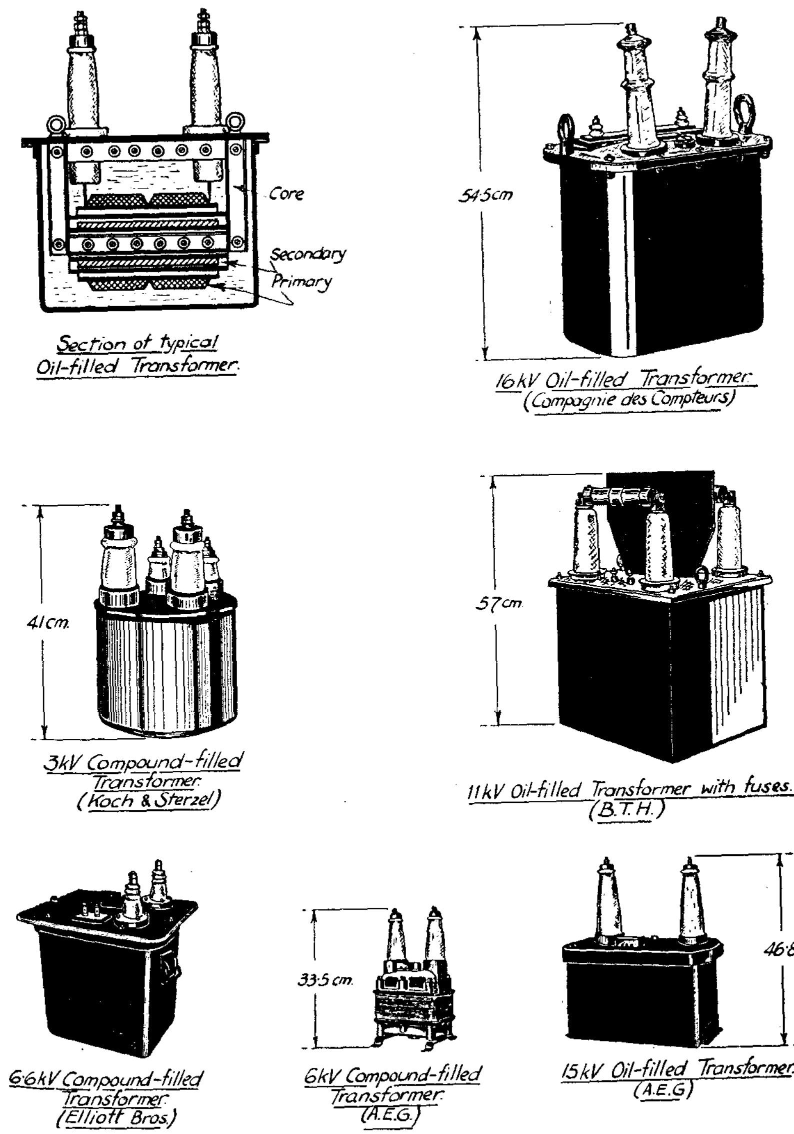
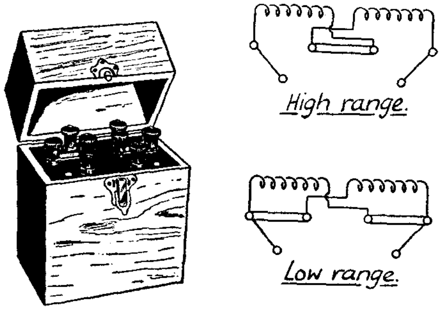
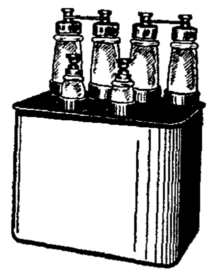


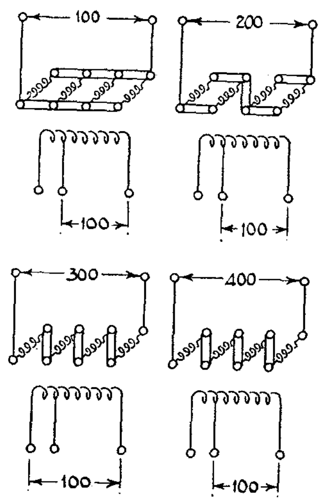
FIG. 116. OIL- AND COMPOUND-FILLED VOLTAGE TRANSFORMERS

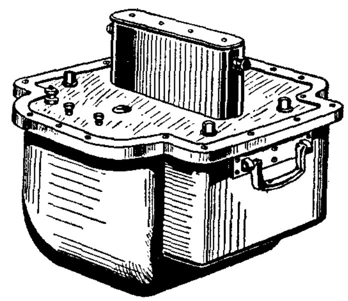


(a) Two-range portable voltage transformer. (Compagnie des Compteurs)



(b) Two-range oil-immersed voltage transformer. (Koch and Sterzel)





(c) Portable multi-range, compound-filled voltage transformer. (Koch and Sterzel)

(d) Use of series-parallel primary with tapped secondary.

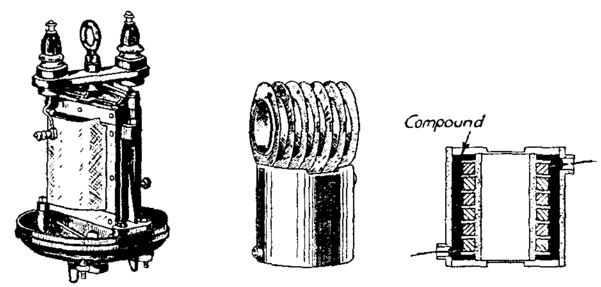
FIG. 117. MULTI-RANGE VOLTAGE TRANSFORMERS

dry-type voltage transformers with porcelain insulation were introduced by the firm of Koch & Sterzel, manufactured in accordance with the ingenious designs due to F. J. Fischer.*

Dry-type voltage transformers for low voltages, with taped

* F. J. Fischer, "Trocken-Spannungswandler mit Porzellan-Isolierkörper," *K.u.S. mitt.*, No. T17, pp. 1–27 (1930); W. Reiche, "Trocken-Spannungswandler," *Elekt. Wirts.*, vol. 31, pp. 83–89 (1932); "Trocken-Spannungswandler. System F. J. Fischer," *Arch. f. Tech. Mess.*, Z.384–2 (1932).

coils and air clearances, are quite common, and several examples have been noticed in Section 7. The use of a similar construction at high voltages results in a transformer of grotesque proportions and excessive bulk, on account of the large clearances required when air is the major insulating material. For example, at 30 kV the least distance between any part of the h.v. side and earth is about 26 cm.; on this basis Reiche has shown that an air-insulated transformer for this voltage occupies a volume 115 cm. long, 25 cm. broad and 86 cm. high! It is essential, therefore, to replace the air by



Transformer with cover removed — Porcelain bobbin and Container. — Assembly of Primary winding.

FIG. 118. EARLY PORCELAIN-INSULATED VOLTAGE TRANSFORMER

material with a higher dielectric strength, if high-voltage transformers of reasonable bulk are to be designed. For this purpose oil, compound, paper and porcelain suggest themselves; of the two solid materials capable of dry use paper is inadmissible on account of its inflammable nature, so that porcelain is the dry insulator *par excellence*. In addition to its high dielectric strength, porcelain is non-hygroscopic, mechanically rigid, and incombustible. Its thermal conductivity is poor, so that free circulation of heat from the windings is hindered; hence for the same temperature rise a porcelain-insulated transformer is larger and possibly dearer than one with oil insulation. Although the elimination of oil results in the porcelain-insulated transformer being non-explosive on the occurrence of an internal fault, a considerable amount of smoke may be evolved by the smouldering of the organic insulation in the primary coil; on this account the dry-type voltage transformer is less fire-proof than the corresponding current transformer, where the very small amount of inflammable organic material and the possibility of sand-filling renders smouldering rather unlikely to occur. To this defect there appears to be no solution other than sufficiently liberal design. A further defect of porcelain is that the dielectric strength falls with rise of temperature, so that this must be strictly limited. Also it is brittle and must be protected against mechanical damage.

The idea of encasing the high-potential parts of a voltage transformer in porcelain was exploited by the Siemens & Halske A.G.* as long ago as 1901. A series of three transformers, covering ranges up to 3 000, 12 000 and 24 000 volts respectively, was developed on the principle illustrated in Fig. 118. The transformer shown in the diagram is for a ratio of 10 000/120; it is provided with a perforated metal cover, removed to show the internal construction.

The Fischer-type transformer consists of a porcelain body in which the lower part resembles an enlarged cotton reel while the upper portion is a normal insulating bushing, as shown in Fig. 119 (*a*). The two parts are easily prepared in a potter's lathe and united before firing to form a single ceramic piece. The reel contains the high-voltage coil wound in layers, the flanges being of tapering section to equalize the electric stress in the porcelain; the beginning of the innermost layer goes through the bushing to the h.v. terminal while the end of the outer layer is earthed. The secondary winding is wound on a separate insulating tube placed concentrically within the primary; the iron core is of the shell type. Fig. 119 (*b*) shows the complete transformer in section, while Fig. 119 (*c*) shows the outside view of a 30 kV indoor unit from the low-voltage and high-voltage sides respectively. As the latter diagram shows, the windings and core are enclosed for protection in a two-part metal housing. The outer surfaces of the flanges, the lower part of the bushing and the inner cylindrical surface of the reel close to the secondary are covered with a deposited layer of copper, which is earthed; the layer is slit radially along the flanges and axially inside the reel to avoid the production of a short-circuited turn round the core. Protection of the transformer against the effect of surges is obtained in an ingenious way. The outer cylindrical surface of the reel is metallized and the thin layer is divided by a spiral cut into a rhombus-shaped piece wrapped on the surface. The high-voltage lead is attached to the rhombus at its upper end, while the lower end is connected to the beginning of the primary

* D.R.P. No. 126 730 (6th Jan., 1901). F. Schrottke, *Elekt. Zeits.*, vol. 22, pp. 657–667 (1901).

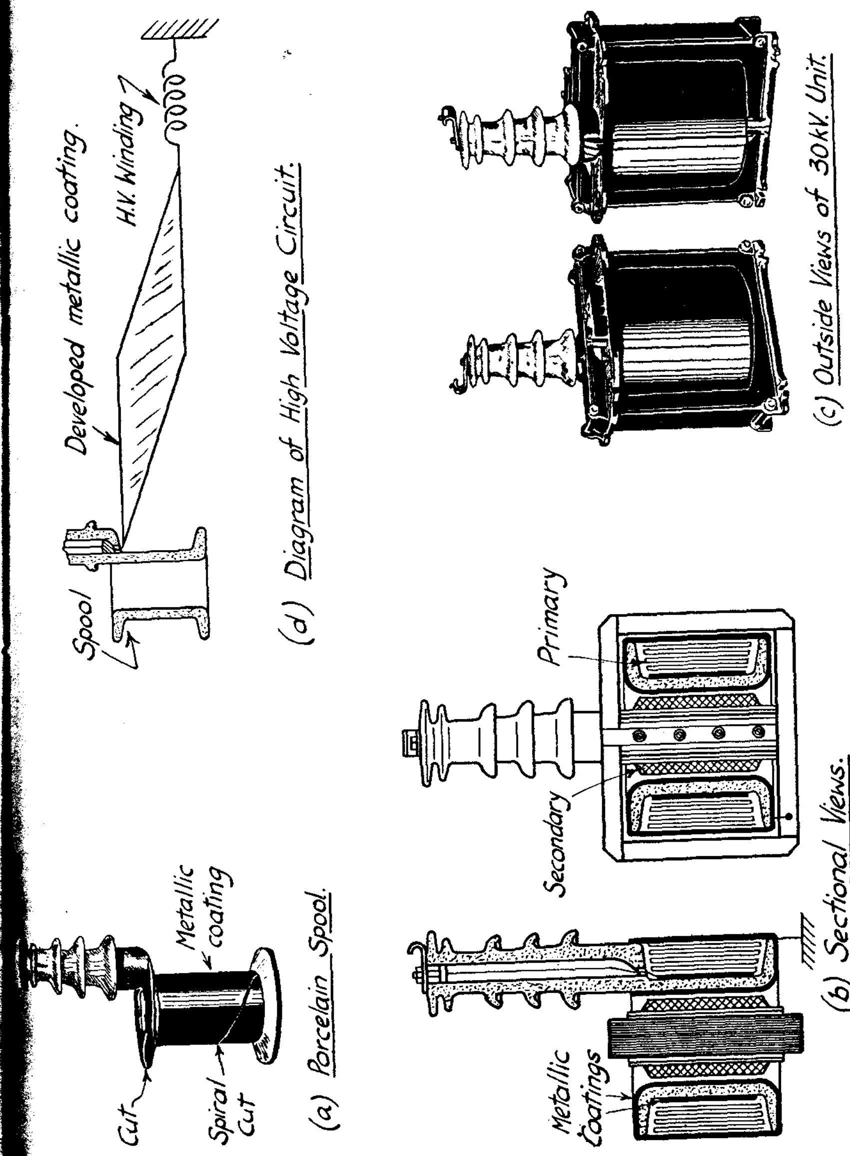


FIG. 119. FISCHER'S DRY-TYPE, PORCELAIN-INSULATED VOLTAGE TRANSFORMER WITH RADIAL POTENTIAL GRADIENT

coil; the rhombus thus forms an initial turn or entrance winding having considerable area presented to the first layer of the primary coil. The last turn of the primary consists of a thin sheet of copper serving as an exit winding with a large area in contact with the last layer of the coil; the whole arrangement is shown diagrammatically developed in Fig. 119 (*d*). It is not difficult to show that the capacitance between the inner and outer metal sheets and their capacitances with respect to the turns of the primary coil result in surge voltages being uniformly distributed over the coil; consequently, external surge protective devices are unnecessary. The *modus operandi* of this capacitive protection will be discussed in Section 12. Each turn of the primary coil is well insulated and all air spaces between the turns are filled with an insulating paste.

Fischer-pattern transformers are made for working voltages between lines of 3, 10, 20, 30, and 45 kV. Since the transformers work with one pole earthed, i.e. with the winding subjected to the star voltage, it is necessary to use three transformers in star-connection for three-phase circuits. The transformers are tested to withstand 1·2 times line voltage, to cover the contingency of operation with one transformer faulted and the other two subjected to a semi-permanent application of line voltage. For outdoor use the transformers are provided with skirted insulators of brown-glazed porcelain and with external metal casings of galvanized sheet iron, as in Fig. 120 (*a*). At voltages above 45 kV satisfactory porcelains are not easily obtainable; for 60 and 100 kV circuits cascade-connected units are manufactured, particulars of which will be given on p. 262. The following table gives the principal particulars of the transformers.

