33

Power Transformers

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Contents

33.1 Introduction

A transformer consists essentially of two or more electric circuits in the form of windings magnetically interlinked by a common magnetic circuit. An alternating voltage applied to one of the windings produces, by electromagnetic induction, a corresponding e.m.f. in the other windings, and energy can be transferred from the primary circuit to the other circuits by means of the common magnetic flux.

References to various specialist papers relating to design and operation of power transformers are given at the appropriate points in the text and listed at the end of this chapter. A recommended comprehensive textbook on all aspects of transformer design is *Large Power Transformers*.[1] The relevant British Standard Specification[2] is *BSEN 60076-1:1997. Power Transformers*. BSEN 60076 contains information relating to standard characteristics, guaranteed performance and tolerances, testing and operation, and conforms with the International Electrotechnical Commission (IEC) *Publication 60076: Power transformers: Parts 1 to 12*.

The British electricity supply industry issued a series of documents relating to transformers. All are listed in The Electricity Council's *Catalogue of Engineering Documents* and the more important are:

ESI Standard 35-1: Distribution transformers (from 16 kV A to 1000 kVA) (1985)
ESI Standard 35-2: Emergency rated system transformers (35/11.5 kV) (1982)
British Electricity Board Specification (BEBS) 72: Transformers and reactors (1966). In 34 sections, this specification relates to large transformers above 20 MVA
BEBS T3 Transformers for 33 kV and 22 kV systems (up to 20 MVA) (1962)

These documents are no longer maintained under revision by the Electricity Council as most Electricity Companies are now developing Functional Specifications, but they are available on demand.

33.2 Magnetic circuit

The magnetic circuit, or core, provides a closed ferromagnetic path for the flux. To prevent excessive eddy current loss within the metal of the core itself it must be laminated in a plane parallel to the flux path and the individual laminations must be insulated from each other.

33.2.1 Core steel

For many years power transformer core laminations were cut from sheets of special 4% silicon steel produced by a hot-rolling process. During the 1940s, an improved material was developed, known as cold-rolled grain-oriented strip (c.r.o.s.). This material has a silicon content of approximately 3% and is produced in strip form in rolls of up to 5 t.

Because of the effect of the cold-rolling process on the grain formation, the magnetic properties in the rolling direction are far superior to those in other directions.[3,4]

A heat-resistant insulation coating is applied by thermochemical treatment to both sides of the steel during the final stage of processing. The coating is approximately 1 μm thick and has only a marginal effect on the stacking factor.

Traditionally, a thin coat of varnish had been applied by the transformer manufacturer after completion of cutting and punching operations, but improvements in the quality and adherence of the steel manufacturer's coating and in the cutting tools available have eliminated the need for the second coating and its use has been discontinued.

Guaranteed values of loss (in watts per kilogram) and apparent power (in volt-amperes per kilogram) apply to magnetisation at 0° to the direction of rolling. Both real and apparent power loss increase significantly (by a factor of 3 or more) when c.r.o.s. is magnetised at an angle to the direction of rolling. Guarantees do not apply and the transformer manufacturer must ensure that a minimum amount of core material is subject to cross-magnetisation. This is to minimise the total core loss and (equally importantly) to ensure that the core temperature in the area is kept within safe limits.

Cold-rolled grain-oriented strip cores operate at nominal densities of 1.6–1.8 T. This compares with 1.35 T used for hot-rolled steel, and is the principal reason for the remarkable improvement achieved in the 1950s in transformer output per unit of active material. British c.r.o.s. steel is produced in two magnetic qualities (each having two subgrades) and four thicknesses (0.23, 0.27, 0.30 and 0.35 mm), giving a choice of seven different specific loss values. In addition, the designer can consider using Japanese-made steel of higher quality, available in three thicknesses (0.23, 0.27 and 0.3 mm).

The decision on which grade to use for a particular application depends on the characteristics required in respect of impedance and losses, and particularly, on the assigned capitalised value of the iron loss. The higher labour cost involved in using the thinner materials is another factor to be considered. The different materials are identified by code names. For example, the material previously known as 27 MOH is now called 103-27-PS, where the digits signify:

103: a guaranteed 50 Hz specific loss at B = 1.7 T of 1.03 W/kg;
27: a thickness of 0.27 mm; and
P5: the steel manufacturer's code for the higher quality steel previously identified by suffix 'H'.

The lower grade material is known as N5 and the first figure in the code is then an indication of the loss per kilogram at B = 1.5 T, e.g. the complete code might be 089-27-N5 (loss = 0.89 W/kg).

The Japanese grade ZDKH steel is subjected to laser irradiation to refine the magnetic domains near to the surface. This process considerably reduces the anomalous eddy current loss but the laminations must not be annealed after cutting.

33.2.1.1 Cutting and punching

Cold-rolled grain-oriented strip is produced in the form of strip up to about 850 mm wide. In the past it was common practice for the transformer manufacturer to buy full-width coils and slit these to the width required. It is now more usual to purchase the strip ready cut to width. This is more expensive unless the manufacturer has a very high turnover of core laminations, but the extra cost is offset by the elimination of the slitting operation and the wastage incurred by ever-increasing stocks of unused off-cuts. The only cutting process now undertaken by the transformer manufacturer is to crop to length by guillotine.

Where bolt-holes are employed, it is preferable to use a single hydraulic press to crop the strip material to length and punch bolt-holes simultaneously. Following cutting and punching, the individual laminations may need to be dressed to remove any edge burrs, but as deburring may harm the magnetic properties of the material, it is preferable that high quality cutting tools are maintained in good condition so that deburring is unnecessary.

Cutting and punching adversely affect the magnetic properties of the material and, until recently, it has been considered desirable that the finished laminations (or for small units the complete cores) should be stress-relief annealed to remove cutting strains. Various types of annealing furnace have been used, including the batch furnace and the continuous belt furnace, in which small stacks of laminations (up to 10 or 12 plates deep) pass slowly through a heating zone at about 800 °C in an inert atmosphere of nitrogen. In the single-sheet roller hearth furnace, single laminations pass relatively rapidly through the heating zone; with this furnace the laminations are in the heated zone for a comparatively short time and it is unnecessary to provide an inert atmosphere to prevent oxidation.

The elimination of bolt-holes and improvements in cutting tools have led to a reduction in cutting strains and in the loss thereby incurred. The margin for reducing loss by annealing has been reduced and the process has generally been discontinued. (There is, for instance, obviously proportionately less area affected by cutting strains in a wide lamination than in a narrow one. As a rough guide, annealing is not considered to be necessary for strip over 200 mm wide.)

Although c.r.o.s. is now used for virtually all 'power' transformer cores from 1 kVA upwards, there are other special low-loss steels (e.g. Mumetal) used for the cores of instrument transformers. These materials have markedly superior magnetic properties (i.e. magnetising vars and power loss) at low densities, but they saturate at much lower levels than c.r.o.s. They are therefore not economic for power transformers, where the advantage of a high operating flux density overrides all other factors.

33.2.2 Magnetic circuit design

The two fundamental types of construction used, shown diagrammatically in *Figure 33.1*, are known as *core* and *shell*, respectively. The normal arrangement of a core-type transformer is for circular primary and secondary windings to be arranged concentrically around the core leg of substantially circular cross-section. In the shell type the magnetic circuit is of rectangular cross-section formed by a stack of laminations of constant width. The coils are straight-sided and the primary and secondary windings are interleaved in a sandwich fashion. The number of alternate high-voltage/low-voltage groups is dependent upon the required reactance characteristics of the transformer.

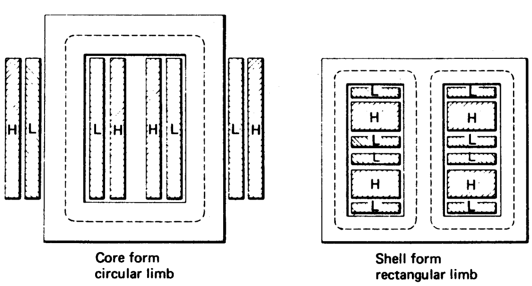

Figure 33.1 Basic cell and magnetic circuit arrangements

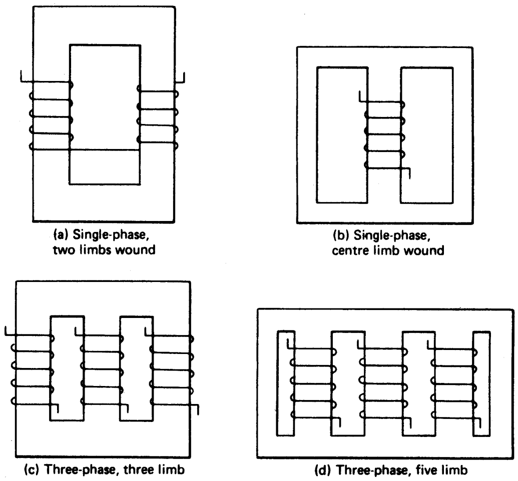

Figure 33.2 Core arrangements

In the UK the core-type transformer is used for all power-system applications. The shell form is used only for special applications, usually where very heavy current low-voltage outputs are required for such purposes as electric arc furnaces or short-circuit testing stations. The shell form is also used in the USA, France, Spain, Portugal and Japan for power transformers of the largest sizes and highest voltages. The fact that both core- and shell-type transformers have existed side by side for many years indicates that neither has any significant economic advantage. There is, however, a discernible trend away from the shell towards the core type of construction, due entirely to economic considerations.

Core-type transformers (circular coils on circular limbs) are built in various forms, as shown in *Figure 33.2*. The choice is dictated by the type of winding or the need to meet transport loading restrictions. Thus, a five-limb core will have a smaller overall height than a three-limb core for a three-phase transformer. A very large high-voltage single-phase transformer might also have to be designed with a multi-limb core.

The basic parameters of the core are: (a) the core circle diameter, (b) the yoke height, (c) the limb centres, and (d) the limb length. The normal practice in a design office is that the first three are related to a range of fixed standards, while a limited variation on core size is secured by change of limb length. The relation between the core circle diameter D and the rating S of a transformer is given approximately by

$$D = k(S)^{1/4}$$

where k is a constant depending on the type of transformer.

Thus, if a 500 kVA transformer has core circle diameter of 190 mm, then a 1000 kVA transformer of the same voltage ratio and service conditions would have $D = 220$ mm approximately. The actual diameter adopted would depend on the nearest standard diameter available.

The e.m.f. per turn E_t is a function of the frequency f, the peak flux density B_m and the net core area A_i:

$$E_t = 4.44 f B_m A_i$$

33.2.2.1 Limb space factor

To obtain the most economical use of core steel and copper it is essential to utilise as much as possible of the available

Table 33.1 Core utilisation factors

No of steps	1 (square)	2	3	4	5	6	7
Fraction of core circle areas	0.64	0.78	0.85	0.89	0.91	0.92	0.94

core circle. Consequently, the limb sections are built in steps; the greater the diameter, the larger the number of steps. Optimum utilisation factors for cores with 1–7 steps are given in *Table 33.1*.