Working Voltage, kV.	Output in VA for Accuracy of		Height of Insulator mm.	Weight kg.
	Class 0·5	Class 1		
3	40	80	75	16
10	80	160	135	33
20	120	240	185	52
30	150	300	260	70
45	150	300	400	170

A special design is provided for use in open-air substations; in this the porcelain body is modified to act as a suspension insulator, as in Fig. 120 (*b*), and the transformer is inverted.

In the design shown in Figs. 119 and 120 the potential increases radially outward through the thickness of the primary coil, the gradient being borne by the porcelain flanges. Fischer* has described another design in which the potential rises axially and, as the reel has a greater

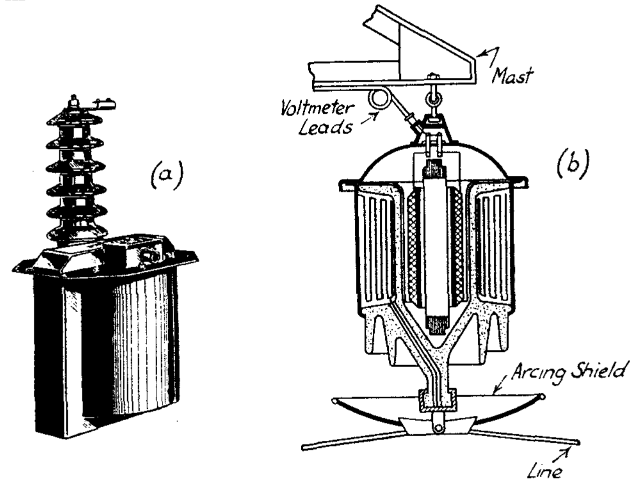


FIG. 120. DRY-TYPE TRANSFORMERS FOR OUTDOOR USE

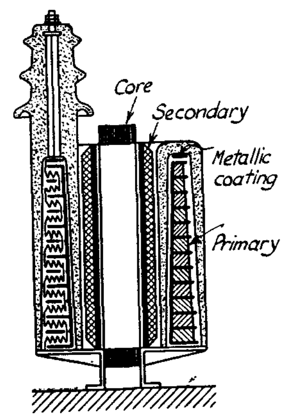


FIG. 121. PORCELAIN-INSULATED TRANSFORMER WITH AXIAL POTENTIAL GRADIENT

length than the flange depth, the potential gradient along the porcelain is much reduced. As Fig. 121 shows, the porcelain body consists of a ring-shaped container of U-section open at the bottom and provided

* F. J. Fischer, "Trocken-Messwandler," *K.u.S. Mitt.*, No. T18, pp. 1–20 (1931).

at the top with a terminal insulator. The thickness of the porcelain walls is graded according to the increasing potential. The primary consists of a number of impregnated disk coils wound on individual paper cylinders or porcelain bobbins, and after assembly the remaining spaces are filled with insulating paste. Other constructional details resemble those of the type described above. Transformers of this design are made by the Siemens & Halske A.G.* and by the Compagnie pour la Fabrication des Compteurs.†

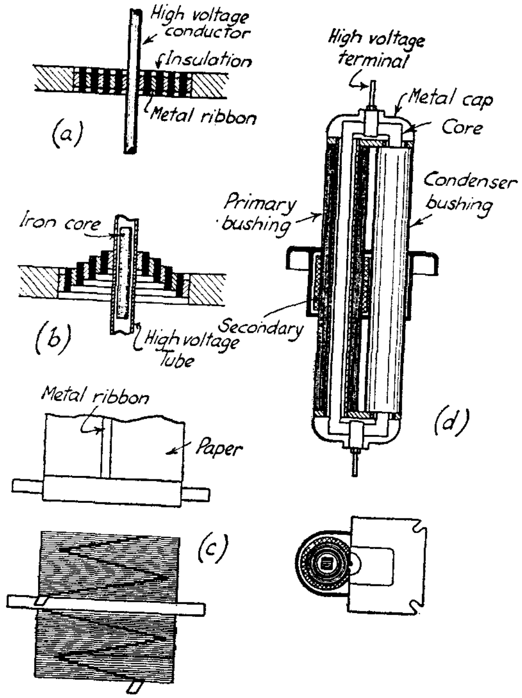


FIG. 122. BUSHING-TYPE VOLTAGE TRANSFORMER

A further interesting dry-type voltage transformer on an entirely new principle is also due to Fischer. Referring to Fig. 122 (*a*), a high-voltage conductor is shown passing through a circular opening in an earthed frame, the conductor being supported by a "bushing" consisting of a flat metal ribbon and an insulating band which are wound together in a flat spiral around the conductor. One end of the metal ribbon is connected to the conductor and the other to the earthed frame. The

* Siemens und Halske A.G., "Trocken-Spannungswandler," *Arch. f. tech. Mess.*, Z384–3, Aug. (1932).

† A. Iliovici, *Bull. Soc. Franç. des Elecns.*, vol. 2, pp. 1126–1128 (1932).

radial distribution of potential is thereby divided into fine steps determined by the resistance and self-inductance of each turn of the spiral coil. By making the conductor hollow and providing an iron core, as in Fig. 122 (*b*), the inductive effect is greatly increased, and it is possible to adjust the inductive and resistive drops in such a way that the voltage division is practically uniform from turn to turn. The conical arrangement increases the external surface.

In actual practice a paper bushing is constructed by winding in with the paper sheet a thin copper ribbon, as indicated in Fig. 122 (*c*), the inner end being attached to the conductor and the outer end earthed. By this means the potential distribution in the bushing is determined by the inductive effect of the turns and not by the effects of capacitance, as would be the case in a normal condenser bushing; it will be noticed that the insulation is not subjected to the total voltage gradient but only to some fraction thereof, dependent upon the distribution of the turns. The current flowing in the winding is proportional to the potential difference between the conductor and earth; by combining such an arrangement with a core and secondary winding a dry voltage transformer is readily made. Fig. 122 (*d*) shows one possible design and requires no further comment.

9. **Voltage transformers for very high voltages (cascade transformers).** The normal design of oil-immersed voltage transformer, based upon that of the power transformer, is quite satisfactory for lower voltages, but for higher voltages becomes increasingly uneconomical. The output required from a voltage transformer is so small as to have little effect on the design, which is influenced far more by the voltage than by any other factor. Insulation requirements fix the space required by the primary winding, the size of the tank, and the dimensions of the leading-in bushings. Consequently the bulk, weight, and cost of voltage transformers of normal design bears at the higher voltages no relation whatever to the very modest output demanded for measurement purposes; in fact, they are virtually power transformers used at but a small fraction of their possible output and, as such, are uneconomical in their use of active material.

The weight and price of voltage transformers increase more rapidly than the square of the voltage. Fig. 123 shows curves plotted from figures given by Keinath for oil-immersed transformers of the usual type; above 80 kV the weight and list price (the latter expressed relatively to the cost of a 30 kV transformer) increase very rapidly, while the cost per kV of test-voltage similarly expressed rises almost linearly with the

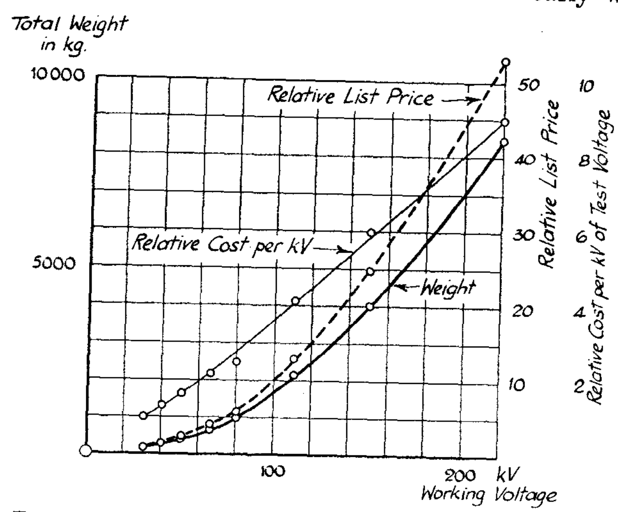


Fig. 123. Weight and Cost of H.V. Oil-filled Voltage Transformers

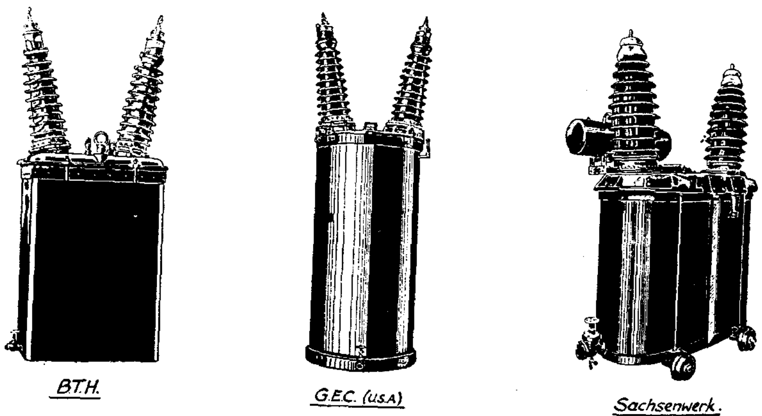


Fig. 124. Oil-immersed Voltage Transformers for 110 kV

voltage. These figures become even more impressive when individual cases are considered. Fig. 124 shows three typical designs for 110 000/110 transformers for use in the open air, the first of British, the second of American, and the third of

German manufacture. The British transformer is 381 cm. (150 in.) high, occupies a floor space 153 cm. × 110 cm. (60 in. × 43 in.) and weighs 6 640 kg. (14 600 lb.) including oil. The American transformer is 430 cm. (169 in.) high, contains 779 gallons of oil, and weighs complete 4 440 kg. (9 750 lb.); its output is 500 VA and its list price in 1927 was $3 850 (about £770 at par). The figures for the German transformer are somewhat similar. All are virtually power transformers and are excessively large and costly.

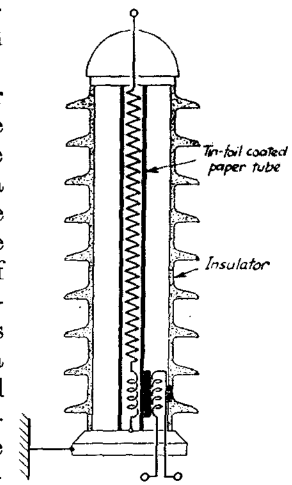


Fig. 125. Imhof's Voltage Transformer (Trüb, Täuber)

Many transmission systems all over the world operate at voltages above 110 kV (*cf.* the 132 kV sections of the British grid) and there are in America and on the Continent considerable networks at 220 kV. In view of the disproportionate size and cost of normal voltage transformers by comparison with other apparatus, it is important to determine whether a radical alteration in the design will result in a lighter and cheaper transformer, combining at the same time the reliability and safety of the oil-immersed unit. Several successful solutions of this problem have been obtained, all on the Continent, where the widespread h.v. networks have made the problem of peculiar urgency; it is to these solutions that we shall now turn.* All the new designs have a common feature in the elimination of the leading-in bushing, which contributed a considerable proportion to the height and cost of the old type and to some extent determined the size of the tank also. Further, the new designs are all intended for use in three-phase systems and measure the voltage between line and earth. Four principles have been used, and considerable numbers of transformers of the four types are in wide use; they are—

(i) Resistance-transformer combination.
(ii) Reactance-transformer combination.
(iii) Transformer within insulating casing.
(iv) Cascade grouping of transformer units.

* B. Kalkner, "Gewinnung von Messspannungen bei sehr hohen Betriebsspannungen," *E.u.M.*, vol. 49, pp. 227–228 (1931).

Imhof's* voltage transformer, shown diagrammatically in Fig. 125, is made in Switzerland by the firm of Trüb, Täuber & Cie. It consists of a high resistance composed of a number of flat coils of very fine constantan wire mounted one above the other within an insulator filled with oil; the direction of winding of successive coils is reversed so that the resistor is approximately non-reactive. The upper end of the resistor is joined to the high-voltage line; the lower end is earthed through the primary of a small transformer. Since the current flowing to earth is proportional to and in phase with the voltage, an ammeter in the secondary circuit may be scaled directly in volts; the primary current is 5 mA and the secondary current 0·5 ampere. The output is 15 VA and the accuracy within Class 1. Corona discharge is avoided by shielding the resistor with a tinfoil-coated paper tube; the voltage gradient is only about 1 000 volts per cm., so that there is high dielectric strength. The diameter of the base is 65 cm.; the greatest diameter above the base is 20·7 cm. for the indoor type and 41·6 cm. for the outdoor type. The table gives some dimensions for the standard sizes.

Normal line voltage kV.	64	110	135	150	220
Height, cm.	180	233	252	269	343
Weight, kg. (indoor)	160	175	190	200	225
Weight, kg. (outdoor)	240	280	310	330	400
Oil weight, kg.	25	35	40	45	60

For comparison, a normal design of transformer by the same firm for a line voltage of 120 kV is 340 cm. high, weighs 5 000 kg., contains 2 400 kg. of oil and requires a floor space of 2·6 sq. m. Although Imhof's transformer has enormous advantages in weight and price over the ordinary type, it has the disadvantage of a very small output; the overload capacity is also low, in consequence of the ease with which the fine resistance wire can be damaged by excessive current. The high accuracy and lightness recommend the design for laboratory use.

Goldstein† has described a transformer for 220 kV made by

* A. Imhof, "Ein neuer Spannungswandler für Höchstspannungen," *E.u.M.*, vol. 46, pp. 1074–1076 (1928).

† J. Goldstein, "Ein neuer Spannungswandler für Höchstspannungen," *Elekt. Zeits.*, vol. 52, pp. 378–379 (1931; *Elec. Times*, vol. 79, p. 787 (1931).

the A.E.G. and developed from a suggestion due to Biermanns; in principle it resembles Imhof's design with the resistor replaced by an inductive reactance as shown in Fig. 126. The choking coil is composed of a number of disk coils assembled in the form of a stack between the iron core at the base and a wood block at the top; the whole is insulated by a system of paper tubes and is firmly clamped together. If desired, the

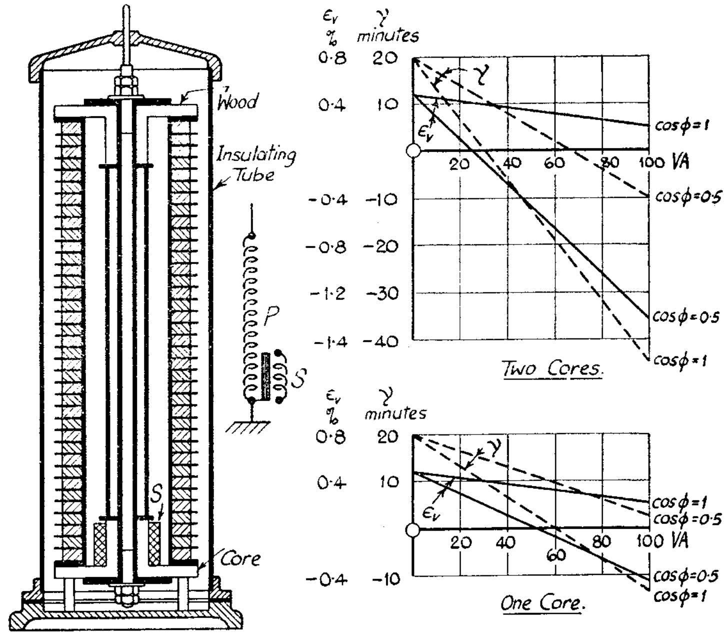


Fig. 126. Goldstein's Voltage Transformer (A.E.G.)

wood block may be replaced by a second iron core. The lower core carries the secondary winding which forms a transformer with the lower part of the choking coil. An oil-filled insulator surrounds the whole; this may be a paper tube for indoor use or a skirted porcelain for outdoor service. The choking coil is designed to take a sufficiently large current so that the primary current is hardly changed by the demand of the burden; the reaction of the secondary is further minimized by using a strong flux in the core. Variation of ε_v and γ with secondary VA is shown in the diagram. With two cores the core flux density is about 2 000 lines per sq. cm.; a burden of 50 VA gives errors within the limits of Class 0·5. With the lower core only, the flux density is about 3 000 lines sq. cm., and the choking coil is about 30 per cent less inductive and takes a correspondingly greater current; the burden for Class 0·5 accuracy rises to 100 VA. The arrangement is smaller and lighter than the resistance type; for example, the 220 kV unit is only 260 cm. high. Its output is much larger and, though adequate for many practical purposes, still falls considerably short of that obtainable from transformers of normal design.

The Brown-Boveri Co.* have obtained great advantages in size and cost over the old type of transformer but with similar outputs, by adopting the insulating-container design, similar to that used for h.v. current transformers (see p. 195). As shown in Fig. 127, the container consists of a porcelain insulator mounted between two caps, the upper of which forms the h.v. terminal while the lower one is earthed. The transformer consists of a two-limbed core with the windings on one limb only; the end coils of the primary are reinforced with additional insulation as a protection against surges. The primary extends almost the whole length of the insulating cylinder and nearly touches it along a vertical line at one side. Insulated wire rings are fixed to the surface of the primary coil and are connected to successive points in the winding in such a way that the potential increases from ring to ring from the bottom to the top in a series of equal steps. These rings surround the transformer and lie near the inner surface of the porcelain insulator, along the whole length of which they impress a practically uniform potential gradient. The iron core is connected to the mid-point of the primary and is insulated from the lower cap for half the voltage. The secondary winding is situated near the core at the lower end, its two ends being led out through the side of the lower cap. Although the transformer is intended to work in a three-phase circuit with the voltage between line and neutral it is insulated to withstand to earth 1·2 times the line voltage applied continuously; this covers the contingency in a circuit with uninsulated neutral receiving an earth fault on one line, see p. 264. The transformer is designed to give its highest accuracy between 0·8 and 1·2 times rated star-voltage; this is illustrated by the error curves in Fig. 127,

* A. Meyerhans, "Ein neuer Spannungstransformator für Höchstspannungen," *Elekt. Zeits.*, vol. 51, pp. 17–18 (1930); *B.B.Rev.*, vol. 17, pp. 89–92 (1930); *Elec. Times.*, vol 77, pp. 257–258 (1930). G. Courvoisier, "Messwandler. Brown-Boveri Spannungs- und Stromwandler," *Bull. Schw. Elekt. Verein*, vol. 24, pp. 88–93 (1933).

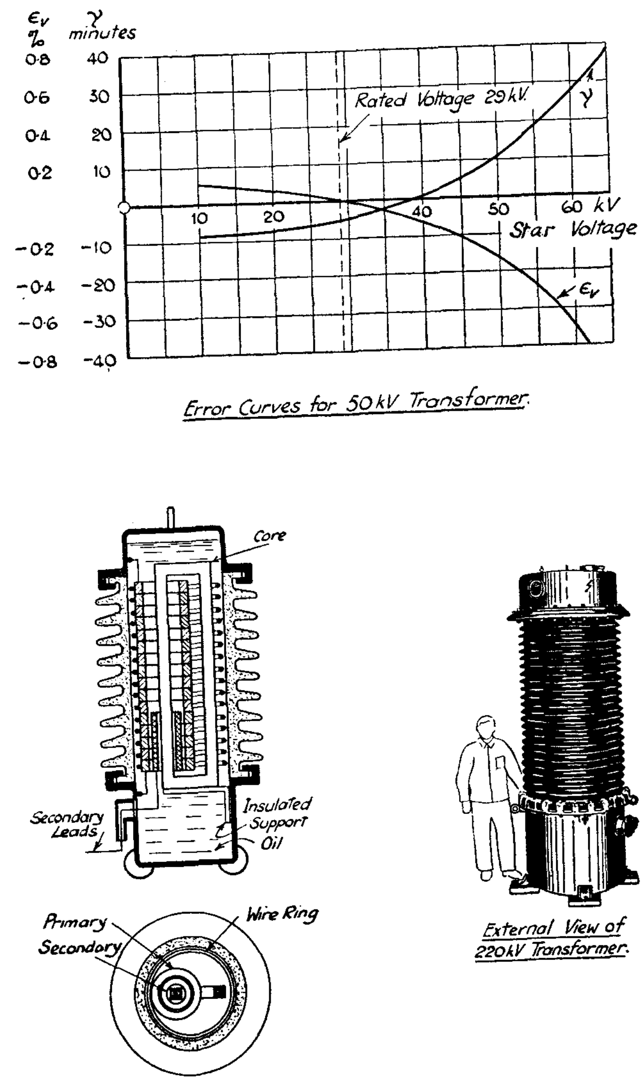


FIG. 127. MEYERHANS' VOLTAGE TRANSFORMER (BROWN-BOVERI)

which show the variation of ε_v and γ with voltage for a 50 kV transformer loaded with a constant resistance corresponding with 200 VA at the rated star-voltage of $50/\sqrt{3} = 29$ kV. Class 0·5 accuracy is easily secured with an output not less than 200 VA. The following table shows that in respect of accuracy and output the new transformers are the equal of the old type—

Line voltage, kV.	50	66	87	110	150	220
Output VA, Class 0·5	200	200	200	200	250	250
Output VA, Class 1	600	600	600	600	750	750
Max. continuous load in kVA.	2	2·5	3·5	5	7	10

The transformers are oil-filled. Experience shows that no expansion vessels are necessary as the temperature rise of the oil is slight; consequently, there is no danger of oxidation, since the casing is closed. Breathers are provided to prevent the ingress of moisture. As regards bulk, the new transformers have great advantages over the old, as is illustrated by the following figures for 50 kV and 150 kV open-air transformers—

	50 kV.		150 kV.	
	Old	New	Old	New
Floor space, sq. cm.	123 × 94	58 × 58	240 × 240	80 × 80
Height, cm.	170	135	420	240

Fig. 127 shows the external appearance of the 220 kV unit and gives some idea of its size in comparison with a man of average height.

So successful has this type of transformer proved in practice that it may be considered as superseding the old type for future developments. Its only serious rival is the cascade transformer, now to be considered, which is widely used in e.h.v. networks on the Continent. Some firms* have even abandoned the cascade design in favour of the new type, claiming that the latter is cheaper to manufacture and gives high accuracy with greater outputs than can be obtained from the cascade type.

In general, the fundamental principle of cascade connection

* G. Keinath, *Bull. Schw. Elekt. Verein*, vol. 24, p. 96 (1933), discusses this question and gives a photograph of a Siemens-Schuckert transformer for 110 kV. The patent situation is also a contributory factor in the abandonment of the cascade design by some makers.

is to subdivide the total voltage between n transformers joined in series in such a way that each bears $1/n$ of the voltage. By this means the windings of each unit may be much more lightly insulated from their cores than would be the case were the whole voltage borne by a single transformer. Fig. 128 (*a*) shows three iron-cored choking coils joined in series between line and earth, each being insulated from its core for $\frac{1}{6}$ of the total

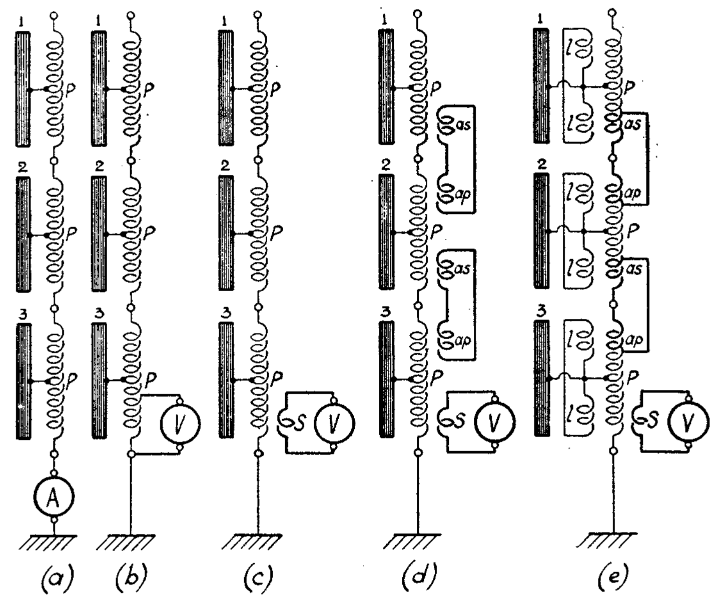


FIG. 128. ILLUSTRATING THE PRINCIPLE OF THE CASCADE VOLTAGE TRANSFORMER

voltage. The cores are mounted one above the other by insulating supports which withstand the voltage to earth of the several sections. An ammeter in series at the earthed end measures a current which is proportional to the line voltage. In Fig. 128 (*b*) a voltmeter in parallel with a portion of the lower coil gives a reading proportional to the total voltage, but its presence will seriously disturb the equality of the voltages across the separate coils. The same is true of Fig. 128 (*c*), where the lowest coil has been provided with a secondary winding, thus acting as a transformer. In consequence of the fact that the upper coils are not magnetically connected to the lowest the potential distribution is upset, the lowest unit getting less and the upper units more than an equal share; regarded as a voltage transformer the ratio error and phase-angle can only be kept small if the secondary output is slight. To equalize the voltage distribution with large outputs it is necessary to interlink the coils magnetically by converting them all into transformers joined in cascade after the fashion commonly used in h.v. testing transformers, as shown in Fig. 128 (*d*). The uppermost unit is provided with an auxiliary secondary, *as*, by means of which a voltage can be injected into the unit next below via its auxiliary primary, *ap*. This unit in turn has an auxiliary secondary, by means of which it is interlinked with the unit below it, and so on. For the most perfect results the magnetic leakage between the primary *P* and the auxiliary coupling winding *as*, *ap* of any given unit must be kept small; the ideal arrangement, therefore, is to adopt a concentric grouping of the various coils. Unfortunately, constructional difficulties and insulation requirements do not always permit of the concentric arrangement; the effect of magnetic leakage can then be annulled by using short-circuited, leakage-compensating windings, shown in Fig. 128 (*e*), which act in the way already explained in connection with current transformers (see p. 137). A certain economy in winding is obtained by the auto-transformer principle, as indicated in the diagram.

The earliest application of the cascade principle was in the *raising* of voltage for testing purposes, i.e. in h.v. testing transformers where it was desired to effect some saving in the considerable cost of insulation.* It was not until several years later that the application was made to the *lowering* of a voltage for measuring purposes, though Schrader† as far back as 1914 had patented a voltage transformer consisting of two

* The original idea is contained in the following German patents in the name of F. Dessauer, D.R.P. 336 779 (30th Sept., 1915); D.R.P. 339 223 (17th May, 1918); D.R.P. 368 474 (24th June, 1920); D.R.P. 430 081 (11th Sept., 1920), *inter alia*. The reader will also find useful information in the following papers: E. Welter, "Ueber einen neuen Hochspannungstransformator nach Dessauer für sehr hohe Spannungen," *Elekt. Zeits.*, vol. 39, pp. 373–375, 383–387 (1918). F. Dessauer, "Ueber die Transformator mit gesteuerter Beanspruchung des Isoliermaterials," *Elekt. Zeits.*, vol. 44, pp. 1087–1092 (1923). W. Hess, "Erfahrungen und Fortschritte im Bau des Lufttransformators für sehr hohe Spannungen und dessen Schaltungen," *E.u.M.*, vol. 44, pp. 641–651 (1926). E. Wirz, "Transformatoren mit Wicklungen in Kaskadenschaltung," *Bull. Schw. Elekt. Verein*, vol. 18, pp. 257–279, 355–370 (1927). W. Gauster, "Ueber Hochspannungs-Prüftransformatoren," *E.u.M.*, vol. 49, pp. 809–814, 828–831 (1931). K. Fischer, "Die Energiewanderung bei der Stufenschaltungen von Transformatoren," *Helios*, vol. 37, pp. 253–257 (1931).

† Siemens and Halske A.G. (C. Schrader), "Spannungstransformator," D.R.P. 293 757 (26th July, 1914).

units, each with a primary and a secondary winding. The primaries were joined in series, as also were the secondaries; leakage was annulled by the use of short-circuited tertiary windings. Fischer* in 1920 revolutionized the design of cascade testing transformers by introducing the insulating casing type with its great saving of bulk, but does not seem to have followed up his idea in its application to voltage transformers until some years later. It is to Pfiffner† that credit must be given for the first practical cascade voltage transformer. While Fischer designed his voltage transformers upon the Dessauer principle, Pfiffner arrived at his design by modification of the series-connected earthing coil, in much the same way as we have described in connection with Fig. 128. Pfiffner's first transformers for 60 kV were put into use in France in 1922; in the following year no less than 75 transformers were installed in France and Italy for voltages up to 150 kV. The theory of the cascade voltage transformer was first given in 1929 by Wirz.‡

Pfiffner's § cascade transformer is shown diagrammatically in Fig. 129. It consists of a number of porcelain-encased units assembled one above the other in the form of a column and connected in cascade after the manner of Fig. 128 (*e*). Each unit contains a shell-type transformer for a normal voltage of 30 kV mounted vertically in a compound-filled porcelain container provided with screw-fitting metal caps. The act of screwing the sections together automatically makes the necessary electrical connections. The complete apparatus is surmounted by a metal cap containing the surge protective resistance.