In practice these areas are reduced by the lamination stacking factor, depending on the thickness of the interlaminar insulation and the tightness of the core clamping. With the latest core steel insulation and without varnish, stacking factors of up to 97% can be achieved. With large transformers allowance must be made for loss of area due to cooling ducts in the core, and the area will also be affected by the relative size of the individual core steps, which can depend on the width necessary to accommodate core clamping plates.

Cores having more than seven steps (up to as many as 15 or more) are common, but the improvement in utilisation decreases with an increasing number of steps and is offset from the production point of view by the increasing complexity involved in producing a greater number of widths.

33.2.2.2 Yoke dimensions

As the yoke height is not restricted by a winding, the area selected may be larger than that of the corresponding limbs. Dissimilar steps between the limb and yoke packets, however, can give rise to cross-flux, and the resultant increase in core loss may offset benefits accruing from the greater yoke area; this factor is of particular significance with c.r.o.s. Apart from very small cores, modern practice is to step the yoke and limb sections in a similar, or preferably identical, manner.

When the magnetic circuit is completed by a single-path yoke, e.g. a one-phase two-limb core (*Figure 33.2*(*a*)), or a three-phase three-limb core (*Figure 33.2*(*c*)), yoke areas at least equal to the limb section are necessary. Where the yoke path is split, the yoke area can be appropriately reduced, e.g. with a one-phase centre-limb-wound core (*Figure 33.2*(*b*)), the yoke area can be halved, and with a three-phase five-limb core (*Figure 33.2*(*d*)), the yoke area can be reduced to about 0.55–0.6 of that of the corresponding limb.

33.2.2.3 Core clamping and core joints

Bolt-holes cause local flux deviation and crowding, which results in increased noise and loss. These effects have led to the development of boltless cores, which are held together by circumferential bands. These bands are sometimes of steel with suitable insulated sections, but synthetic-resin-impregnated glass fibre tape is preferable, as it eliminates any risk of the band becoming involved in an electrical failure or becoming overheated owing to eddy currents. Banded cores are now used even in the largest transformers. Other methods of clamping include bolts passing through oil ducts in the core to avoid holes in the sheet, and reduction of the bolt area by the use of high-tensile steel.

The introduction of c.r.o.s. necessitated a modification of the traditional rectangular overlap (*Figure 33.3*(*a*)) between yoke and leg laminations commonly used with hot-rolled

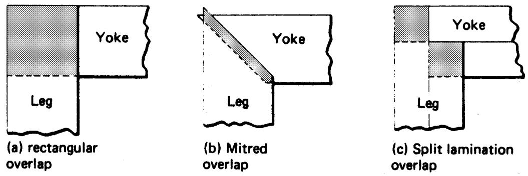

Figure 33.3 Types of joint in cores (shaded portions indicate overlap areas)

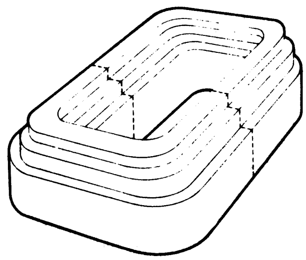

Figure 33.4 Strip-wound core (cuts in legs for butt-jointed core are shown by the dotted line)

strip cores. To achieve minimum loss by taking maximum advantage of the directional properties of c.r.o.s., the area overlap has been minimised by means of mitred joints (*Figure 33.3*(*b*)). The affected area can also be reduced by using split laminations (*Figure 33.3*(*c*)), with the split joint butted in small cores, or separated to form a cooling duct in the case of large cores.

By eliminating core joints, or by arranging that joints do not disturb the optimum flux path, maximum advantage can be taken of c.r.o.s. Such conditions are achieved with the wound core (*Figure 33.4*). This construction is widely used for transformers up to 25 kVA, the limitation in rating being imposed by special coil-winding requirements which involve a split former so that the coils can be wound on the completed core. A variation called a C core, of slightly reduced efficiency, is a wound core cut across the centre of the leg section, thus involving a butt joint in each limb.

33.2.2.4 Core building factor

The total core loss divided by the total mass of the completed magnetic circuit gives the specific loss of the built core. If this figure is divided by the specific loss of the material used (from tests on samples or from the steelmaker's guarantee), the result is the core building factor, a measure of the effectiveness of the magnetic circuit design. Building factors vary with the size of core, smaller cores generally giving factors near to unity. Building factors for large cores can be kept to less than 1.2 if full attention is paid in the design to make the best use of the directional properties of the steel.

33.2.3 Magnetic circuit characteristics

The magnetic circuit characteristics are the no-load core loss and the magnetising current. The former is commonly divided into hysteresis and eddy current components. The hysteresis loss depends on the peak flux density and the frequency, while the eddy current loss depends on the r.m.s.

flux density and on the degree of subdivision (i.e. lamination) of the core. The specific loss components are given by

$$p_h = k_h f B_m^n \quad \text{and} \quad p_e = k_e f^2 B^2 t^2$$

where B_m is the peak and B the r.m.s. flux density, f is the frequency, t is the lamination thickness, and k_h and k_e are constants for a given material. The exponent n is empirical, with a value generally not very different from 2.

The measured no-load loss includes I^2R loss due to the no-load current; and dielectric loss (especially for large high-voltage transformers); these components can often be neglected.

The no-load current I_0 can be taken as comprising an active component I_{0a} in phase with the applied voltage V and accounting for the no-load power input P_0, together with a reactive or magnetising component I_{0r} (*Figure 33.5*). The two components are not physically separable, as both are concerned together in the magnetisation of the core. The no-load current is normally expressed in terms of the full-load current as a percentage or per-unit (p.u.) value. For distribution transformers in the range 500–1000 kVA and built of c.r.o.s., the no-load current is of the order of 1.5% (0.015 p.u.). Values for large high-voltage transformers may be less than 0.5%.

The saturation characteristic of the steel is such that the no-load current increases rapidly when the transformer is overexcited. If with c.r.o.s. the normal peak density is 1.6 T, the no-load current will be at least doubled by a 10% overvoltage. Further, the harmonics in the current waveform will be substantially increased. Provided that the circuit connections permit, the most pronounced harmonic is the third, although fifth and seventh harmonics can become significant at high densities. If the circuit connections do not permit third-harmonic currents to flow (in a three-phase transformer there must be either a neutral connection to a source of zero sequence current, or a delta connection within the transformer in which third harmonics can circulate), the flux waveform will distort because of the lack of the component. The distortion appears as a third-harmonic ripple in the secondary line-to-earth voltage.

This effect is most noticeable in single-phase transformers or in a five-limb, three-phase core. In both cases there is a free path in the core for a third harmonic component in the main flux. In a three-phase, three-limb core a third harmonic in the flux is in phase in each limb and the lack of a return ferromagnetic path results in the suppression of the third harmonic components. The effect on the magnetising current is that, although there is not any true third harmonic therein, there is a triple frequency component divided 1:2:1 in the core. To a large extent this satisfies the need for a third harmonic and the distortion of the flux wave (and hence of the output voltage) is negligible.

The magnetic path length associated with the central phase of a three-phase three-limbed core-type transformer (*Figure 33.2*(*c*)) is significantly shorter than that of either of the outer phases. The configuration shows that the outer path lengths include two half-yokes in addition to the limb. As a consequence, the magnetising current and core loss values are asymmetric, to an extent depending on the path length ratio. If the central path length is one-half that of either outer, then its magnetising current is likely to be about 30% less, and this is independent of the peak flux density level.

33.2.3.1 Magnetising inrush current

When a transformer is 'switched-in' on no load, it may take an initial *inrush* current greatly exceeding normal no-load value, and sometimes greater than full-load current. The inrush transient decays to normal no-load level within a few periods. The first peak depends on the voltage at the instant of switching, and on the magnetic state of the core as left after the previous switching-out. If the instant of switch-on corresponds to a voltage zero, the flux must, in the first half-period, produce a complete change of $2\Phi_m$ from zero, as shown in *Figure 33.6*. The peak flux therefore rises to twice normal peak Φ_m. The maximum flux reached will be increased to $(2\Phi_m + \Phi_1)$ if there is a residual flux ϕ_1 already present in the core in the same direction as that to be taken by the first half-cycle of flux growth. These high-flux conditions demand very high peaks of exciting current with large harmonic content. As the core steel will saturate, much of the flux will follow an 'air' path, and the peak inrush current is consequently influenced by the area enclosed by the winding excited.

Under adverse conditions the magnitude and asymmetry of inrush currents may cause maloperation of overcurrent or balanced forms of protection, but in practice the worst conditions are statistically unlikely, and terminal voltage drop will reduce the peaks. In a three-phase transformer the inrush conditions must differ for each phase.

33.2.3.2 Magnetostriction

Magnetostriction is a property of magnetic material whereby a small change in linear dimensions (usually an elongation) follows the flux cycle in a complex pattern. In transformer steel the linear change is a few parts in a million. It causes vibration of the core at twice supply frequency and at multiples thereof, producing sound waves. Magnetostriction in the material of the core is the main source of transformer noise.

33.2.3.3 Noise

The unremitting hum of a transformer installed in a residential area can lead to complaints and in extreme cases to legal action. Careful design and manufacture is necessary to ensure that the noise emitted is within the level normally

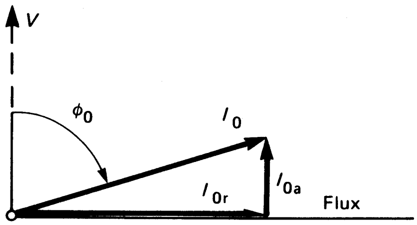

Figure 33.5 Phasor diagram of no-load current

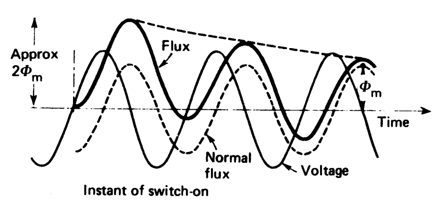

Figure 33.6 Flux transient for switching at voltage zero (no residual)

accepted as reasonable for a given size of transformer. The Electricity Supply Industry Standards (*ESI 35-1 Distribution transformers up to 1000 kVA* and *ESI 35-2 Emergency rated system transformers*) and British Electricity Board Specification (BEBS) T2 for the large units contain curves relating MVA rating and noise level which form part of the manufacturer's contractual obligations. BEAMA publication No. 227, *Guide to Transformer Noise Measurement,* is a useful reference work on the subject. IEC 60076-10 describes the way in which sound measurement tests are made.[5]

If it is expected that the noise emitted from a particular installation may create a nuisance, various mitigating measures are possible, including the following:

(1) Specifying a noise level less than the normal standard. Usually not economic (or even feasible) if reductions of more than about 10 dB below the standard level are likely to be necessary.
(2) Concealing the transformer behind a screen of trees or a wall. Sometimes the psychological effect is greater than the actual measured reduction in noise level at the point of complaint.
(3) Completely enclosing the transformer in a 'sound-proof' housing. This is expensive, as obviously special measures have to be taken to emit heat without emitting noise.
(4) A combination of (2) and (3) in which specially designed coolers form a screen wall completely surrounding the transformer. When introduced in the 1960s this appeared to be a promising development from the point of view of amenity in respect of both appearance and noise, but the idea never became popular.

In certain applications in Germany and Austria it has become necessary to install transformers with a very low noise level, up to 20 dB below the UK standard levels. In these cases it is necessary to design the transformers to operate at nominal flux densities of 1.2–1.4 T.