The Siemens & Halske ‖ cascade transformer is of a somewhat similar type and is illustrated in Fig. 130. Each unit consists of a shell-type transformer mounted horizontally in a porcelain casing. The unit is intended to operate normally with a star voltage of 22 kV, corresponding with a line voltage of 38 kV.; it is tested to operate continuously with this line voltage or for 10 hours at a voltage 1·2 times as great, i.e.

* Koch & Sterzel A.G. (F. J. Fischer), "Aus Gliedtransformatoren mit stufenweiser Steigerung der Spannung gebildeter Hochspannungs-Staffeltransformator," D.R.P. 478 117 (15th June, 1920).

† E. Pfiffner, "Drosselspule für hohe Spannungen," D.R.P. 364 336 (6th Jan., 1921).

‡ E. Wirz, "Der Kaskadentransformator mit ungleichmässig verteilten Wicklungen als Spannungswandler," *Arch. f. Elekt.*, vol. 21, pp. 563–592 (1929).

§ E. Pfiffner, "Kaskaden-Erdungsspulen und- Messwandler," *Elekt. Zeits.*, vol. 47, pp. 44–46 (1926).

‖ G. Keinath, "Spannungswandler in Kaskadenschaltung für höchste Spannungen," *Siemens Zeits.*, vol. 8, pp. 629–637 (1928); "Die neuen Spannungswandler in Kaskadenschaltung," *E.u.M.*, vol. 47, pp. 206–207 (1929); "Die Entwicklung der Siemens Messgeräte," *Siemens Jahrbuch*, pp. 55–74 (1929); "Spannungswandler in Kaskadenschaltung für höchste Spannungen," *Elekt. Zeits.*, vol. 51, pp. 60–6 (1930).

45 kV. Each unit is filled with a plastic compound to exclude moisture. The primary winding consists of 20 separate coils; the coupling coils of thicker wire are placed at the ends of the primary, the whole being connected similarly to Fig. 128 (*e*). The following table gives the number of units and overall heights of transformers for use up to 220 kV; for all voltages the diameter of the base plate is 110 cm. and of the insulator 68 cm. over the ribs.

Line voltage, kV. . . .	38	75	110	150	185	220
No. of units	1	2	3	4	5	6
Overall height, cm. . . .	85	120	155	190	225	260

Considerable savings in weight and cost are effected, as the following figures indicate—

Line Voltage kV.	Weight in kg.		Relative Cost	
	Usual Type	Cascade Type	Usual Type	Cascade Type
110	2 175	775	100	55
150	4 000	1 000	200	75
220	8 500	1 500	400	120

The temperature rise with rated star-voltage is only 25° C. The filling compound is such that it remains plastic even at the low temperatures encountered in the open-air during winter conditions. Protection against surges is provided by an external series resistor of 2 000 ohms per 20 kV, consisting of wire fused into enamel and contained within the elements of a suspension-insulator chain. The accuracy of the cascade set falls well within the limits of Class 1 or better, and outputs up to 150 VA are readily obtainable.

Koch & Sterzel A.G.* are responsible for some striking

* F. J. Fischer, "Kaskaden-Transformatoren," *K.u.S. Mitt.*, No. T16, pp. 1–47 (June, 1929). K. Gründig, "Kaskaden-Messwandler," *E.u.M.*, vol. 48, pp. 633–636 (1930); *Elekt. Zeits.*, vol. 53, pp. 341–342 (1932); "Fortschritte im Bau von Kaskadenmesswandlern," *Elekt. Wirts.*, vol. 29, pp. 576–579 (1930). "Hängende Kaskadenspannungswandler," *Elekt. Zeits.*, vol. 51, p. 1403 (1930). "Kaskaden-Spannungswandler," *Arch. f. tech. Mess.*, Z39–4 (1931). "Kaskaden-Spannungswandler für einphasigen Wechselstrom, hergestellt von der Koch und Sterzel Aktiengesellschaft in Dresden," *Elekt. Zeits.*, vol. 53, p. 132 (1932). W. Reiche, "Kaskaden-Spannungswandler," *Arch. f. tech. Mess.*, Z387–1 (Jan., 1933).

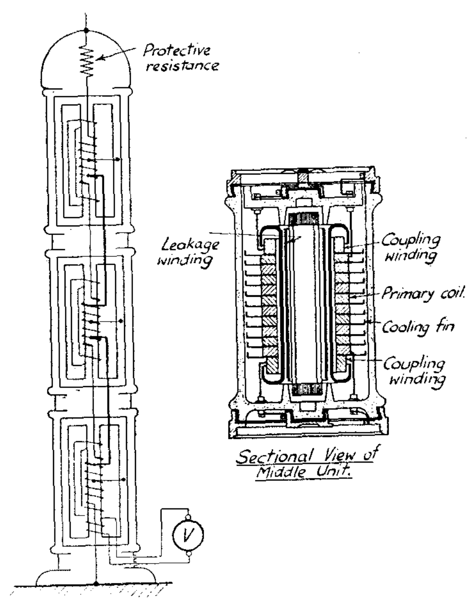


FIG. 129. PFIFFNER'S CASCADE VOLTAGE TRANSFORMER

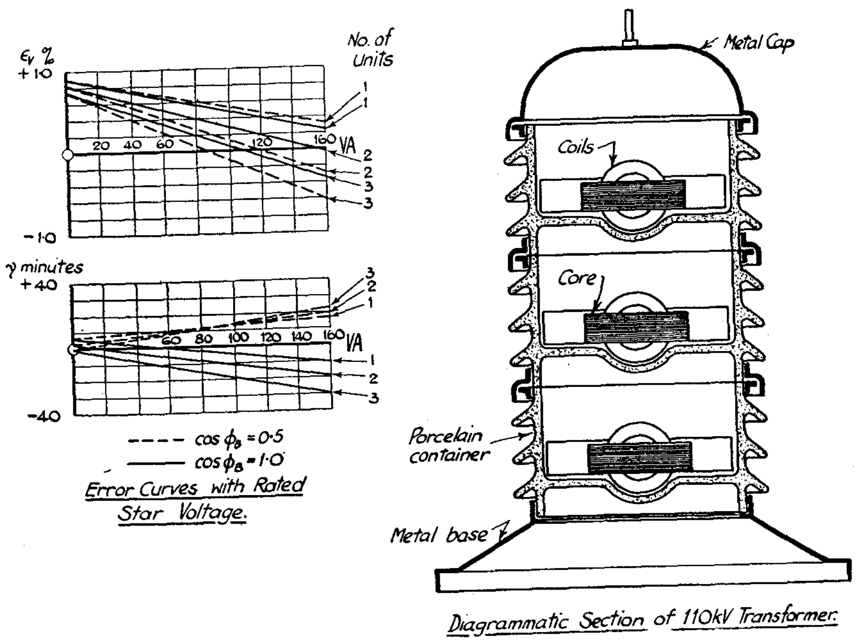


FIG. 130. SIEMENS & HALSKE CASCADE VOLTAGE TRANSFORMER

developments in the design of cascade voltage transformers and are the premier exponents of this type on the Continent. The 110 kV unit is a two-stage arrangement, of which the

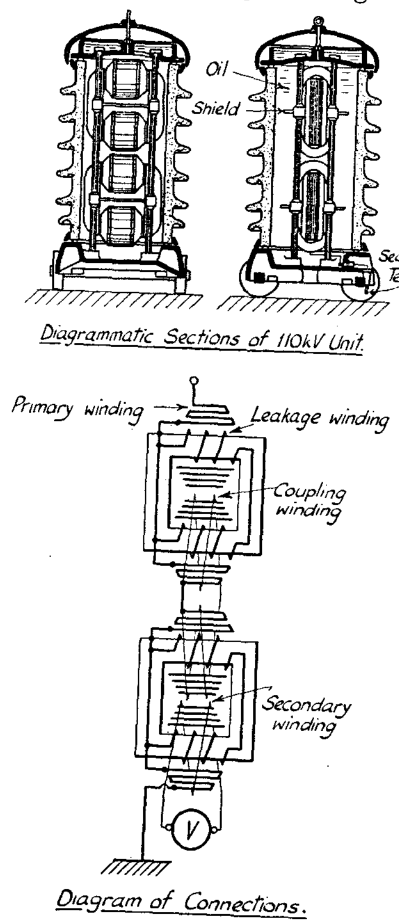


FIG. 131. KOCH & STERZEL CASCADE VOLTAGE TRANSFORMER FOR 110 kV

connections and a diagrammatic section are shown in Fig. 131; it comprises two core-type transformers connected in cascade with coupling and leakage windings as illustrated. All the windings are concentrically arranged upon two limbs of each core, the primaries being insulated for one-quarter of the total voltage. The two cores are supported one above the

other inside an oil-filled porcelain casing carried upon a metal base with wheels, and surmounted by a metal cap which serves as the h.v. terminal and as an oil conservator; these details are indicated in Fig. 131. Fig. 132 shows the cascade transformer in comparison with a transformer of the usual construction; the former has about half the height and one-fifth of the weight of the latter. For 220 kV four cores with eight primary coils are used, the whole consisting of two complete 110 kV units

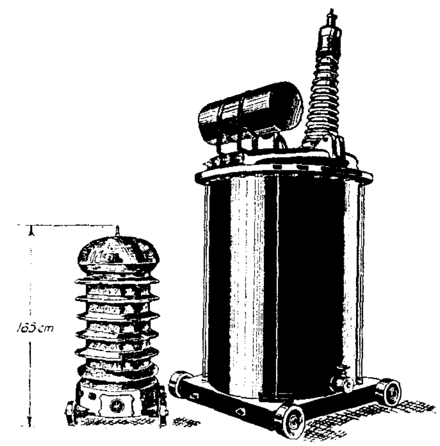


FIG. 132. 110 kV VOLTAGE TRANSFORMERS OF CASCADE AND NORMAL CONSTRUCTION

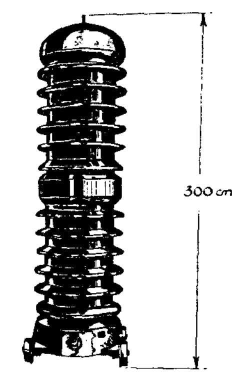


FIG. 133. KOCH & STERZEL CASCADE VOLTAGE TRANSFORMER FOR 220 kV

mounted one above the other as shown by Fig. 133. The following table shows the economy of height and weight obtained with this design: the outputs are ample for all practical purposes.

Line Voltage	Working Star-Voltage	Test Voltage	Output in VA		Weight kg.	Height cm.	Diam. of Base, cm.
			Class 0·5	Class 1			
110 kV	63·5 kV	250 kV	200	600	1 370	165	85
220 kV	127·0 kV	460 kV	150	500	2 600	300	85

In open-air substations it is often desired to reduce the floor area to a minimum, while height is practically unlimited. To suit these conditions the Koch & Sterzel A.G. has developed

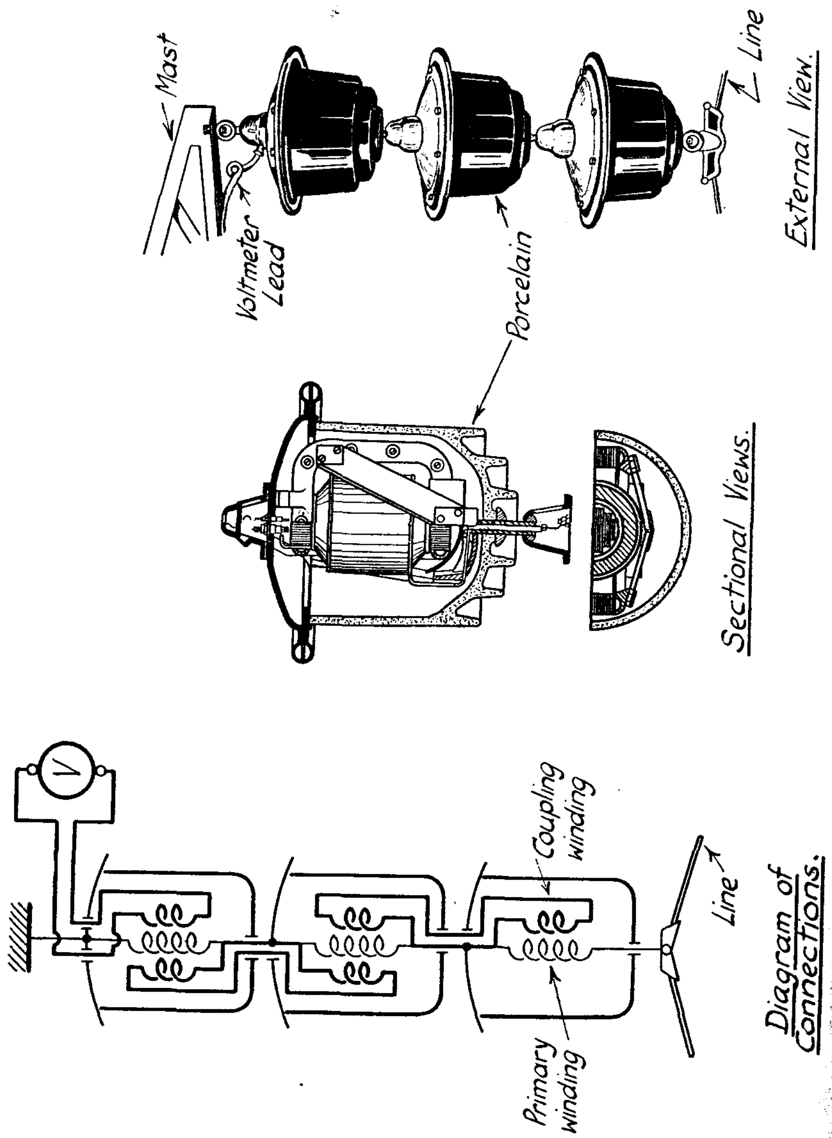


Fig. 134. Suspension-type Cascade Voltage Transformer

a suspension-type cascade transformer illustrated in Fig. 134. Each unit consists of a shell-type transformer, with concentric primary and coupling windings, contained within a porcelain shell filled with oil; since magnetic leakage is very small, leakage windings are unnecessary. A suitable number of units are cascade-connected and are hung in the form of an insulator chain between the suspension mast and the line. The arrange-

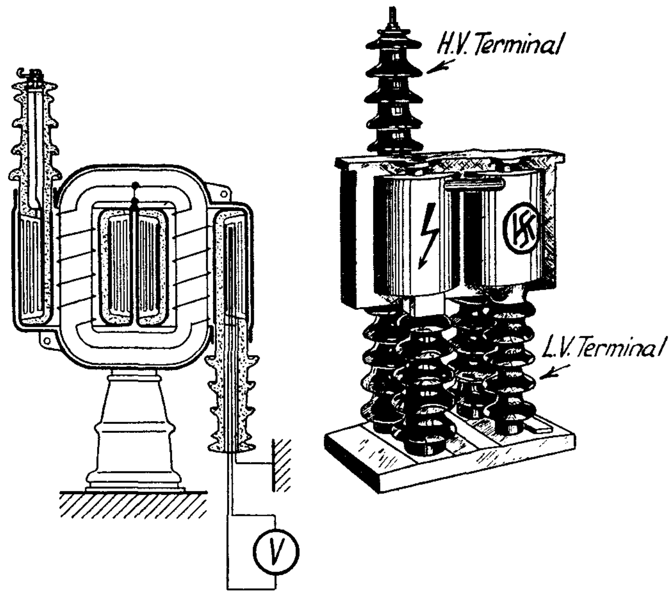


Fig. 135. Dry-type Cascade Transformer for 60 kV.

ment gives high accuracy with adequate output and is the lightest and cheapest cascade transformer in use.

Line voltage kV.	35	70	115	140	210
No. of units	1	2	3	4	6
Output, Class 0·5, VA.	350	275	200	150	100
Output, Class 1, VA.	700	600	400	300	200
Weight, kg.	115	230	345	460	700

The same firm manufacture a dry-type, porcelain-insulated cascade transformer for indoor or outdoor use, using the principle of construction described on p. 240. Referring to Fig. 135, two dry-type spools are put upon opposite legs of a two-limbed core. The high voltage comes in at the upper bushing to the entering winding and primary of the left-hand spool; the other end of the primary and the metal casing of the whole transformer are connected to the core. The outer end of the right-hand primary is joined to the core, its inner end formed by the metallized layer, is earthed; the secondary winding lies near the earthed end. Since the core is at mid-potential it must be insulated for half the voltage; this can be done by mounting it upon insulating supports, or the whole transformer may be inverted and hung from a suspension insulator. Short-circuited windings are provided to minimize leakage. The transformer is constructed for 60 kV and 100 kV, in both cases giving Class 0·5 accuracy with 120 VA and Class 1 with 360 VA.

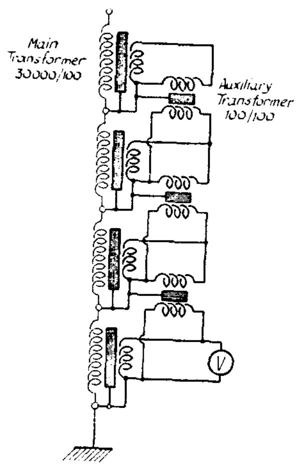


FIG. 136. COMPAGNIE DES COMPTEURS CASCADE VOLTAGE TRANSFORMER

The Compagnie des Compteurs* make a cascade transformer on a slightly different principle, illustrated by Fig. 136. Each main transformer is designed for a ratio of 30 000/100, the primaries of a suitable number being joined in series; the lowest transformer supplies the load. To equalize the voltages over the sections, small auxiliary transformers of ratio 100/100 are used. A main transformer and its auxiliary transformer are contained in an oil-filled metal case provided with insulating feet; a complete outfit for any desired voltage is arranged by standing a suitable number of units one upon the other. Thus, a 150 kV cascade set has 5 units, weighs 2 300 kg and contains 750 litres of oil; the output is small, being 40 VA for Class A of the French Rules and 120 VA for Class B.

Although most types of cascade transformer give sufficient output for all practical purposes it will have been observed that there is a marked falling off in the output obtainable for

* A. Iliovici, *Bull. Soc. Franç. des Elecns.*, vol. 10, pp. 1191–1215 (1930); *ibid.*, vol. 2, pp. 1117–1131 (1932); *Rev. Gén. de l'Él.* vol. 34, pp. 585–586 (1933). See also, P. de la Gorce, "Les transformateurs de mesure," *Congres Int. d'Él. Paris*, Report 21, 2nd Section, pp.1–18 (1932).

a given class of accuracy as the voltage increases. This is due to the obvious fact that the series connection sums up the errors of ratio and phase-angle of the individual units. A transmission voltage of 220 kV is the largest value at present in use, but there is no doubt that the future will see the adoption of still higher voltages. When this occurs it is doubtful whether cascade transformers will be able to give the desired output of 150–200 VA with adequate accuracy for metering, and it would seem that the future most probably lies with insulated-casing transformers of the type described on p. 250, since these are subject to no such limitations. As indicated earlier, some firms have already abandoned the cascade design in favour of the latter type.

10. **Three-phase and five-limb transformers.** The preceding sections have considered the voltage transformer as a single-phase unit, even though used in a three-phase circuit. In practice the three-phase system is almost universally used and it is necessary, therefore, to give some attention to voltage transformers under the conditions of three-phase working. There are two main principles. Individual single-phase transformers such as we have considered, suitably connected to the circuit, may be used; or special three-phase transformers with the windings on a common magnetic circuit can be employed. The use of separate single-phase transformers is now standard practice in high voltage circuits above about 20 kV; below this voltage the three-phase transformer is common. While the separate transformers utilize more material and may be more costly than the three-phase transformer, they offer greater ease of replacement when damaged; moreover, types of construction, such as have been described in Section 9, become available at the highest voltages and result in the aggregate of transformers being actually cheaper than the three-phase unit.

In a three-wire circuit with an insulated neutral point, power is usually measured by the two-wattmeter method, which requires two voltage transformers connected in "vee," as shown in Fig. 137. The primary windings must be designed to work at the line p.d.; the common point of the secondary side is earthed (see p. 287). In a three-phase four-wire circuit three wattmeters and three voltage transformers are required. The same is true of a three-wire system with an earthed neutral since an earth fault may temporarily convert the system into a four-wire network. In such cases the transformers are connected star-star, as in Fig. 137; the secondary neutral point is always earthed and the primary neutral is earthed also. It is preferable that the primary neutral should be connected to that of the supply, to provide a path for the third-harmonics in the

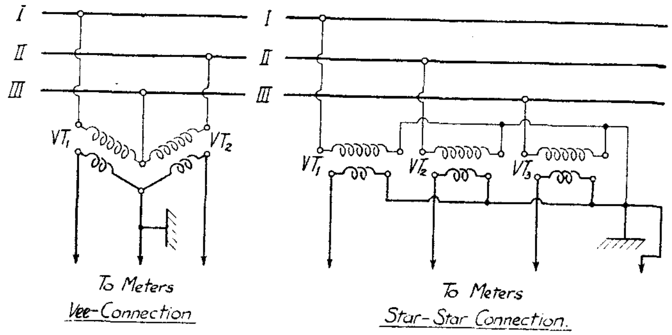


FIG. 137. VEE- AND STAR-CONNECTION OF INDIVIDUAL TRANSFORMERS IN THREE-PHASE CIRCUIT

magnetizing currents and thereby eliminate triple-frequency terms from the secondary star-voltages. Exact balance of the secondary voltages and equality of errors in the three phases are also assured.

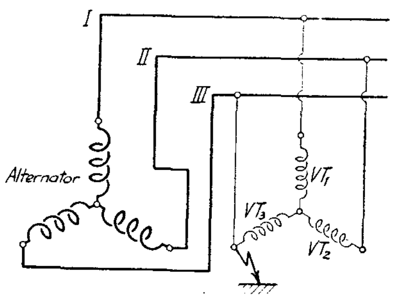


FIG. 138. EARTH FAULT IN THREE-PHASE CIRCUIT WITH UNEARTHED NEUTRAL POINT

Referring to Fig. 138 a three-phase system with insulated neutral point is shown. In the normal condition the p.d. between the high voltage terminal of each voltage transformer and earth is equal to the star-voltage. If an earth fault occurs on one line the p.d. between the unfaulted line and earth rises to a magnitude equal to the line voltage; such a condition may continue for hours.* Consequently, voltage transformers intended for use in this way should be insulated so that under earth-fault conditions they will safely withstand between their h.v. terminals and earth a voltage at least equal to the line voltage. Reference to Section 9 will

* H. Piloty, "Nullpunktstrom, Nullpunktsspannung, Nullpunktsleistung, Nullpunts-Blindleistung," *A.E.G. Mitt.*, Part 10, pp. 397–402 (1926); "Was messen Wattmeter und Zähler in Hochspannungsanlagen bei Erdschluss?" *A.E.G. Mitt.*, Part 6, pp. 253–255 (1927).

show that many modern h.v. transformers are designed to fulfil this condition.

When three transformers are star-connected as in Fig. 137, it is important to know the line-line values of ratio error and phase-angle for the whole arrangement. No ordinary method enables these values to be measured directly; they are, therefore, computed from the measured line-neutral values obtained by testing each transformer separately. Suitable formulæ have been given by Crawley* and will be derived by a method

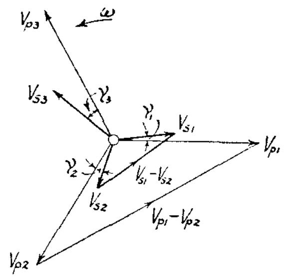


FIG. 139. CALCULATION OF LINE-LINE RATIO AND PHASE-ANGLE FOR STAR-CONNECTED TRANSFORMERS

differing from his. Assuming the primary star-voltages to be a symmetrical three-phase system as in Fig. 139, in vector notation

$$\mathbf{v}_{p2} = (\cos 120^\circ - j \sin 120^\circ)\mathbf{v}_{p1} = -\left(\tfrac{1}{2} + \frac{\sqrt{3}}{2}j\right)\mathbf{v}_{p1}$$

Let ε_{v1}, ε_{v2}, ε_{v3} be the fractional ratio errors of the transformers and γ_1, γ_2, γ_3 their phase-angles. Then if the transformers are all of the same nominal ratio K_{nv}, while their actual ratios are K_{v1}, K_{v2}, K_{v3}, the reversed secondary voltages of transformers 1 and 2 can be written, with ε the naperian base (p. xxiv),

$$-\mathbf{v}_{s1} = \frac{1}{K_{v1}} \varepsilon^{j\gamma_1} \mathbf{v}_{p1} \text{ and } -\mathbf{v}_{s2} = \frac{1}{K_{v2}} \varepsilon^{j\gamma_2} \mathbf{v}_{p2}.$$

Remembering that $1/K_v = (1 + \varepsilon_v)/K_{nv}$ (p. 12) and that γ is small,

$$-\mathbf{v}_{s1} \doteqdot \frac{1}{K_{nv}} (1 + \varepsilon_{v1})(1 + j\gamma_1)\mathbf{v}_{p1} \doteqdot \frac{1}{K_{nv}} (1 + \varepsilon_{v1} + j\gamma_1)\mathbf{v}_{p1},$$

* A. C. Crawley, "Calculation of line-to-line ratios and phase-angles of a combination of three single-phase voltage transformers star-connected on a three-phase system, the star point being earthed," *Journal I.E.E.*, vol. 69, pp. 1293–1294 (1931).

and

$$-v_{s2} \doteqdot \frac{1}{K_{nv}}(1+\varepsilon_{v2})(1+j\gamma_2)v_{p2} \doteqdot \frac{1}{K_{nv}}(1+\varepsilon_{v2}+j\gamma_2)v_{p2},$$

neglecting second order products of small quantities. The line-line voltages on the primary and secondary sides are

$$v_{p1}-v_{p2} = v_{p1} + \left(\tfrac{1}{2}+\frac{\sqrt{3}}{2}j\right)v_{p1} = (\sqrt{3})\left(\frac{\sqrt{3}}{2}+\tfrac{1}{2}j\right)v_{p1},$$

$$-(v_{s1}-v_{s2}) \doteqdot \frac{1}{K_{nv}}\Big[(1+\varepsilon_{v1}+j\gamma_1)+(1+\varepsilon_{v2}+j\gamma_2)\left(\tfrac{1}{2}+\frac{\sqrt{3}}{2}j\right)\Big]v_{p1}.$$

The ratio of the secondary to the primary line quantities is then

$$\frac{v_{s1}-v_{s2}}{v_{p1}-v_{p2}} \doteqdot -\frac{1}{K_{nv}}\,\frac{\Big[(1+\varepsilon_{v1}+j\gamma_1)+(1+\varepsilon_{v2}+j\gamma_2)\left(\tfrac{1}{2}+\frac{\sqrt{3}}{2}j\right)\Big]}{(\sqrt{3})\left(\frac{\sqrt{3}}{2}+\tfrac{1}{2}j\right)}$$

$$\doteqdot -\frac{1}{K_{nv}}(1+\varepsilon_{va}+j\gamma_a) \text{ say,}$$

where ε_{va}, γ_a are the line-line ratio error and phase-angle for lines 1 and 2. Rationalizing the denominator,

$$(\sqrt{3})(1+\varepsilon_{va}+j\gamma_a) = (1+\varepsilon_{v1}+j\gamma_1)\left(\frac{\sqrt{3}}{2}-\tfrac{1}{2}j\right) + (1+\varepsilon_{v2}+j\gamma_2)\left(\frac{\sqrt{3}}{2}+\tfrac{1}{2}j\right);$$

Separating the components,

$$\varepsilon_{va} = \tfrac{1}{2}(\varepsilon_{v1}+\varepsilon_{v2}) + \frac{1}{2\sqrt{3}}(\gamma_1-\gamma_2) = 0{\cdot}5\,(\varepsilon_{v1}+\varepsilon_{v2}) + 0{\cdot}289\,(\gamma_1-\gamma_2),$$

$$\gamma_a = \tfrac{1}{2}(\gamma_1+\gamma_2) - \frac{1}{2\sqrt{3}}(\varepsilon_{v1}-\varepsilon_{v2}) = 0{\cdot}5\,(\gamma_1+\gamma_2) - 0{\cdot}289\,(\varepsilon_{v1}-\varepsilon_{v2}).$$

The corresponding expressions for ε_{vb} and γ_b, relating to lines 2 and 3, are obtained by permuting 1 into 2, 2 into 3; similarly for ε_{vc} and γ_c, relating to lines 3 and 1, convert 1 into 3 and 2 into 1 in the subscripts of the above expressions.*

Wellings and Mayo† have pointed out that it is possible to

* For simple methods of calculating three-phase transformer burdens and ratings, see A. Garnett, "Three-phase voltage transformer burdens," *M.V. Gazette*, vol. 13, pp. 351–353 (1932).