33.3 Windings and insulation

Because of their direct association with power systems, the windings and associated insulation are the most vulnerable parts of a transformer. They must be designed and constructed to withstand the voltage stresses and thermal conditions of normal service, the mechanical and thermal stresses resulting from system faults and short-circuits, and transient overvoltages such as those generated by lightning and switching. The core and windings together must meet specified impedance and loss requirements. In view of the almost total predominance in Britain of core-type transformers, the following section relates only to windings for this type.

33.3.1 Types of coil

The simplest *helix* coil consists of a single layer, formed by turns lying directly side by side, extending over the axial winding length. Each turn may comprise a single conductor or a number of conductors in parallel, the helix at each end of the coil being supported by a suitably shaped edge block to give adequate mechanical strength in an axial direction (*Figure 33.7(a)*). This type of coil, single or double layer, is used for the low-voltage windings of small and medium-sized transformers.

When the current rating necessitates a large number of conductors in parallel for each single turn, the individual

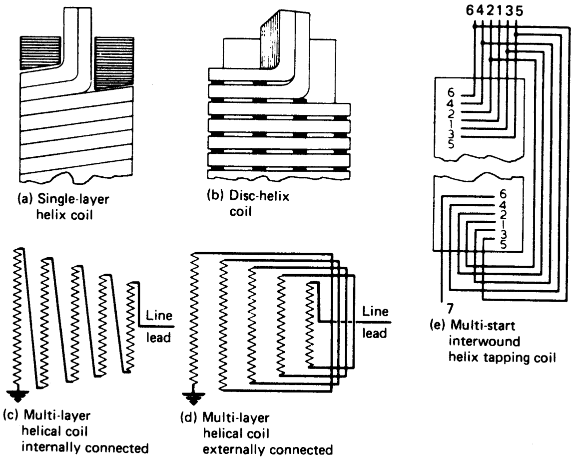

Figure 33.7 Forms of coil

strips can be laid one above the other in a radial direction, as either a single column or two columns in parallel, each turn or column separated by spacers to provide sufficient cooling surface (*Figure 33.7(b)*). This type of coil, sometimes termed a *disc helix,* is used for the low-voltage windings of large transformers.

Multilayer helix coils can be employed for the high-voltage windings of large transformers. Because of the high capacitance between the individual layers, this type of winding has good inherent strength against incoming surge voltages. It is fairly simple to calculate the surge response of the multilayer winding, but difficult to ensure that the long thin layers of conductors have adequate strength to resist axial forces. As ratings increase for a given primary service voltage, a *disc* coil (see below) becomes relatively less difficult to design from the point of view of predicting surge strength and more satisfactory because of its high inherent strength against axial forces. The use of the multilayer helical coil is thus generally confined to the smaller megavolt-ampere ratings of any given voltage class above about 200 kV.

This type of coil shows particular advantage when the transformer neutral is directly earthed. The inside layer of the winding is then near earth potential, thus reducing the major insulation between high- and low-voltage windings. The length of the individual layers decreases progressively towards the outer layer to provide increased insulation to-earth at the line end. Interlayer connections, usually top-to-bottom, can either be arranged internal to the coil between the layers, or formed by external joints (*Figure 33.7(c, d)*). Multilayer coils are often used for the high-voltage windings of small distribution transformers, in this case wound as continuous layers, with top-to-top and bottom-to-bottom interlayer connections.

Another form of layer coil is a *multistart interwound* helix employed for the separate tapping windings of large transformers when a considerable range of voltage variation is required. The coil is so arranged that each single conductor forms one tapping section, with the requisite turns distributed over the winding length to provide axial ampere-turn balance for the various tapping positions. The individual conductors are physically located so that the voltage between them is reduced to a minimum (see *Figure 33.7(e)*).

A *crossover or bobbin* coil is wound on a former between side cheeks. It is, in effect, similar to a multilayer winding, except that the layers are short. The interlayer insulation needs to be extended at the ends to guard against failure by creep at the edges; alternatively, it can be folded round the last turn of each layer, or the overhang crimped to form a trough of depth equal to the thickness of the conductor. The assembly of separate coils is connected in series, with horizontal cooling ducts provided by spacers between the individual coils. Intercoil connections are usually made back-to-back and front-to-front, with adjacent coils reversed. Back-to-front connection requires insulation of the intercoil connections corresponding to the voltage developed across the coil (see *Figure 33.8*). Cross-over coils, generally of round wire, are employed for the high-voltage windings of distribution transformers up to about 1000 kVA.

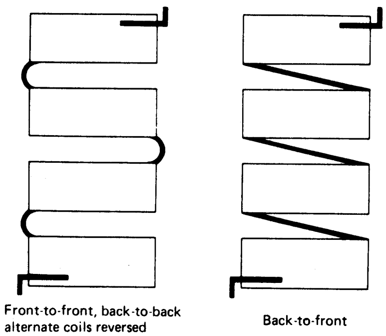

Figure 33.8 Cross-over coils: intercoil connections

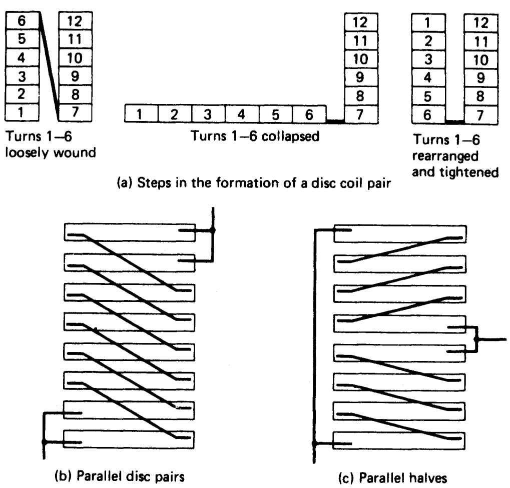

Figure 33.9 Disc coil windings

Because of the increase in the cost of copper, more attention is being paid to the use of aluminium for transformer windings. Aluminium is a less effective conductor than copper, but despite this intrinsic disadvantage (which results in a larger transformer for a given efficiency) there is a net saving in overall cost. Aluminium strip can be used to wind any of the types of coil described above, but it is also uniquely used in foil form. This is because aluminium can be rolled to a thinner and more flexible foil than copper. The foil is used in bobbin-type coils of one turn per layer with intercoil connections as shown in *Figure 33.8*.

The *disc* coil differs from other windings in that adjacent turns, consisting of strip conductor, are wound one above the other in a radial direction from the centre outwards; thus, the coil might be compared with a cross-over coil comprising one turn per layer. To achieve the required disposition of turns, the coils are formed in pairs, the requisite turns for one disc being loosely wound so that the conductor finishes in a position to provide the start of the inside turn of the second disc, which can then be wound from the inside outwards, the turns of the first disc being rearranged by folding one inside another in such a manner that the start of the coil is located as an outside turn (*Figure 33.9*(*a*)). The coil is then tightened to remove slack from the reformed disc.

Disc coils can be wound either as individual pairs, which are then assembled and connected in series by external joints, or as a continuous winding where, following formation of one pair, the procedure is repeated without cutting the conductor or removing the coil from the lathe. The continuous coil avoids assembly and joining and saves joint space, an advantage with an inside winding. For large currents the coils can be wound with multiple conductors, or constructed as separate parallel connected pairs (*Figure 33.9*(*b*)). Alternatively, two half-windings, one half reversed with respect to the other, can be stacked as in *Figure 33.9*(*c*) with the line connection taken from the centre of the stack; this method is common for large high-voltage transformers having a directly earthed neutral. Horizontal cooling ducts are provided by spacers between individual discs and between disc pairs.

The disc coil is a general-purpose winding element, applied to the higher-voltage windings of transformers above 1 MVA up to the highest ratings and voltages, and also for the lower-voltage windings (normally 33 kV upwards) of medium and large power transformers. *Table 33.2* gives a survey of typical applications of the various forms of winding.

33.3.2 Insulation

Materials of classes A, E, B, F, H and C (in temperature sequence) are recognised in IEC 60076 as being suitable for transformers. A, B, H and C are most common, but F is being used to an increasing extent. All these are employed in dry-type transformers, the silicon treated materials being

Table 33.2 Transformer windings

Service	*Rating* (MVA)	*High-voltage winding*		*Low-voltage winding*	
		kV	Type	kV	Type
Distribution	<1	11, 33	Foil, cross-over or multilayer	0.43	Helix
System	1–30	33, 66	Disc	11	Disc, helix or disc-helix
Transmission	>30	132–500	Disc or multilayer	11, 33, 66	Disc or disc-helix
Generator	>30	132–500	Disc or multilayer	11–22	Disc-helix

advantageous (but at extra cost) by reason of their water-repellent properties. For windings immersed in hydrocarbon oil (BSEN 60296) or in synthetic liquids, the coil insulation is usually a class A material. Cotton is confined to small units, with paper and paper derivatives used for most purposes up to the largest ratings; but synthetic enamel is widely used as interturn insulation in small transformers and in the low-voltage windings (up to about 17.0 kV) of large transformers.

Most power transformers are immersed in hydrocarbon oil. To reduce fire risk, chlorinated biphenyls (e.g. Pyroclor) were used in the past, but as these liquids are toxic (and difficult to dispose of safely), they have virtually been banned on environmental grounds. Silicone based liquids and synthetic esters are available without these disadvantages, but they are relatively expensive, and the varnishes and binders usable with hydrocarbon oil may not be suitable for use with silicone fluids. Where fire risk is unacceptable, air-cooled 'dry'-type designs with glass and epoxy resin insulation are usually preferred. Gas filled transformers using electronegative sulphur hexafluoride gas (SF_6) at low pressure for distribution transformers and up to 6 atm for high-voltage power transformers eliminate fire risk, but the cost is high, the force-cooled heat exchangers are complicated, and the transformers have short thermal time constants, giving reduced overload capability. However, they are particularly suited to underground installations, and where land prices are high they can be justified when the cost evaluation recognises that no fire-fighting equipment is necessary.

33.3.2.1 Insulation design

For transformers of small and medium size, the inner (low-voltage) winding is insulated from the core by pressboard or a synthetic resin-bonded paper (s.r.b.p.) cylinder, with axial bars of pressboard or equivalent material arranged round it to form cooling ducts for the inside surface of the winding. With disc or disc-helix coils, the bars have a wedge section on which intercoil or interturn dovetail-slotted spacers can be threaded. Similar bars are placed over the outer surface of the inner winding and, if necessary, between layers of a helix winding. The main high-voltage/low-voltage insulation is provided by another pressboard or s.r.b.p. cylinder. The arrangement of bars and spacers is repeated for the outside (high-voltage) winding. Insulation to earth at the ends of the windings takes the form of blocks keyed to the axial bars in line with the spacers, to form a series of columns round the windings by which the windings can be effectively clamped. The cross-section of a typical arrangement is shown in *Figure 33.10*.