† *Journal I.E.E.*, vol. 68, p. 714–715 (1930).

adjust the voltage transformers on a three-phase circuit to be entirely free from ratio error and phase-angle. The ratio error can be brought to zero by suitable turns-ratio adjustment (see p. 228). A zero phase-angle can be obtained by providing each transformer with an auxiliary secondary winding, as

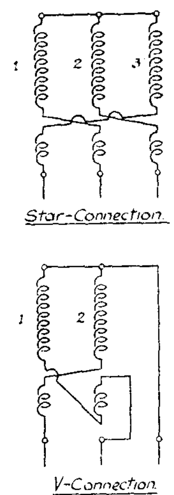


FIG. 140. COMPENSATING PHASE-ANGLE IN THREE-PHASE TRANSFORMERS

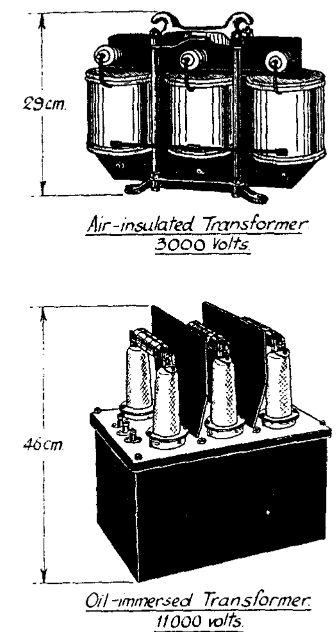


FIG. 141. THREE-PHASE VOLTAGE TRANSFORMERS

shown in Fig. 140, into which an appropriate e.m.f. is injected by interconnecting them with the main secondary windings.

At the lower voltages three-phase transformers with a three-limbed magnetic circuit for the three windings are very common. Fig. 141 shows two typical examples, one air-insulated for 3 kV (K. & S.) and the other oil-insulated for 11 kV (B.T.H.). The primary and secondary windings are usually connected star-star. Since the phases are interlinked both electrically and magnetically the symmetry of the secondary voltages is much more dependent upon the equal loading of the phases than is the case with independent transformers; the disturbance may be very considerable in such an extreme case as a severe fault on one phase, since this causes great changes in core flux. Even in normal circumstances the fact that the magnetizing current of the outer phases exceeds that of the middle phase makes the ratio error and phase-angle of the phases dissimilar; in fact, the accuracy attainable with the three-phase transformer is lower than with three independent transformers. Some manufacturers have endeavoured to equalize the accuracy of the phases by arranging the limbs parallel to one another at the corners of an equilateral triangle, but the construction of the core is difficult and it is questionable whether the result obtained is worth the trouble involved.

In some three-phase, high-voltage networks the neutral point of the alternator is not directly earthed, but the potential of the system is established with respect to earth by the use of earthing coils. These normally consist of oil-immersed, iron-cored choking coils, constructed like a transformer primary winding, three of which are star-connected with their neutral point solidly earthed. The three-phase network virtually becomes a four-wire system in which the power can only be correctly measured by three-element meters, necessitating the use of three voltage transformers. Since these in every way resemble the construction of earthing coils it is economical to use the voltage transformers themselves as earthing coils and thereby to eliminate the latter as separate entities. For this purpose three independent voltage transformers may be used; many of the h.v. voltage transformers described in Section 9 are designed with the object of serving simultaneously as earthing coils. Fig. 142 shows the normal star-star connection. By providing each transformer with a tertiary winding and connecting these in open delta, the arrangement can be made to give an audible or visual signal or to operate a relay when an earth fault occurs on one of the primary phases. In the normal state with balanced voltages and fluxes, the resultant voltage at the terminals of the open delta will be zero. When one phase is faulted to earth, the resultant voltage is no longer zero and can either operate the relay actuating the circuit-breaker, or indicate to the attendant, by lighting a lamp or sounding a buzzer, that a fault exists. Similar arrangements of transformers are also used with certain types of protective gear where line-to-earth voltages are to be correctly indicated under all conditions.

The use of a three-limbed transformer is not so satisfactory for this purpose; on earth fault the disturbance of the flux in

the interlinked magnetic circuit seriously upsets the symmetry of the secondary voltages on the unfaulted limbs. To restore some measure of independence to the phases, five-limbed cores are used, the fourth and fifth limbs providing low reluctance

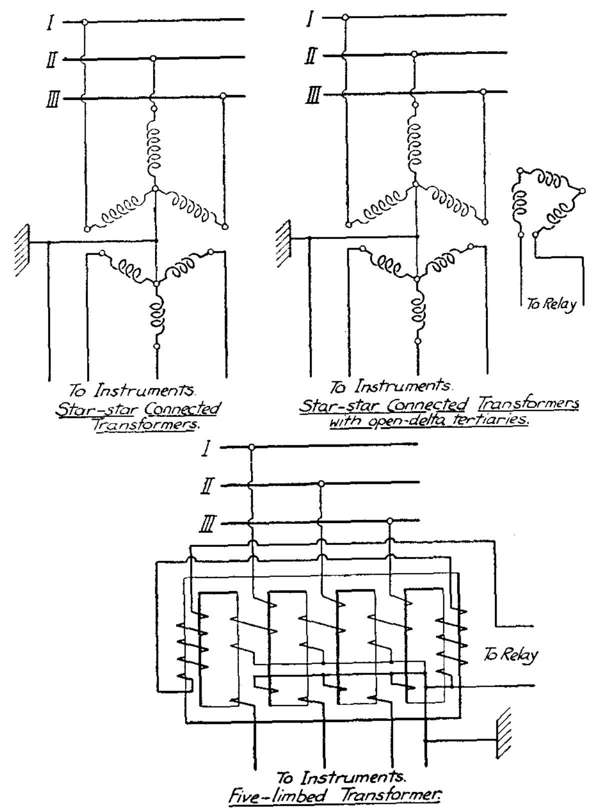


FIG. 142. USE OF THREE SINGLE-PHASE TRANSFORMERS AND OF FIVE-LIMBED TRANSFORMER FOR EARTHING

paths for the yoke leakage flux, as in Fig. 142. Under normal conditions the fluxes in the outer limbs are very small and will induce small voltages in tertiary windings placed upon them; joining these windings in series, their resultant voltage is nearly zero. When an earth fault cuts one phase out of action, the outer limbs carry a considerable flux from the unfaulted limbs and a voltage of 100 or more is set up in the tertiary windings; this can operate a signal or actuate a relay.

These five-limbed transformers attain a size similar to small power transformers, with high voltage bushings, oil tank and conservator, etc.; for example, a typical 100 kV transformer has a limiting output of 30 kVA and weighs 6 500 kg. The five-limbed transformer is cheaper and less bulky than three single-phase transformers of normal construction, such as is shown in Fig. 132, but the latter is cheaper in regard to reserve plant. Consequently, as regard total cost, two five-limbed transformers should be compared with four single-phase transformers when spares are taken into account, and the latter are then definitely cheaper. The advantage of price can be made even more striking, and at the same time the bulk and weight can be greatly reduced, by using insulated-casing transformers or cascade transformers in place of the normal design; this, indeed, is the modern solution to the earthing problem.

11. **Combined voltage and current transformers.** The complete equipment of voltage and current transformers required for metering at high voltages, especially in three-phase circuits, is both bulky and costly; consequently, numerous attempts have been made to combine the various units in some way that will reduce the floor space occupied by the aggregate and lower its cost. One simple solution of the problem is to accommodate voltage and current transformers of normal construction in a common oil tank with high voltage terminals common to both elements. Such a combined arrangement may consist of a complete set of transformers for a two-wattmeter method of measuring power, and is quite frequently used at the lower voltages. At high voltages it is usual to prefer, for reasons of cheaper replacement, a single voltage and current transformer in a common tank; several such arrangements have been described in the technical press. For example, Sanders* mentions a Westinghouse design used in the 132 kV open air substations of the Philadelphia Electric Co.; this contains in a single tank a 1 000 VA voltage transformer for 132 kV/110 or 63·5 volts and a 50 VA current transformer for 600 300 150/5 amperes. The whole is 675 cm. (265 in.) high to the top of the bushing and weighs 19 100 kg. (42 000 lb.).

Such combined transformers are of considerable size and are very uneconomical in their use of high-voltage insulation.

* H. M. Sanders, "High tension metering," *Elec. World*, vol. 94, pp. 1168–1169 (1929). Also see, "Metering transformers," *Elect. J.*, vol. 28, pp. 612–614 (1931).

Since the primary windings of both the voltage and current transformers must be insulated for the same voltage to earth, great economy will be effected if a common high-voltage

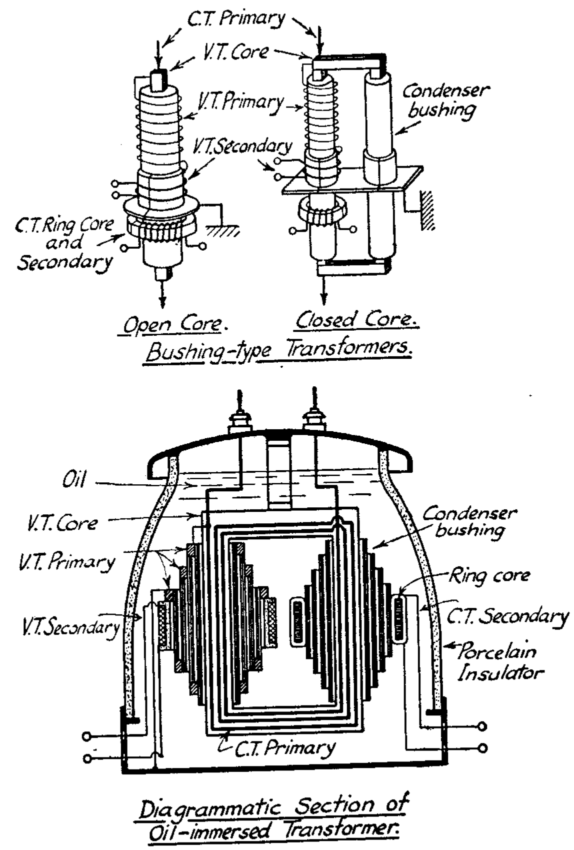


FIG. 143. IMHOF'S COMBINED VOLTAGE AND CURRENT TRANSFORMER

insulation can be provided for both; several designs have been put into practice embodying this principle. Fig. 143 shows a simple arrangement due to Imhof,* consisting of a paper condenser bushing, upon the upper part of which the primary winding of the voltage transformer is mounted. The secondary

* A. Imhof, "A new measuring transformer," *Int. Conf. H.T.E.S.*, 6th session, paper 65, vol. 2, pp. 261–268 (1931); "Un nouveau transformateur de mesure," *Rev. Gén. de l'Él.*, vol. 30, pp. 435–436 (1931); "Ein neuer Messwandler," *E.u.M.*, vol. 50, pp. 77–78 (1932).

is fixed upon the earthed flange, this being slit to prevent it acting as a short-circuited turn around the primary conductor of the current transformer. The iron core of the voltage element has an open magnetic circuit, resulting in a low output if the accuracy is to be kept within the standard limits. The primary of the current element may be this core itself, or a copper conductor parallel to it; the secondary is toroidally wound upon a ring core, which is split so that it is unaffected by the voltage element flux. Improved characteristics can be obtained in the voltage transformer by using a closed magnetic circuit provided with a small air-gap so that it cannot act as a closed loop through the current transformer core (see Fig. 143). A diagrammatic assembly of the complete arrangement is given in the lower part of Fig. 143; the transformer is suitable for 110 kV circuits and is made by the Micafil Co. of Zürich.

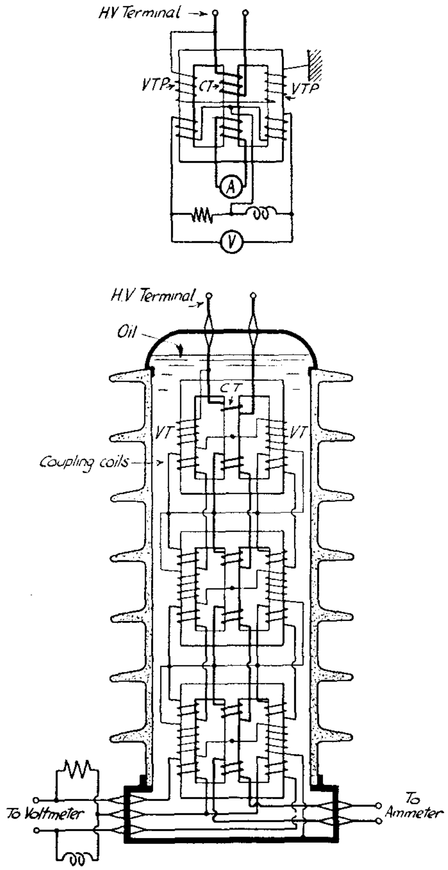


FIG. 144. SCARPA'S COMBINED VOLTAGE AND CURRENT TRANSFORMER

Another interesting arrangement due to Scarpa,* is shown in Fig. 144. This consists of a three-limbed core, the outer limbs each carrying one-half of the voltage transformer windings while the middle limb accommodates the windings of the current

* G. Scarpa, "Trasformatori misti per la misura contemporanea ed indipendente della tensione e della corrente," *L'Elettro.*, vol. 20, pp. 247–251 (1933). For useful abstracts see, *Archiv. f. tech. Mess.*, Z389–1, (June 1933), and *Elec. Rev.*, vol. 113, p. 730 (1933).

transformer. If the construction were quite symmetrical the voltage transformer flux would not influence the current transformer coils and conversely; any slight dissymmetry could be compensated by the bridge arrangement of resistance and choking coil shown in the diagram. A single element serves for 50 kV circuits; at higher voltages a suitable number of

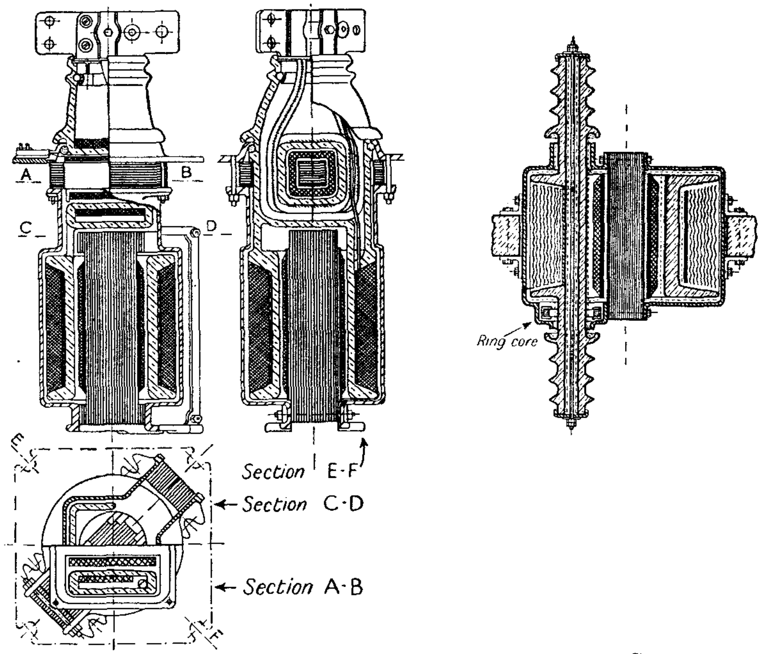


FIG. 145. FISCHER'S DRY-TYPE COMBINED VOLTAGE AND CURRENT TRANSFORMERS

units are cascade-connected, as shown for a 150 kV combination in Fig. 144. The accuracy of this transformer with its full load of 30 VA falls within the Class 0·5 limits. To save space the core limbs are built at the corners of an equilateral triangle; the overall dimensions of the 150 kV transformer being 99 cm. × 84 cm. × 214 cm. high (39 in. × 33 in. × 84 in.).