Insulation arrangements for dry-type transformers are similar to those described, except that the materials chosen

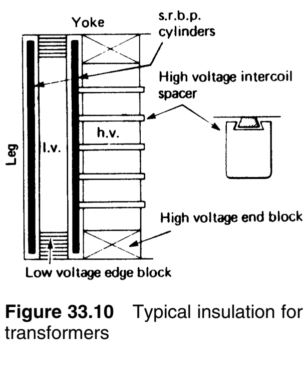

Figure 33.10 Typical insulation for small and medium-sized transformers

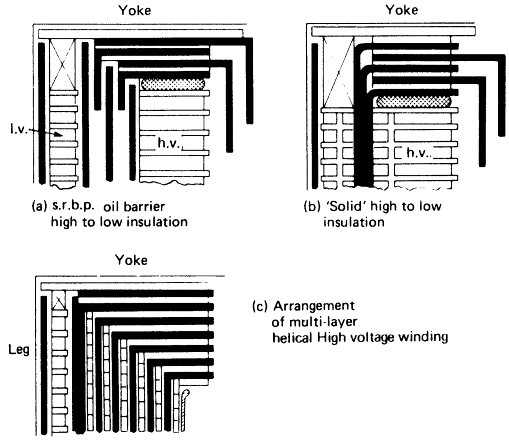

Figure 33.11 Insulation design

are appropriate to the insulation class. For example, the cylinders and bars can be made from suitably impregnated glass fibre; ceramic materials may be used for the coil spacers and glass tape for interturn insulation.

When operating voltages are such that thick major insulation is required between windings, it is customary to use a number of concentric thin-walled cylinders, spaced by axial bars, the insulation being carried round the ends of the outer (high-voltage) winding by means of flanged collars interfitting with the ends of the tubes (*Figure 33.11*(*a*)). Alternatively, with high-voltage windings at above 110 kV, so-called *solid* insulation can be used, comprising layers of pressboard or paper wound directly over the inner winding, the high-voltage winding being assembled directly over the outer layer, with cooling ducts transferred from the inside turns to some point in the winding. In this case the pressboard or paper wraps are extended beyond the axial winding length and flanged at the ends to assist with the insulation to earth (*Figure 33.11*(*b*)). A combination of s.r.b.p. cylinders and pressboard wrappings can also be employed, the wrappings being located over the outer cylinder again flanged at the ends. Further, the s.r.b.p. tube can be manufactured such that the bonding is limited to the central portion, leaving the ends plain so that these in turn can be flanged.

With multilayer helical high-voltage windings, the interlayer insulation is provided in the form of a combination of paper or pressboard wrappings, and bars for cooling ducts, with the paper between the individual layers flanged at the ends (*Figure 33.11*(*c*)). When internal interlayer connections are involved (*Figure 33.7*(*c*)), the interlayer paper wrappings may be formed in tapered halves so that the maximum thickness of insulation is provided at appropriate places between the actual connection and the layers. Paper is used almost exclusively for the interturn insulation of high-voltage windings.

33.3.3 Winding design

The main factors to be taken into account in winding design are:

(1) To provide adequate insulation strength to withstand (a) power frequency applied or induced overvoltage tests to prove the insulation to earth and between windings; (b) an induced voltage test for internal winding insulation (interturn, intercoil and between phases);

(c) an impulse voltage test to prove the ability of the insulation structure to withstand transient overvoltages such as may result from atmospheric surges; and (d), in some cases, a switching surge test to prove the strength to resist surges arising from switching operations. At system voltages of 500 kV and above switching surges rather than lightning control the design.

(2) To ensure that the load loss (i.e. the sum of the I^2R and stray losses) does not exceed the guaranteed performance figure.
(3) To provide adequate cooling to meet guaranteed temperature rise limits.
(4) To ensure adequate short-circuit strength.
(5) To achieve the required impedance characteristic.

Transformer windings may be fully insulated, where the insulation to earth at all points will withstand the separate source voltage test specified for the line terminals, or have graded insulation, where the insulation to earth is reduced from that required at the line terminals to a smaller amount at the neutral end. The insulation on a graded insulated winding will withstand only a separate-source voltage test corresponding to the insulation level at the neutral. In the latter case an induced voltage test is employed to test not only the internal insulation and that between phases, but also the insulation to earth at the line end.

The required level of insulation at the line end is normally designated as the *basic insulation level* (b.i.l.). This value is specified by the purchaser of the transformer and is determined by taking into account the maximum expected atmospheric or switching surges which may be imposed on the transformer, plus a small margin of safety.

The b.i.l. for any particular installation at a given system voltage is governed by the type and effectiveness of the protection against lightning and the combination of line and circuit-breaker characteristics that control the switching surge limit.

For systems where the neutral is isolated, or earthed through an impedance (e.g. an arc-suppression coil) such that, during a line-to-earth fault, the voltage to earth of the unfaulted lines can exceed 80% of the normal line-to-line voltage, fully insulated systems are essential. They are called *non-effectively earthed* systems. Graded insulation is permitted in effectively earthed systems, where the method of earthing at each transformer is such that the 80% value is not exceeded for any operating condition. The requirement is met when the zero phase sequence/positive phase sequence (z.p.s./p.p.s.) reactance ratio of the system is less than 3, and the z.p.s./p.p.s. resistance ratio is less than 1.

Uniform insulation must be provided for all delta-connected windings, and for star-connected windings where the neutral is not earthed. Grading may be applied in the latter case if the neutral is earthed. Where earthing conditions permit grading, they also, in general, allow forms of overvoltage protection for which test voltage levels are lower.

Over the past 50 years a major effort has been made by the International Electrotechnical Commission (IEC) to arrive at agreed international standard test voltages for lightning and switching surge impulse levels and the associated power frequency induced voltage test levels. The effort to accommodate all the different test levels already established by different supply authorities on the basis of their own assessment of the insulation level required on their systems to minimise total cost has led to a complicated set of tables, including a variety of alternative choices for the test voltages appropriate to the various system voltages. IEC 60076: Part 3 includes over six pages of tables and text relating thereto and reference should be made to this document if details are required.[6]

Two fundamental points arise:

(1) The adoption of any one so-called 'standard' insulation level for a particular transformer installation is, of itself, of little or no value. There are at least ten major variables involved in the design of a large transformer (e.g. MVA rating, frequency, system voltages on both high and low voltage, and impedance) and the inevitable differences that arise in any one or more of these mean that each order will require a unique new design. It is of little importance whether or not the specified insulation level is one of the so-called 'standards levels'. The designer will provide what is appropriate.
(2) At the highest voltage levels (>700 kV) there is growing evidence that the trend (particularly in the USA and Canada) towards progressively lower insulation levels for a given system voltage has gone too far. In its simplest terms a reduction in impulse test level represents a reduction in the margin of safety against insulation failure.

References 7 and 8 both include details of recent changes in customers' specification to call for significantly higher impulse test voltages than those previously specified and which have now proved to be inadequate for reliable service.

33.3.3.1 Surge voltage distribution

The voltage distribution in power frequency voltage tests is substantially uniform between turns and coils, and corresponds to the normal service condition in respect of voltage to earth. Under impulse test, however, the distribution can be far from uniform. An impulse voltage wave has a steep front and a long tail. The standard form, defined in IEC 60071, has a front rising from zero to peak value in 1.2 μs, and falling thereafter on the tail to 50% of peak value in 50 μs. This is termed a 1.2/50 μs wave (*Figure 33.12*(*a*)). Impulse voltage tests on transformer windings include the application of a *full wave* and a *chopped wave* impulse, the latter being a full wave shortened by sparkover of a rod gap or its equivalent. American practice adds a front-of-wave test, in which a voltage rising at approximately 1 MV/μs is chopped on the wavefront. The three forms of impulse test voltage are shown in *Figure 33.12*(*b*).

A full wave application tests the ability of the insulation structure to withstand voltage surges; a chopped wave test simulates stresses that occur on the collapse of a surge tail by operation of a rod gap or a flashover to earth. Transformers for systems operating at 300 kV or above may be also required to demonstrate ability to withstand switching surges, typically by a 100/1000 μs wave (see Section 33.14).

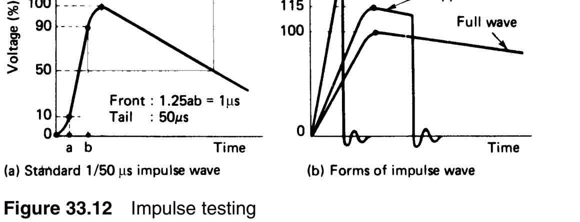

Figure 33.12 Impulse testing

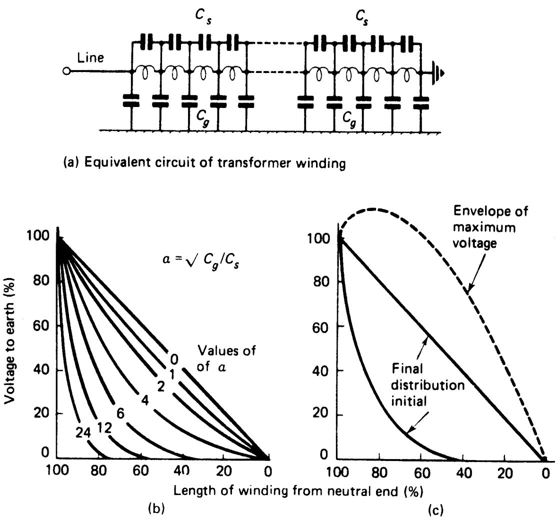

Figure 33.13 Voltage distribution

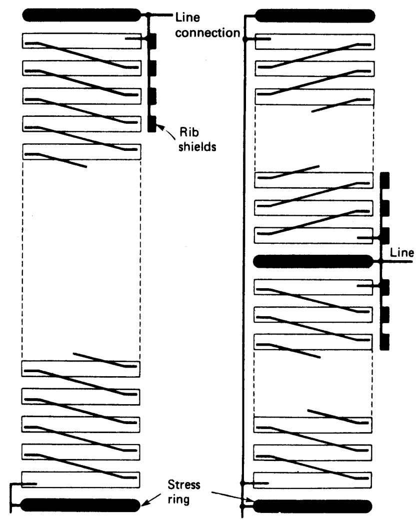

Figure 33.14 Disc windings fitted with stress rings and rib shields

Ignoring resistance, a transformer winding and its surroundings may be represented by an inductor-capacitor network (*Figure 33.13*(*a*)). When a steep-fronted surge is applied to the line terminal, the initial voltage distribution is governed solely by the capacitance network, in particular by the ratio $\alpha = \sqrt{(C_g/C_s)}$ of the capacitance to earth and in series. The greater the value of α, the greater is the divergence from uniform voltage distribution from line to ground, as shown in *Figure 33.13*(*b*). For a uniform winding of identical sections having the same capacitance values C_s and C_g, the initial voltage to earth at any point x from the remote end (with x expressed as a fraction of the winding length) is:

isolated-neutral winding $e_x = E(\cosh \alpha x/\cosh \alpha)$

earthed-neutral winding $e_x = E(\sinh \alpha x/\sinh \alpha)$

for a surge voltage peak of E.

If the surge voltage is maintained, an approximately uniform voltage distribution will be reached, but between these two states (if they differ) a complex array of damped oscillations will occur, creating abnormal stresses in the insulation (*Figure 33.13*(*c*)).

A chop occurring between 3 and 10 μs after application of the impulse voltage will result in augmented interturn and intercoil stresses, although the voltages to earth are normally reduced. The stressing again depends on the initial distribution and on the actual chopping instant. The chop may be regarded as a unit-function voltage, of polarity opposite to that of the incoming surge, and superimposed on the conditions existing within the winding at the instant of chopping.

With the front-of-wave test a higher voltage is applied, but its duration is shorter and the increased stresses are generally confined to the entrance insulation (particularly the bushing). Internal voltage stresses are usually less than those arising from a chopped wave test.

The ratio α is high for a small transformer. For transformers of higher rating and especially for higher line voltage, C_g decreases because it is determined largely by clearances, while C_s increases because of the greater radial depth of the winding. Thus, $\alpha = \sqrt{(C_g/C_s)}$ is lower and the initial voltage distribution approximates more closely to the uniform. To reduce stress concentrations at the ends, disc-coil windings are provided with stress rings that act as radial shields, although they do not materially improve the axial distribution. Axial improvement can be gained by the addition of rib shields to the line-end turns (*Figure 33.14*) or by several other means of controlling the electric field distribution.

Compared with a disc winding, a multilayer coil has a higher series capacitance and therefore a superior transient distribution, although electric field shielding at the ends of the layer may be necessary. The choice between disc-coil and multilayer windings depends, therefore, on the specified impulse level and on the rating.

33.3.4 Leakage field

Problems related to leakage field are significant factors in determining whether a transformer will be reliable in service. *Figure 33.15* shows a cross-section of the core and windings of a 240 MVA autotransformer and a flux plot of the leakage field set up by the load currents in the windings. The critical areas, where special precautions would be necessary to prevent local heating, are the tank wall, the coil support bracket and, to a lesser extent, the face of the core.

A precise knowledge of the shape and magnitude of the leakage field is essential for calculation of impedance, determination of stray loss and consequent heating and the magnitude and direction of short-circuit forces.

Even with modern computer programming, it is difficult to obtain an accurate three-dimensional plot of the leakage field. The computer gives a good two-dimensional plot but approximation and simplification are necessary to determine the third dimension. In spite of this limitation, however, numerical calculation gives the best results in determining leakage field strength with the best results obtained using Finite Element numerical solutions. The difficulties in calculation arise because of the irregular geometry of the windings and the presence of both non-magnetic and magnetic (with non-linear characteristics) components within the field.

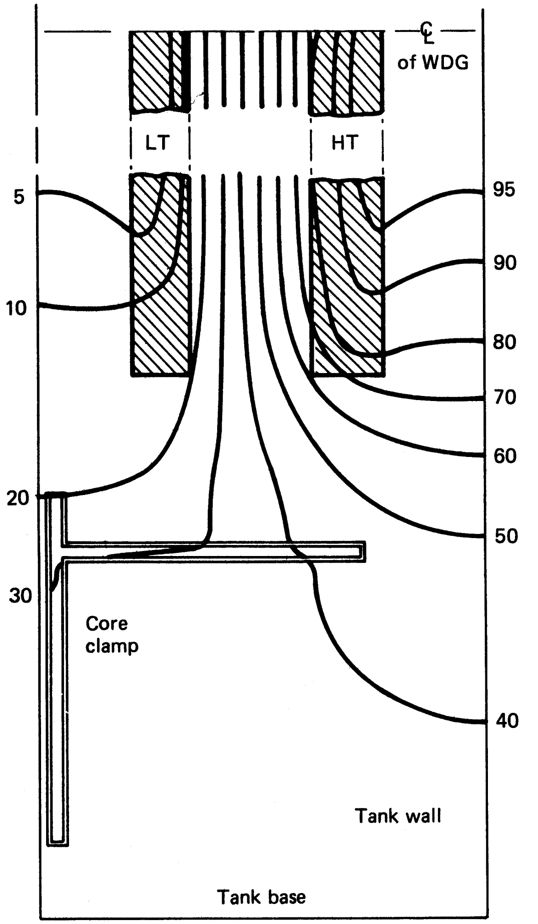

Figure 33.15 The leakage flux point of a 240 MVA transmission auto-transformer, showing leakage flux concentration in the tank wall and the bottom yoke core clamp

33.3.5 Impedance voltage

The impedance voltage of a transformer can be defined as that voltage required to circulate full-load current in one winding with the other winding(s) short-circuited. It comprises a component to supply the *IR* drop and another to overcome the e.m.f. induced in leakage inductance. On larger transformers the resistance component is usually negligible and the percentage value of the impedance is the ratio between total magnitude of the leakage flux and the main flux in the core. The leakage flux is a function of the winding ampere-turns and of the area and length of the paths of the leakage flux. By adjustment of these parameters the transformer can be designed for a range of reactances. The most economical arrangement of core and windings results in a 'natural' value of reactance. This value can be varied to some limited extent without any great influence on the cost and performance of the transformer. Interleaving the windings and so reducing the effective area of the leakage paths will reduce reactance. High reactance requirements usually result in greater stray load loss, because of the necessarily greater leakage flux.

It is usual to express the leakage impedance Z of a transformer as a percentage (or per-unit) value. The per-unit value is IZ/V, and the percentage value is 100 (IZ/V), where I and V refer to the full-load current and rated voltage of one of the windings, and IZ is the voltage measured at rated current during a short-circuit test on the transformer. In the case of a transformer with tappings, the impedance is conventionally expressed in terms of the rated voltage for the tapping concerned.

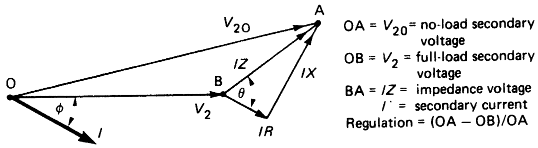

Figure 33.16 Regulation

33.3.5.1 Regulation

The regulation is the difference between the no-load and full-load secondary voltages expressed in terms of the former, with constant primary voltage. The difference is the result of voltage drops due to resistance and leakage reactance; it is proportional to load but is strongly influenced by the load power factor. *Figure 33.16* gives a diagram to show the voltage drop IZ in the leakage impedance Z of the transformer (as obtained from a short-circuit test). The regulation is a maximum when the load phase angle ϕ is equal to the angle θ in the impedance triangle of R, X, and Z. If the load is leading reactive, the regulation is reduced; it may even be reversed so that the secondary voltage rises on load. Formulae (IEC 60076) for the regulation ε of a two-winding transformer on full-rated load, in terms of the percentage IR drop voltage ε_r and the percentage reactance voltage ε_x are:

$$\varepsilon = \varepsilon_r \cos\phi + \varepsilon_x \sin\phi + (\varepsilon_x \cos\phi - \varepsilon_r \sin\phi)^2/200\% \qquad (33.1)$$

for transformers having impedance voltages up to 20% and

$$\varepsilon = \varepsilon_r \cos\phi + \varepsilon_x \sin\phi\% \qquad (33.2)$$

is a simplified expression for cases in which the impedance voltage does not exceed 4%. For unity p.f. load, (33.1) reduces to $\varepsilon = \varepsilon_r + \varepsilon_x^2/200$ and (33.2) reduces to $\varepsilon = \varepsilon_r$.

33.3.6 Losses

The load (or 'copper') loss comprises two components; a direct I^2R loss due to ohmic resistance of the windings, and a stray loss arising from eddy currents in the conductors due to their own flux, influenced by the tank and by steel clamping structures. The eddy loss is negligible when the section of the conductor is small. When the current is too great for a single conductor without excessive eddy loss, a number of strands must be used in parallel. Because the parallel components are joined at the ends of the coil, steps must be taken to circumvent the induction of different e.m.f.s in the strands, which would involve circulating currents and further loss. Forms of conductor transposition have been devised for this purpose.

Ideally, each conductor element should occupy every possible position in such a way that all elements have the same resistance and the same induced e.m.f. Transposition, however, involves some sacrifice of winding space. If the winding depth is small, one transposition halfway through the winding is sufficient; or in the case of a two-layer winding,

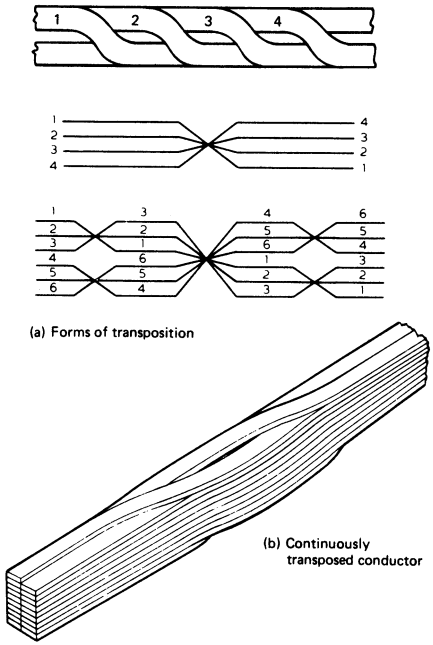

Figure 33.17 Conductor transposition

at the junction of the layers. Windings of greater depth need more transpositions.

Typical forms of transposition are shown in *Figure 33.17*. The methods apply mainly to helical coils. In disc windings where there are two or more conductors in parallel, the connections between the discs can be arranged to give the necessary effect.

Stray loss may also be produced by radial components of leakage flux, but can be minimised by careful ampere-turn balance of the windings.

33.3.6.1 Efficiency

Efficiency is the ratio between power output and power input. Its actual value is less important than that of the magnitude of the losses, which determine heating, cooling, rating and the cost of supplying the losses under given loading conditions in a system.

For a given system voltage and transformer tapping, the flux density has constant peak value, and the core loss p_i is considered to be constant. The load loss p_c varies with the square of the loading, and because of the change of conductor resistivity with temperature is commonly stated at 75 °C. If the power input is P_1 and the power output is P_2, the efficiency is

$$P_2/P_1 = P_2/(P_1 + p_i + p_c) \text{ per unit.}$$

33.3.7 Cooling

The majority of transformer windings are cooled by thermal circulation of oil. Even where pumps are fitted to provide forced cooling, it is common for the transformer to operate without the pump up to some proportion of its forced cooled rating. It is, therefore, important to ensure that the natural thermal circulation of the oil is such that there is a flow over the main cooling surface of the coils. This is a simple matter where the main cooling surfaces are vertical, but when (as in disc windings and particularly on large transformers), the major cooling surfaces are horizontal, special means must be taken to ensure that the oil will flow across the horizontal surface under both natural and forced cooling conditions. Oil-flow barriers are introduced for this purpose.

33.3.8 Short-circuit conditions

Under conditions of system fault, mechanical and thermal stresses of considerable magnitude can be imposed on a transformer winding.

Mechanical forces of magnetic origin may be resolved into two components: (1) *radial*, due to the coil currents lying in the axial component of the leakage flux, tending to burst the outer and crush the inner winding; and (2) *axial*, due to the radial component of the leakage flux arising from ampere-turn unbalance, tending to displace the windings (or parts thereof) with respect to each other. Axial forces may increase the unbalance that produces them, and repeated short circuits may have a cumulative effect. Windings must be designed and built to withstand the mechanical forces, an important aim being to minimise ampere-turn unbalance between windings, especially that caused by tappings.