Fischer* has designed a number of dry-type, porcelain-insulated voltage-current transformers, two examples of which are shown in Fig. 145. The one consists of a cross-hole current transformer of the type illustrated in Fig. 85 combined with a dry-type voltage transformer such as Fig. 119; the porcelain

* See *K.u.S. Mitt.*, No. T17 (May, 1930), No. 18 (Feb., 1931).

bodies are fashioned into a single ceramic piece. The current transformer body takes the place of the voltage transformer bushing and enables the h.v. lead to be taken to the winding of the voltage element. The second example shows that by taking a voltage transformer, as in Fig. 119, and moulding a second bushing upon the other flange in a line with the first bushing, it is possible to combine a porcelain-insulated, bar-type current transformer with a dry-type voltage transformer. Some of Fischer's other designs show even greater resource and ingenuity, for an appreciation of which the reader is referred to his interesting papers.

12. **Protection against overload and faults.** Excessive loading of the secondary winding or a fault in the secondary circuit external to the transformer are provided against by the use of secondary fuses. It is not possible to clear such overloads by primary fuses since the necessary fuse wire would be impracticably fine. Secondary fuses may be placed outside the transformer or they may be put inside the oil tank just behind the secondary terminals; in any case they must be regarded as an integral part of the secondary burden and be in circuit when the transformer is tested for accuracy. An example is shown in Fig. 146.

Faults inside the transformer, whether due to short-circuits within the primary or secondary windings or to earthing of the windings, must be cleared by fuses on the primary side. Since a voltage transformer is directly connected to the station bus-bars an internal fault throws a severe short-circuit upon the system, of a magnitude such that no fuse could be reasonably expected to clear in a sufficiently short interval. Consequently, it is usual to limit the fault current by including a high resistance in series with the fuse. Single-phase transformers must be fused on each pole; three-phase transformers must have a fuse in each line. Each fuse has its own resistor, the latter being connected on the line side of the fuse where it is more effective as a surge protector (see Section 13). Some idea of the necessity for the resistor may be gathered from tests made by Torchio* upon a fine-wire fuse enclosed in a fibre tube. When directly connected across a 6 600 volt supply the fuse was blown to pieces and the arc maintained so that the circuit had to be opened manually; the fuse had a resistance of 79 ohms,

* P. Torchio, *Trans. Amer. I.E.E.*, vol. 40, pp. 61–86 (1921). See also P. M. Hess, "Potential transformer fuse tests," *Elec. World*, vol. 83, pp. 467–471 (1924), for further tests.

through which the steady current would be 84 amperes, but an oscillogram showed the initial rush of current to be 1 970 amperes. This test shows that the mere fineness of a fuse is no guarantee that adequate protection can be secured, since on a dead short-circuit a low resistance arc is maintained and the current may reach very high values. A similar fuse tested with a series resistor opened the circuit within $\frac{1}{50}$th of a cycle and without visible disturbance. The resistors very commonly consist of resistance alloy wire embedded in a base of vitreous enamel; a unit is mounted in spring clips carried upon porcelain insulators appropriate to the voltage. A 12 kV resistor is shown in Fig. 146. In selecting a resistor something of a compromise is necessary, since it must have a value high enough to limit the current and to enable the fuse to act with certainty, while at the same time its value must not be so great as to impair the accuracy of the transformer. A reference to Figs. 106 and 108 will show that a series resistor increases the effective primary resistance drop and consequently tends to increase the drop of voltage between no-load and full-load. In addition it increases the no-load phase-angle, and may either increase or diminish the full-load phase-angle according to the nature of the burden. Edgcumbe and Ockenden (loc. cit., 1927) recommend that the resistance in series with each pole should be about 200 ohms per kV; much smaller values, down to about 15 ohms per kV, are now considered good practice.

The commonest type of fuse is of the cartridge pattern, a fine wire being contained within a tube of porcelain, glass, fibre or insulating card; in order to quench the arc it is usual to fill the tube either with a powder, such as diatomacious earth, or with a liquid, such as carbon tetrachloride or oil. The fuses are carried in clips upon the tops of porcelain insulators mounted on the cover of the transformer (see Figs. 115, 116 and 141); alternatively, the fuse may be mounted apart from the transformer, as in Fig. 146. In other cases the fuses may be immersed in oil within the transformer tank. Messrs. Ferranti* use such an oil-immersed fuse, shown in Fig. 146, in which the fine fuse wire is contained in a tubular lamp enclosed within a bakelite tube; the fusing current is 0·5 to 0·9 ampere and faults are cleared without trouble within $\frac{1}{4}$ cycle.

The G.E.C. of America† use a spring-operated cartridge fuse

* "High voltage transformer fuse," *Elecn.*, vol. 109, p. 518 (1932).

† A. R. Hand, "Spring-type potential transformer fuses," *Gen. Elec. Rev.*, vol. 35, pp. 113–119 (1932).

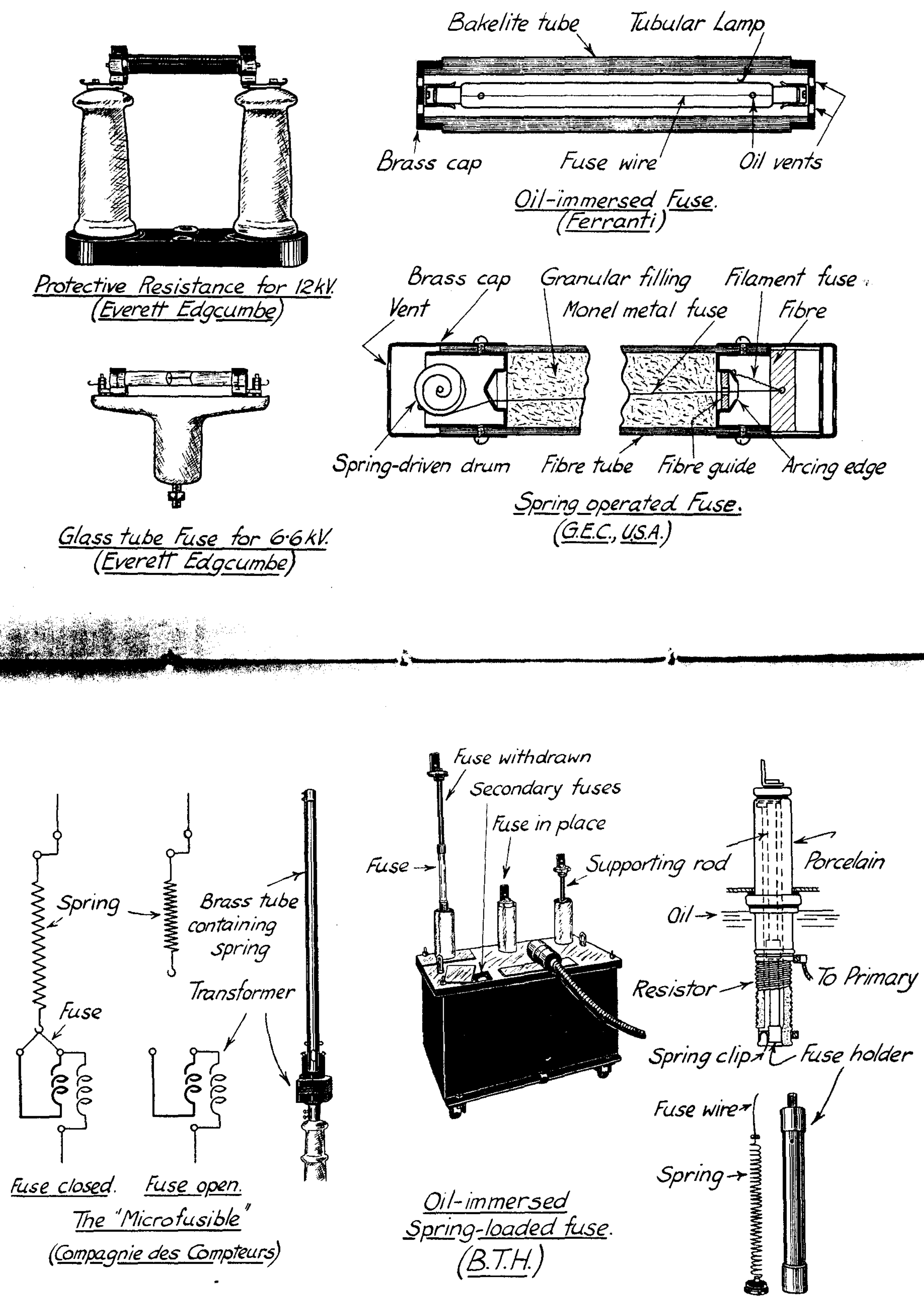


Fig. 146. Series Resistors and Fuses

shown in section in Fig. 146. The fuse proper is a monel metal wire maintained in tension by a spring-driven drum which can reel-in the wire in 0·1 sec. when the far end is released. A short filament wire fuses first, as it is much finer than the main wire, setting up an arc which severs the main link at the arcing edge; the arc is then drawn out and extinguished in the granular refractory filling. A fuse rated for 15 kV, 0·3 ampere can carry 0·2 ampere continuously and fuses at 0·5 ampere; it is 12·5 in. long, 1·5 in. diameter, and weighs 17 oz. Oscillograms show that faults are intercepted at the zero point of the current wave in the next half-cycle following the incidence of the fault.

The Compagnie pour la fabrication des Compteurs have replaced the fine wire by a fuse of more substantial character in their "Microfusible," illustrated in Fig. 146. The arrangement consists of a small current transformer with its primary in series with the h.v. line, while its secondary is closed through a short fuse melting at about 5 amperes. A spiral spring fixed at its upper end inside a metal tube has its lower end hooked under the fuse wire; when the latter melts, the spring is released and breaks the circuit, introducing an air-gap of a length determined by the safe breaking-distance for the primary voltage. The complete device is mounted upon the primary terminal insulator as shown in the diagram, and is applied with success up to 35 kV.

The B.T.H. Co.* have designed a very compact fuse and resistor, shown in Fig. 146, both of which are immersed under oil in the transformer tank. The fuse wire is a single strand of platinoid, 0·004 in. diameter, fixed at its upper end to the top cap of an insulating tube; the lower end of the wire is attached to a spring which is normally in tension and provides a quick break when the fuse melts. The top cap and the lower cap to which the other end of the spring is fixed are both perforated to permit free circulation of oil. The fuse unit is supported by a metal rod bearing the main circuit terminal at its upper end, and is contained within the primary terminal bushing, the lower end of the fuse unit engaging with a spring clip at the bottom of the insulator. The resistor consists of a resistance wire wound in spiral grooves cut upon the outer surface of the lower portion of the insulator. This concentric arrangement of the fuse and resistor has the advantage that the latter acts as an electrostatic shield which effectively

* See J. G. Wellings and C. G. Mayo, loc. cit. *ante*; also *British Patent No.* 300 234.

prevents corona on the fuse wire; experience has shown that at voltages above 11 kV corona discharge from an unshielded wire may cause corrosion of the fuse and ultimate open-circuiting. As is shown in the diagram, the removal of the fuse for inspection or replacement is a very simple matter.

13. **Voltage rises and surge phenomena.** Transient disturbances of the primary voltage applied to a voltage transformer will occur whenever abrupt changes are made in the voltage or current of the system to which the transformer is connected. These transients consist of travelling electromagnetic waves which move away from the site of the disturbance with the velocity of light and impinge upon the transformer windings, with effects which it is the purpose of this section briefly to discuss. The transient voltages are either high-frequency damped oscillations or unidirectional impulses of steep wave-front, and are produced by a variety of causes, among which may be cited switching phenomena, arcing earths, intermittent leakage over the line insulators and lightning. Of these causes experience has shown that transients produced by lightning are more frequent and much more severe than those due to other causes. Direct lightning strokes are very rare, most of the trouble due to lightning being attributable to the electrostatic charges induced upon the transmission lines by clouds over them.

If a positively-charged cloud passes over a transmission line it will induce a negative charge on the upper surfaces of the wires and a positive charge upon their lower surfaces. The positive charge leaks away to earth over the line insulators, so that the line is left negatively charged at zero electrostatic potential. If the cloud is now discharged by a lightning flash to earth, the negative charge on the line will produce a sudden negative potential, the rate and manner of growth of which depends on the type of lightning discharge. If the discharge is oscillatory the induced disturbance on the line will also be oscillatory, while if the discharge consists of a single impulse there will be an impulsive disturbance set up on the line. Numerous records of surges produced by lightning in the field or by surge generators in the laboratory have been made with the kathode ray oscillograph and with the klydonograph, and have shown that these surges may be either positive or negative and may be oscillatory or single impulses. They are invariably of very short duration, not more than a few microseconds, so that the effects of these surge waves upon any apparatus which lies in their path will be in the nature of an impact.