Thermal stresses arise from the temperature attained by the windings when carrying sustained fault current. The limits of temperature rise permitted by IEC 60076 for copper windings are: 250°C for class A insulation in oil and 350°C for class B in air. Aluminium windings are limited to 200°C for both classes.

Mechanical forces have to be considered relative to the asymmetrical peak current, whereas thermal stresses are governed by the symmetrical r.m.s. value and duration. The fault current is controlled by the leakage impedance of the transformer and the impedance of the supply system. IEC 60076-5 states that for transformers rated 3150 kVA or less, the system impedance shall be neglected in the total impedance if it is equal to or less than 5% of the leakage impedance of the transformer.

The duration for which a transformer can withstand short-circuit current depends on thermal considerations. IEC 60076-5 states that the duration of the short-circuit current to be used for calculation of the thermal ability to withstand short circuit is 2 s unless otherwise specified by the purchaser. The temperature attained by the winding can be calculated by the method described in IEC 60076-5 on the assumption that, during the period of short-circuit, all heat developed by the loss in the windings is stored in the conductor material.[9]

33.4 Connections

Transformer windings can be constructed for connection to a one-phase, two-phase or three-phase power supply. Combinations are also possible, namely three-to-two or three-to-one phase conversion. Six-, 12- and even 24-phase connections may be needed in rectifier transformers. Single-phase transformers can be independent; arranged to provide a two- or three-wire supply, centre-point earthed, or combined to form a three-phase bank. In the case of three-phase windings, three forms of connection are possible; star, delta and interconnected-star (zig-zag). When combined on the same core, a delta winding and an interconnected-star winding can be arranged to provide zero phase displacement, and when either of these is combined with a star winding, a 30° phase displacement results, either leading or lagging. By reversal of one winding with respect to the other when a combination of the same connection is involved, or where the combination is of connections giving the same phase displacement, a 180° phase displacement is produced. A summary of the combinations detailed in IEC 60076 and the corresponding e.m.f. diagrams is given in *Figure 33.18*.

In a star/star connection unbalanced load may result in neutral displacement and third-harmonic currents may circulate between lines and earth. These difficulties may be overcome by providing a delta connected stabilising (tertiary) winding with a rating sufficient to take short-circuit fault currents. The need for this winding depends, however, on the core construction. Where, as in banks of three one-phase units or in five-limb three-phase core-type transformers, there is an independent iron path for the zero-sequence flux in each phase, the z.p.s. impedance is consequently high, making a stabilising winding essential. With three-phase three-limbed cores the z.p.s. fluxes are forced out of the core and the z.p.s. impedance is lower; consequently, a tertiary winding may not be necessary.

33.4.1 Phase conversion

The Scott connection is the most common two-to-three phase conversion. Two one-phase transformers are generally used, with one pair of windings arranged to form a T connection for the three-phase supply. The 'main' unit is wound for the phase-to-phase voltage with a mid-point tapping, and forms the head of the T. The other unit, the 'teaser', is wound for 0.866 times the line voltage and both are designed to carry full line current. A neutral point can be provided by a tapping on the teaser winding at a point 0.577 of the turns from the line end (see *Figure 33.19*). The two units, for operational convenience, can be made interchangeable. A winding arrangement which results in a minimum leakage reactance between the winding halves of the main unit (for example, an interleaved winding) is essential to ensure correct current distribution and to avoid excessive voltage regulation. In the place of two single-phase units, a three-limb core, outer legs wound, may be used if the unwound centre limb is proportioned to suit the flux conditions, i.e. given 41.5% greater section.

As an alternative to the Scott connection, which is basically a one-phase arrangement, a Leblanc connection can be used. It employs a standard, three-limb, three-phase core and a standard three-phase delta connected winding (*Figure 33.20*). Compared with the Scott arrangement, the Leblanc connection requires a smaller core but involves a greater winding section.

Three-phase to single-phase transformation can be achieved by an open delta connection which involves a standard, three-limb, three-phase core, with outer limbs wound. Alternatively, an arrangement similar to the Scott connection can be used. With the open delta connection the output voltages from each limb are 120° apart, so that the voltage applied to the load is 3 times the voltage across one winding, and in the case of the T connection the output voltages are 90° apart, so that the voltage applied to the load is 2 times the voltage across one winding. With either form of connection, if a three-wire one-phase supply is required and the loads on each side of the mid-point are liable to unbalance, the windings should be subdivided and interconnected to distribute more evenly the out-of-balance current and to avoid excessive voltage regulation.

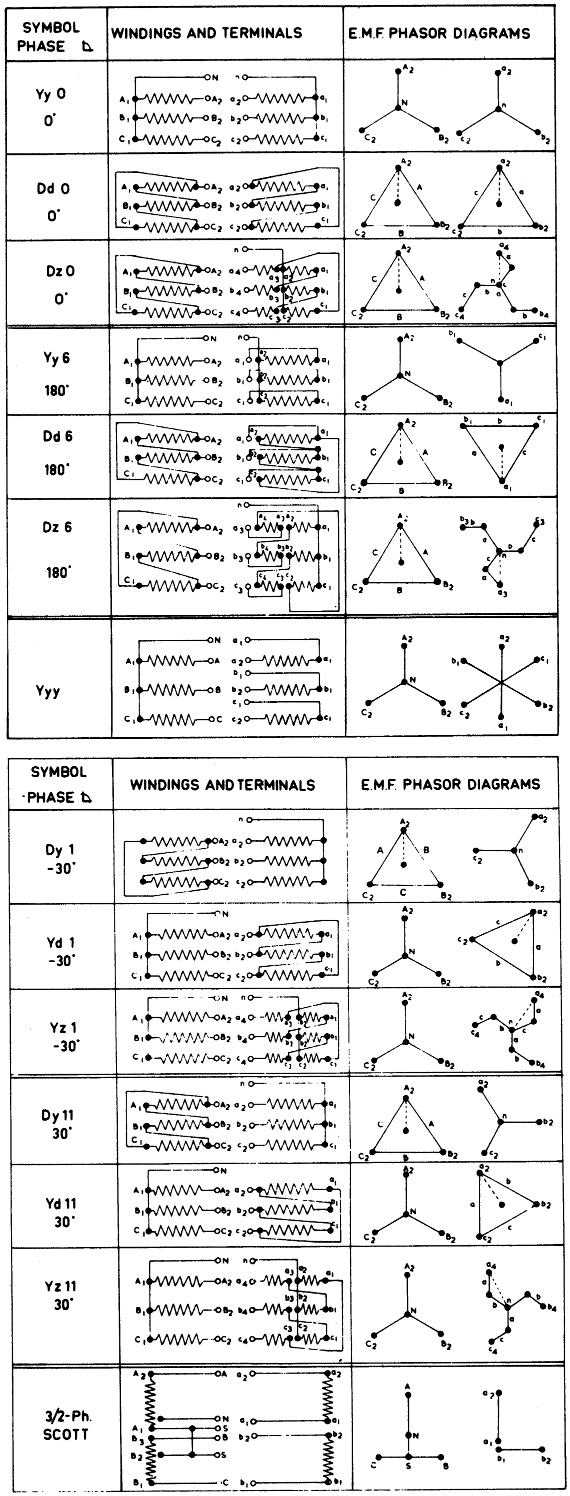

Figure 33.18 Standard connections for three-phase transformers

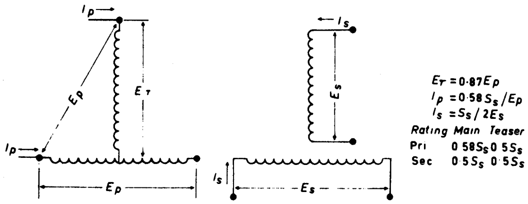

Figure 33.19 Scott three-to-two phase transformation

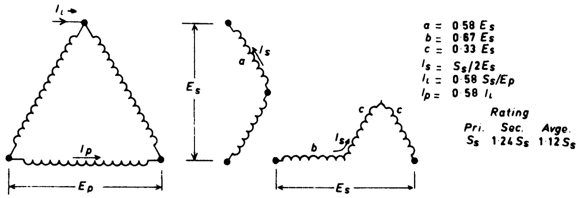

Figure 33.20 Leblanc three-to-two phase transformation. S_s is the kilovolt-ampere rating of the two-phase load

It is important to realise that, although a three-to-one phase connection can be used to transform a line–neutral load on the secondary side to a line–line current on the primary side, it does not result in a balanced primary load. The same degree of unbalance must appear on the primary; or in terms of symmetrical components, all zero- and negative-sequence currents on the secondary will also flow on the primary side.

33.5 Three-winding transformers

Typical applications of three-winding transformers are:

(1) feeding two secondary networks, of different voltage or phase relationship, from a common primary supply;
(2) connecting two generators to the same high-voltage system while maintaining a relatively high impedance between them to limit cross-feed of fault energy;
(3) feeding two parts of a sectionalised low-voltage network so as to limit the fault level of each part without too high an impedance between the high-voltage and the low-voltage sides; and
(4) providing a rectifier with a multiphase (e.g. 12- or 24-phase) supply.

Provided that there is at least one delta connected winding, to permit the flow of third-harmonic currents, there is freedom to adopt star or delta connection to meet phasing or earthing requirements.

33.5.1 Impedance characteristics

Two-winding technology does not apply. The essence of the procedure for a three-winding unit is that the leakage impedance can be represented by assuming each of the three windings to have an individual resistance and leakage reactance, and mutual impedance effects (other than those that result from these individual values) to be absent. The equivalent circuit can be represented by the star network in *Figure 33.21*. The leakage impedance values (in per-unit form to a common kilovolt-ampere base) are given in terms of the conventional two-winding impedances: for resistances

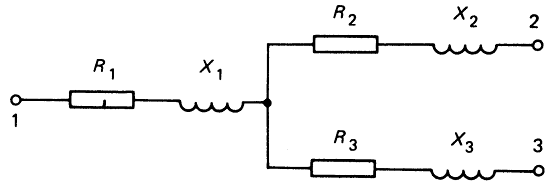

Figure 33.21 Equivalent circuit of a three-winding transformer

$$R_1 = \frac{1}{2}(R_{12} + R_{31} - R_{23})$$

$$R_2 = \frac{1}{2}(R_{23} + R_{12} - R_{31})$$

$$R_3 = \frac{1}{2}(R_{31} + R_{23} - R_{12})$$

X being substituted for R to give the leakage reactances. These for the individual arms are then combined to give the effective values between any pair of terminals: e.g. $R_{12} = R_1 + R_2$, $X_{23} = X_2 + X_3$, and so on. (As the equations for the individual arms include a negative term, some particular evaluations may be found to be negative.)

33.5.2 Tertiary windings for harmonic suppression

The most common three-winding transformer is star/star connected with a delta tertiary to provide a path for z.p.s. currents. If third-harmonic distortion of the main flux (and, hence, of the secondary voltage wave form) is to be avoided, a tertiary must be used on any configuration of core that provides a low-reluctance path for third-harmonic components of the flux. This requirement applies to shell types, and to three-phase core types having more than three limbs; a three-phase three-limb core-type transformer has no ferromagnetic return path for third-harmonic flux components, so suppressing z.p.s. distortion of the flux, and it will operate satisfactorily provided that the load is not significantly unbalanced. For an unbalance exceeding 10%—or if a low zero sequence impedance is required for protection purposes—it would be prudent to include a tertiary. However, a two-winding transformer called upon to supply zero-sequence loads could alternatively be provided with an external source of zero-sequence power (a) by a direct connection between the transformer in question and the neutral of a stand-by unit having a delta winding, or (b) by the installation of a zig-zag connected 'earthing transformer'. If several star/star units are acquired and undue unbalanced loading is not expected, it would be preferable on grounds of cost to specify them without tertiary windings, subsequent remedial action being taken if and when it becomes desirable. Whether or not third-harmonic problems arise depends on the complete installation and how it is operated. The transformer characteristics do not alone determine the issue; other factors are (a) the level of the transformer core flux density (and, hence, the magnitude of the third-harmonic component of magnetising current); (b) the expected degree of load unbalance; (c) the impedance of external sources of zero-sequence current; and (d) the proximity of telecommunication circuits to the external zero-sequence current path. Tertiary windings fitted only for harmonic suppression and not connected to external terminals must be rated to withstand the effects of primary and secondary earth fault currents: tertiary current then depends on the p.p.s., negative phase sequence (n.p.s.) and z.p.s. impedances of both the supply and the transformer. As such fault currents persist for only a few seconds, the temperature rise of the tertiary winding is determined by its thermal capacity.

33.5.3 Tertiary windings for external loads

Tertiary windings providing auxiliary power circuits, or supplying reactive power compensating capacitors or inductors, must have an appropriate continuous rating. The tertiary must withstand the effects of a short-circuit fault across its external terminals, as well as those due to earth faults on the main windings. The conductor sections and the bushings are designed for the most onerous operating condition.

33.6 Quadrature booster transformers

Consider two lines in parallel transmitting power between A and B (*Figure 33.22*): T_1 and T_2 are conventional transformers, either or both having on-load tap changing equipment. The division of load currents I_1 and I_2 between the lines is in inverse proportion to the impedances Z_1 and Z_2. For better load sharing it may be desirable to adjust the division of current. Tap changing the transformers to give a voltage difference V between T_1 and T_2 will cause a circulating current $I_t = V/(Z_1 + Z_2)$ to flow around the loop; and I_t will lag V by the natural phase angle of $Z_1 + Z_2$ increasing the current and I^2R loss in the branches without achieving the desired change in load sharing.

If a booster transformer T_b is introduced into the loop to inject a small voltage in quadrature with the supply voltage, the resulting circulating current will be approximately co-phasal with the active-power component of the load current. It will therefore add arithmetically to the active current in one branch and subtract from that in the other, thus controlling the relation between I_1 and I_2. The adjustment permits an increase in the total load that can be transmitted over the system. The quadrature booster is an important element for power control in parallel circuits. A simple method of deriving the necessary injected voltage is shown for one phase in *Figure 33.23*. A single transformer unit has a delta connected main winding and a tapped series winding to provide an adjustable voltage in quadrature with the phase voltage. For large high-voltage quadrature boosting, two transformers are commonly used in order to provide the necessary dielectric and short-circuit strengths. The first 'excitation' transformer supplies the second 'injection' transformer. By suitable choice of connections either

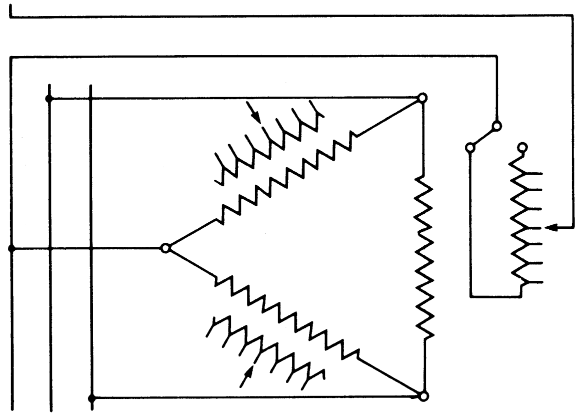

Figure 33.23 Connections for quadrature regulation

quadrature or in-phase regulation can be obtained. By use of two tap changers and more complex tapping windings, separate control of both in-phase and quadrature components can be achieved.

33.7 On-load tap changing

The essential feature of all methods of tap changing under load is that circuit continuity must be maintained throughout the tap stepping operation. The general principle of operation used in all forms of on-load tap changer is that, momentarily at least, a connection is made simultaneously to two adjacent taps on the transformer during the transition period from one tap to the next. Impedance in the form of either resistance of inductive reactance is introduced to limit the circulating current between the two tappings. The circulating current would represent a short-circuit between taps if not so limited. *Figure 33.24* shows in diagrammatic form the use of a centre-tap inductor or auto-transformer as the transition impedance. In *Figure 33.24*(*a*) the load current is shown passing from the maximum tap through the halves of the inductor in opposition, and hence, non-inductively. In *Figure 33.24*(*b*) one of the two tap-selector switch contacts has opened and the load current is carried inductively through one half of the inductor. In *Figure 33.24*(*c*) the inductor is shown bridging the two adjacent tappings. The load current is shared equally between the two tappings

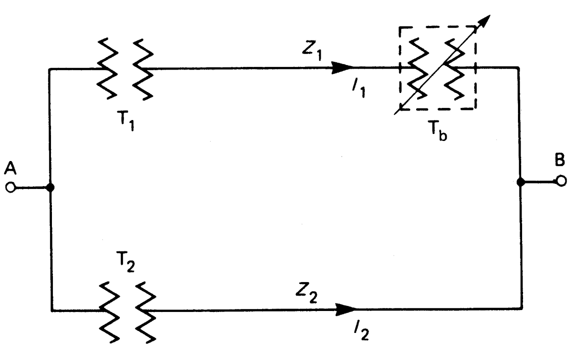

Figure 33.22 Power flow along two parallel lines of different impedance

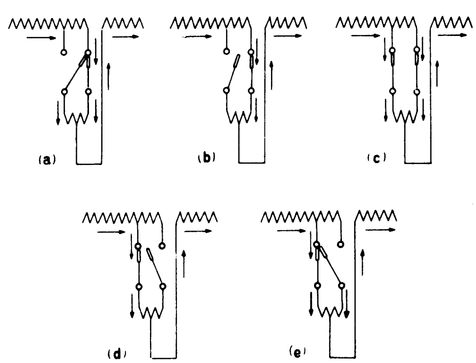

Figure 33.24 Inductor transition

and passes non-inductively in opposition through the halves of the inductor. The tap step voltage is applied to the whole of the winding of the inductor and the circulating current is limited by the total impedance. In this position, in which the tap changer can remain indefinitely, the effective voltage is equivalent to the mean of the two individual tap voltages. *Figure 33.24(d)* shows the momentary condition where one half is connected inductively to the incoming tap position, and *Figure 33.24(e)* shows the final stage of the transition where both selector switch contacts are connected to the incoming tap and the inductor is non-inductively connected.

Circulating-current limitation by centre-tapped inductor was common in the late 1940s, but has since been almost entirely superseded by high-speed resistor transition. The switching sequence is shown in *Figure 33.25* and is similar to that with inductors, except that two resistors are used. Backup main contacts are provided which short-circuit the resistors for normal running conditions.

Advantages of inductor transition were: the inductor could be continuously rated and a failure of auxiliary supply during a tap change did not necessitate the main transformer being taken out of service; also, that the intermediate or bridging position could be used as a running position, giving a voltage equivalent of one-half tap step. The main disadvantage was that the circulating current between taps during the bridging condition was at low power factor, adversely affecting diverter-switch contact life. The inductor itself was costly and occupied a significant amount of space in the transformer tank.

Resistor transition is now used almost exclusively by British and European tap changer manufacturers, although inductor transition is still used in the USA, possibly because it is common practice there to specify a large number of small tap steps, a requirement met by using the bridging position as a running tap.

Resistor transition requires one winding tap for each operating position. The basic disadvantage is that the resistors cannot be continuously rated, if their physical size is to be kept small. It is essential to minimise the period during which they are in circuit. Some form of energy storage has, therefore, to be incorporated in the driving mechanism to ensure that a tap change, once initiated, is completed irrespective of failure of auxiliary supply. Early resistor tap

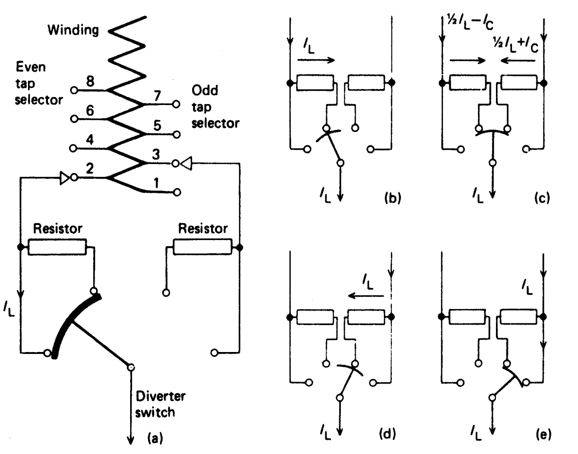

Figure 33.25 Resistor transition. (a) Outgoing tap operating; (b) load current in resistor; (c) resistors in parallel to load current and in series to circulating current; (d) load current in resistor; (e) incoming tap operating

changers operated at low speed and the stored-energy mechanism was a flywheel or a falling mass. All modern tap changers use springs for energy storage, and the total time that a resistor is in circuit during a tap change is limited to a few periods. The advantages of the high-speed resistor tap changer are its compactness and lack of wear of diverter-switch contacts because of the high speed of break, and because the circulating current is at unity power factor. Contact life of 250 000 operations is common, compared with the 10 000–20 000 for reactor tap changers.

Irrespective of the form of transition, all on-load tap changers fall into one of three categories in respect of the switching arrangement. These are as follows:

(1) The oldest (and now least common) arrangement is for a separate contactor to be connected to each winding tap. Contactors are operated by a camshaft to ensure the correct sequencing. A later development was to use mercury switches instead of open-type contactors, giving the advantage of freedom from carbonisation of the coil.
(2) The winding tappings are connected to a series of fixed contacts of a selector switch of either linear or circular form, and an associated pair of moving contacts operates to provide the required switching sequence. Current making and breaking occurs at the selector switch contacts and some degree of oil carbonisation and contact wear is inevitable. This type of tap changer, usually called 'single-compartment', is now common for transformers up to about 20 MVA rating.
(3) For the largest and most important transformers the tap selector switches do not move when carrying current. Current making and breaking is carried out by two separate diverter switches, usually in a separate compartment of the tap changer to minimise the amount of oil contaminated by carbon. The diverter switches operate to make and break the current and are mechanically interlocked with the selector switches, which move only when not carrying current to provide the correct sequence of connection to the winding taps.

At one stage of development of medium-sized tap changers, large mercury switches were used as diverter switches; these could be mounted in a selector switch compartment as there was no risk of oil contamination. A recent development along the same lines is the application of vacuum-switch diverters, capable of many thousand operations without attention and with freedom from contamination. Trials are being made with thyristors to provide 'contactless' switching: while this might yield marginal advantage in minimising maintenance and perhaps improving reliability, the cost and complexity of the control arrangements are likely to be inhibiting factors.