Fig. 147 shows an oscillogram of the largest lightning transient recorded on a transmission line,* attaining 4 500 kV in 1 μsec. and thereafter falling in an oscillatory manner at a much slower rate. The diagram also shows a typical transient of the purely impulsive type, in this case produced by a surge generator. In both cases the surge consists of two parts, (i) the "head" of the wave in which the voltage rises rapidly to a maximum during a very short interval and (ii) the "tail" of the wave in which the voltage gradually dies away. The

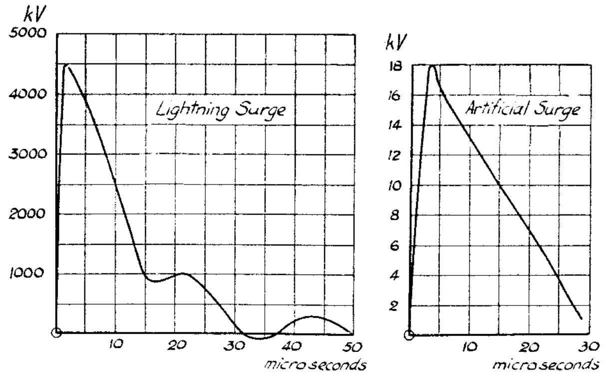


FIG. 147. TYPICAL WAVE-FORMS OF SURGES

head of the surge is responsible for its destructive effects and is equivalent to a small part of a very high frequency oscillation.

The primary winding of a voltage transformer consists of a uniformly-distributed inductance having uniformly-distributed inter-turn self-capacitances and earth-capacitance from each turn to the earthed frame; these capacitances are usually very small. To a reasonably close approximation the self-capacitances can be represented by condensers joined across the terminals of the several coils composing the winding, as C_1, C_2, C_3, C_4 in Fig. 148; in the same way the earth capacitances can be represented by condensers C_{e1}, C_{e2}, C_{e3}, C_{e4} connecting the extremities of the coils to earth. If a voltage of very high frequency or the head of a surge impinges on the h.v. terminal of the transformer, no current will enter the coils because of their great electromagnetic inertia; the inter- and earth-capacitances, on the other hand, present but a low impedance to such high frequency disturbances. Consequently, the initial

* J. J. Torok, "4 500 kV. surge recorded in Arkansas," *Elec. World*, vol. 96, p. 442 (1930).

distribution of potential over the winding when a transient voltage is applied to its terminals is determined entirely by these capacitances and follows some such course as the curve shown in Fig. 148. This shows the well-known result that the initial voltage distribution due to a transient is far from uniform, the voltage gradient being much higher over the turns near the h.v. end of the winding (see also p. 206). For this reason it is very common practice to reinforce the insulation

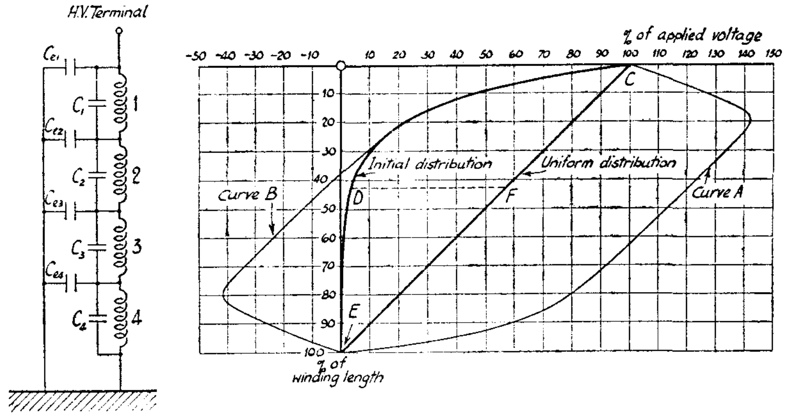


FIG. 148. EQUIVALENT CIRCUIT OF VOLTAGE TRANSFORMER PRIMARY WINDING
POTENTIAL DISTRIBUTION DUE TO SURGE VOLTAGE

of the end turns, but it will be shown later that this is by no means a satisfactory solution of the problem.

After the maximum value of the surge has been reached it begins slowly to decay, the lower rate of change of voltage being equivalent to a low frequency oscillation. The impedances of the capacitances rise to such an extent that the currents taken by them are negligible in comparison with the current that can now flow in the low inductive impedance of the coils. Consequently, the voltage distribution due to the tail of the wave is determined almost entirely by the inductance of the winding and will be uniform, as shown by the straight line in Fig. 148. Passage from the initial non-uniform state to the uniform distribution is not, however, the end of the phenomenon. The winding with its capacitances is an electromagnetic oscillatory system which can be set into free oscillation by the lightning impulse, with the result that the distribution of voltage overshoots uniformity to some such curve as A in the diagram. A further readjustment of the stored magnetic and electric energy during the next half-oscillation causes a return through uniform distribution to a curve such as B. These oscillations are repeated with a period depending upon the inductances and capacitances of the winding and are gradually damped out until the uniform distribution corresponding with normal working conditions is established. The amplitude of the surge oscillations may be greatly increased if the initial impulse has a duration which sets up resonance with the natural frequency of the winding.*

These curves show that the oscillations set up in the transformer by the transient impulse may result in parts of the winding even quite near the earthed end being subjected to voltages and gradients considerably in excess of the values given by uniform distribution. For this reason reinforcement of the end-turn insulation in a transformer likely to be subjected to lightning will not be any guarantee against failure, since breakdown may occur at some point much farther along the winding. Fallou (loc. cit.) has suggested that all grading of the insulation is to be deprecated, and that the whole of the insulation should be capable of withstanding for a very short interval some 20 to 30 times the normal rated voltage to earth.

Numerous methods have been devised with the object of making voltage transformers "surge-proof." The first class of methods consists in the use of external protective devices; the second class involves radical alterations in the construction of the transformer. In both cases the insulation must necessarily be designed to withstand for a short time a voltage much in excess of the normal rated value.

The object of all external protective devices is to modify, by reflection or other means, the shape of the head of the transient disturbance so that it is less steep and consequently less severe in its effect on the transformer. By far the commonest device is a resistor in series with each terminal of the transformer; this resistor is frequently included to limit the fault current (see Section 12) and may thus serve a dual purpose. Part of the energy of the incident wave is absorbed by the resistance, so that the impact upon the winding is lessened. Unfortunately, the magnitude of resistance that will give great

* J. Fallou, "Étude expérimentale des régimes libres et des surtensions par résonance," *Bull. Soc. Franç. des Elecns.*, vol. 6, pp. 237–264 (1926). E. Reimann, "Sprungwellenversuche an Spannungswandlern," *Wiss. Veröff. Siemens Konz.*, vol. 7, part 2, pp. 31–49 (1928).

security against surge effects may be so large that the normal accuracy of the transformer is affected. This objection does not apply to the use of a choking coil in series with each pole. At high frequencies the impedance of the coil is very great, so that the head of the wave is unable to penetrate into the transformer, the wave being reflected at the choking coil terminal. At normal frequencies the low impedance of the coil results in a very small impedance volt-drop and a negligible effect upon the accuracy of the transformer. Fig. 149 shows a method of mounting the choking coils under oil in a 33 kV transformer (Metropolitan Vickers). A second example of inductive protection is provided by the "Microfusible" illustrated in Fig. 146, the small transformer supplying the fuse acting as an effective surge coil.

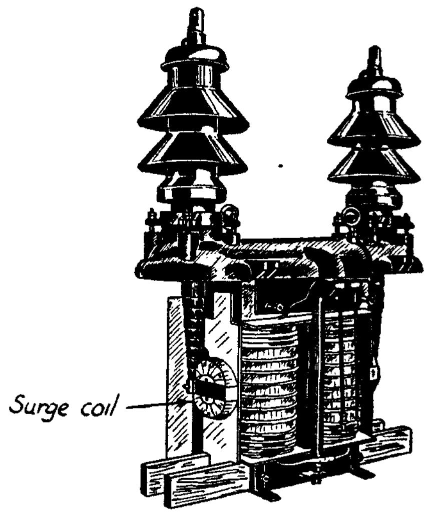


FIG. 149. SURGE COILS IN A 33 KV OUTDOOR VOLTAGE TRANSFORMER

The object of all other methods for rendering a transformer surge-proof is to modify the internal capacitances* in such a way that the initial voltage distribution due to a surge is uniform; consequently, there can be no oscillation set up and no danger of resonance over-voltage. Such a transformer is termed *non-resonant*, uniform distribution being obtained at all frequencies. Referring to Fig. 148, the self-capacitances C_1, C_2, C_3, C_4 are all approximately equal; hence a uniform distribution of voltage at high frequences would be secured if the currents in these capacitances were equal. This is not so, however, since the earth currents flowing through the earth

* H. L. Thomas, "Lightning and its influence on transformer design," *B.T.H. Activities*, vol. 7, pp. 97–100 (May–June, 1931); W. M. Dann, "Surge testing of potential transformers," *Elect. J.*, vol. 30, pp. 145–146, 150 (1933); H. Heyne, "Ein Rundgang durch die Amerikanischen Transformatorenfabriken," *Elekt. Zeits.*, vol. 55, pp. 901–904 (1934); *C.M.*, "De quelques moyens spéciaux de protection des transformateurs contre des ondes à front raide," *A.C.E.C. Rev.*, No. 144, pp. 137–152 (1934).

capacitances must pass through the self-capacitances and will cause unequal drops of voltage in them. To overcome this the G.E.C. of America and the B.T.H. Co. apply an insulated shield outside the winding, one point in the shield being joined to the h.v. terminal, in such a way that capacitances C_{s2}, C_{s3}, C_{s4} are introduced between the coils and the shield. Fig. 150 (*a*)

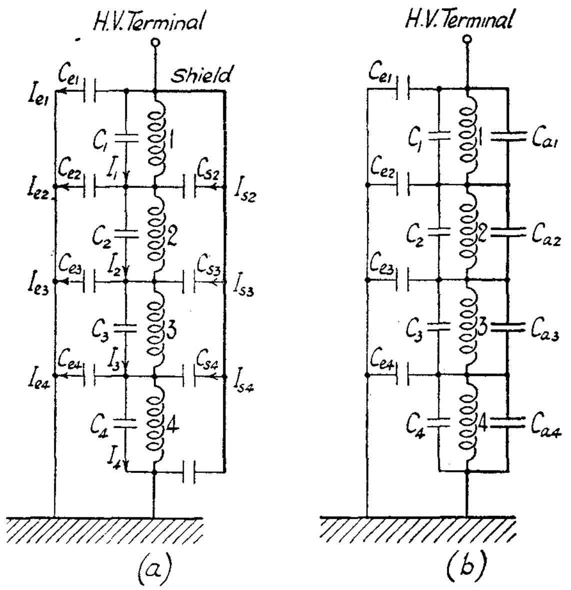


FIG. 150. METHODS FOR SECURING UNIFORM VOLTAGE DISTRIBUTION DUE TO A SURGE

shows that I_1, I_2, I_3 and I_4 will be equal if the currents flowing from the shield are equal to the earth currents, i.e. if $I_{s2} = I_{e2}$, $I_{s3} = I_{e3}$, $I_{s4} = I_{e4}$. By suitably proportioning and placing the shield this condition is readily satisfied in practice. The voltage transformers in use on the 132 kV section of the Grid are shielded in this way, Fig. 151 showing the internal construction. These transformers are 15 ft. 3 in. high to the top of the bushing and weigh 7 000 lb. with oil. Advantage is taken of the uniform voltage distribution to grade the insulation between the h.v. and secondary windings, resulting in a smaller transformer for a given rating

A similar principle is used in the Fischer dry-type transformer described on page 242 and illustrated in Fig. 119, where the capacitance between the rhombus-shaped metallic layer and the primary winding

tends to equalize the surge voltage distribution. The arrangement works excellently in practice.

A second method, used by the Westinghouse Co. of America, is artificially to increase the self-capacitances of the windings by the use of shields and barriers which introduce auxiliary capacitances C_{a1}, C_{a2}, C_{a3}, C_{a4}, which are large in comparison with the natural capacitances of the system (see Fig. 150 (*b*). The initial surge-voltage distribution will be almost entirely determined by these auxiliary capacitances, which can be so proportioned as to make the distribution uniform.

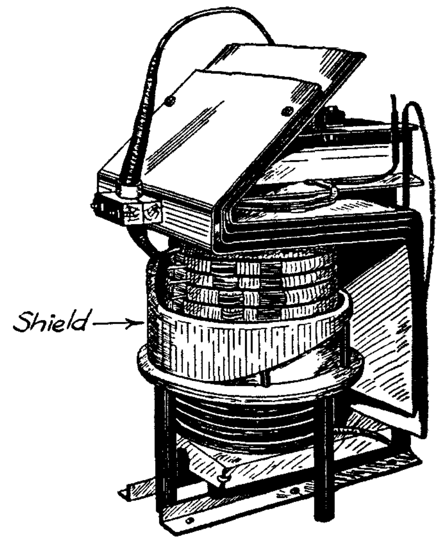


FIG. 151. B.T.H. SHIELDED SURGE-PROOF VOLTAGE TRANSFORMER FOR 132 KV CIRCUIT

A third method, used by the Ateliers des Constructions Électriques de Charleroi, will be understood by reference to Fig. 148. The part *DE* of the initial curve is sensibly straight; it follows, therefore, that if the part *CD* could be straightened and brought up to *CF* the initial distribution would be uniform. This result is secured by interpolating between the first few coils of the winding at the h.v. end insulated metallized rings; these have the effect of increasing the self-capacitance of the first coils and produce the desired result. Earth capacitance currents are minimized by the use of guard rings at the top and bottom of the primary winding; this alone can have quite a beneficial effect on the voltage distribution.

The A.C.E.C. (loc. cit. *ante*) have recently published some interesting comparative tests made on the same transformer when protected in all these various ways; the results are shown by the initial voltage distribution curves in Fig. 152. This diagram is self-explanatory, and clearly shows the close approximation to uniform surge-voltage distribution that can be obtained by the several methods.

Voltage rises of a permanent or semi-permanent kind may be caused in three-phase circuits by defective switching of