33.7.1 Tap changer control

Control gear can vary from simple local push-button control to a complex scheme for the automatic control of as many as four transformers operating in parallel. The objective of automatic tap change control is to maintain output voltage either constant or with a compound characteristic rising with load. The main component is the automatic voltage-regulating device, which consists of a voltage governor, a time-delay relay and compounding elements. The time-delay element prevents tap changes occurring due to minor short-time fluctuations of voltage. It can be set for delay periods of up to a minute. Tap change control circuits necessarily involve auxiliary switches mounted within the driving mechanism of the tap changers themselves, and this has led to a proliferation of types of control schemes each designed to operate with a particular type of tap changer. These variations have made it extremely difficult for the British Electricity Supply Authorities to develop a national standard control scheme. Some of the differences arise in the method adopted to arrange simultaneous or near-simultaneous tap changes of transformers operating in parallel. A further complication arises because of differences between one transformer and another in the tapping range and the number and size of tapping steps. Some of the various types of parallel control schemes are as follows:

(1) Simultaneous operation of two or more tap changers initiated from one voltage regulating relay. Closing of the ‘raise’ or ‘lower’ contact in the voltage-regulating relay closes the appropriate motor contactor in each tap changer, and auxiliary switches lock out further movement until all the tap changers have completed a single change of position. This scheme is, in general, only applicable to tap changers with identical main and auxiliary characteristics.
(2) Master–follower operation initiated from one voltage-regulating relay. This is also suitable for two to four transformers in parallel, although the length of time to complete an initial tap change may be considered to be excessive where more than two transformers are involved. The voltage relay initiates the movement of the ‘master’ tap changer: when this has completed one tap step, the auxiliary switches operate to cause the second transformer of the chain to come into line with the first. This is followed in sequence by the movement of the remaining units. The time for completing one tap step on all units in the bank is, therefore, the sum of the individual operating times. As in (1), this scheme is suitable only for substantially identical tap changers.
(3) Master–follower scheme with multiple voltage-regulating relays; a more complicated version of (2) in that each transformer is equipped with its own voltage-regulating relay and any one of the group may be selected to act as master, the remaining units following in any desired sequence.
(4) Circulating-current control schemes. The foregoing schemes all require multipoint switches in each tap changer, interconnected by multi-core cable. The circulating-current schemes depend on the fact that if two transformers operating in parallel are out of step, a circulating current will flow between them in a direction depending on the relative ratio of transformation. Each transformer is controlled by its own voltage-regulating relay, and as individual characteristics are not absolutely identical, it follows that, when a change of voltage occurs, one relay of the group will initiate a tap change on its associated transformer earlier than the others. As soon as the first transformer of a group has completed a tap change, there will be an imbalance of ratio and a circulating current will flow in the main circuit connections between the transformers. This circulating current is used to control auxiliary relays in each tap changer of the group, so that no further movement can occur to increase the imbalance, i.e. the second and later transformers in the group can change step to come into line with the first unit which has already moved; alternatively, the first unit can move in the reverse direction to bring itself back into its original position and therefore directly in step with the others. This type of scheme allows transformers to operate indefinitely in a ‘one step out’ condition. The wiring is relatively simple, as the only interconnections between units are the secondary leads of the circulating-current transformers. It permits automatic parallel control of transformers of different rating, impedance, tapping range and number and size of tapping steps, as the tap changers take up positions to minimise the circulating current between units. Provided that the c.t.s. are selected to correspond to the rating of each main transformer, optimum loading of the group is achieved.
(5) Parallel control by reverse compounding. All of the schemes mentioned above necessitate secondary connections between the transformers that are to operate in parallel, and all except (4) suit only transformers with near-identical characteristics. Where parallel operation is required between transformers with differing characteristics, or where the transformers are situated some distance apart, it is possible to achieve stable operation with each being controlled by its own voltage-regulating relay by introducing negative compounding of the reactance element of a line-drop compensator. This tends to give a negative compounding characteristic (i.e. output voltage drops as load increases), but compensation can be provided by increasing the positive compounding of the in-phase element. Unless the negative reactance characteristic is introduced, any two tap changers controlled by independent voltage-regulating relays which are not positively locked together will inevitably move quickly to opposite extremes of their range.

33.7.2 Line-drop compensation

This device permits the output voltage of the transformer to be compounded so that it rises with load to compensate for voltage drop in the cables connected to the secondary side, and to maintain approximately constant voltage at a remote point. The line-drop compensator comprises an ‘artificial line’ circuit consisting of adjustable resistances and reactances connected into the voltage relay operating-coil circuit (*Figure 33.26*). A current transformer in the main secondary connection injects current into the adjustable resistance and reactance coils and thus biases the voltage applied to the voltage sensitive element of the regulating relay.

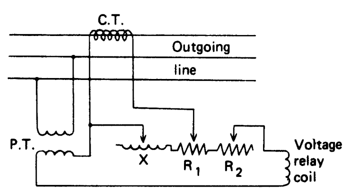

Figure 33.26 Line-drop compensation. R_1 and X are adjustable to suit line characteristics; R_2 adjusts the output-voltage level

33.8 Cooling

Small transformers are air cooled and insulated. For units of larger rating and higher voltage, oil cooling becomes economical, because oil provides greater insulation strength than air for a given clearance, and augments the rate of removal of heat from the windings. With the exception of certain special installations, such as in coal mines or within occupied buildings where mineral oil is undesirable because of the fire risk involved, almost all power transformers are oil immersed. The combination of oil and paper insulation has been used in transformers for many years and there appears little likelihood of its being superseded by any modern synthetic material. A principal reason for this situation is that both materials can be operated safely at the same maximum temperature, approximately 105°C. Any alternative materials would have to show significant advantages in either or both insulating and heat transfer properties compared with the combination of oil and paper.

The most common types of cooling arrangements, detailed below, are identified in IEC 60076 by a system of symbols which indicate the cooling medium in contact with the windings; the cooling medium in contact with the external cooling system; and the kind of circulation for each. The symbols for the cooling media are:

- O for mineral oil or an insulating liquid with fire point $\leq$300°C
- K for an insulating liquid with fire point $>$300°C
- L for an insulating liquid with no measurable fire point
- W for water
- A for air
- G for gas.

The symbols for circulation in a liquid immersed transformer are:

- N for natural thermosyphon flow
- F for forced fluid circulation, but thermosyphon cooling in the windings
- D for forced fluid circulation, with fluid directed into the windings.

IEC specifications stipulate temperature limits for windings (measured by resistance) and insulation and define normal standard values for the temperature of the cooling medium.

33.8.1 Air insulated, air cooled

33.8.1.1 Natural air cooling (AN)

The temperature rise measured by resistance is limited by the class of insulation used. Typical figures are 60 K for class A, 90 K for class B and 150 K for class C materials; all rises being above a maximum ambient temperature of 40°C and a daily average of not more than 30°C. Type AN cooling is generally limited to relatively small units, although the development of high-temperature insulation, such as glass and silicon resins, has resulted in its use on transformers up to 1500 kVA and for special application as in mines.

33.8.1.2 Forced air cooling (AF)

The temperature conditions are the same as for AN, but the improved heat transfer properties resulting from the forced air stream enables the current density in the windings and the flux density in the core to be increased and greater output to be obtained from a given size of unit.

33.8.2 Oil immersed, air cooled

IEC 60076 recognises two maximum oil temperatures: 60°C when the transformer is sealed or equipped with a conservator, and 55°C when the transformer is not so equipped. Winding temperature rise by resistance for oil immersed transformers with ambient air temperatures of 40°C and a daily average of not more than 30°C is limited to 65 K, irrespective of the type of cooling or the cooling medium. The various types of cooling and the new symbols are as follows.

33.8.2.1 Natural oil circulation, natural air flow (ONAN)

The great majority of power transformers up to ratings of 5 MVA are of ONAN type. A plain sheet-steel tank radiates about 13 W/m^2 per degree Celsius rise. Above about 25 kVA, three-phase, an increased cooling surface becomes necessary. This extra surface may be obtained by using fins or corrugations, but the most common method is to employ a tubed tank. The tubes are usually 40–50 mm in diameter, of welded steel construction, having a wall thickness of about 1.5 mm. For medium sizes (2–5 MVA) tubes of elliptical section are preferred, as a greater number can be accommodated on a given tank. For transformers larger than 5 MVA it becomes necessary to employ radiator banks of elliptical tubes, or banks of corrugated radiators.

Transformer tanks have been constructed with finned tubes in order to augment the surface. They are difficult to paint, and are liable to collect water if employed out of doors.

The power dissipated by a tubular tank is a function of the ratio between tank envelope and total surface, for radiation is a function of the envelope, while convection depends upon the whole surface.

33.8.2.2 Natural oil circulation, air blast (ONAF)

By directing an air blast on to an ordinary tubular tank or on to separate radiators the rate of heat dissipation is increased; thus, while the transformer itself is not reduced in size, less external cooling surface is required.

33.8.2.3 Forced oil circulation, natural air flow (OFAN)

OFAN is an uncommon system, but is useful where for reasons of space the coolers have to be well removed from the transformer. The oil is pumped round the cooling system, from which heat dissipation is by natural air convection. The forced oil circulation permits high current densities to be employed in the windings, so that there is a reduction in transformer size.

33.8.2.4 Forced oil circulation, air blast (OFAF)

The OFAF system is employed for most large transformers. The forced oil enables the windings and core to be economically rated, while the forced air blast reduces the size of the radiating surfaces, an important point for transformers of 30 MVA upward. Depending upon the type and disposition of the radiators and on the purchaser's requirements, *mixed* cooling is employed in which the transformer operates as an ONAN unit up to 50% of its forced cooled rating (66% in the USA). As the load increases further, temperature sensitive elements start the pumps and fans of the forced cooling equipment.

33.8.3 Oil immersed, water cooled

Cooling-water inlet temperature limits as defined in IEC 60076 must not exceed 25°C. Oil temperature and winding temperature limits are as for air cooled units.

33.8.3.1 Natural oil, water (internal cooler) (ONWF)

A copper cooling coil is mounted above the transformer core in the upper portion of the transformer tank.

33.8.3.2 Forced oil, water (external cooler) (OFWF)

The OFWF system uses oil/water heat exchangers external to the transformers. The arrangement has a number of advantages over ONWF cooling:

(1) The transformer is smaller in size, as the windings can be more highly rated owing to forced oil flow and the tank is not required to accommodate a large cooling coil.
(2) Condensation troubles are non-existent.
(3) Water leakage into oil is improbable with the oil pressure maintained higher than that of the water. In cases where the cooling water has a high head at the transformer plinth level, it is necessary to employ two heat exchangers in series, i.e. oil/water and water/water; the water in the intermediate circuit between the two coolers is separate from the main water supply and at a low head.
(4) The cooling tubes may be easily cleaned. Water cooling of transformers is common at generating stations (particularly hydroelectric ones), where ample cooling water supplies are available.

33.8.4 Overload capability

The temperature limits for oil, windings and insulation laid down in IEC 60076 are chosen to ensure that a transformer operating within these limits will have a satisfactory life of 20 or more years. The relationship between operating temperature and life is complex. Experimental work indicates that each 8°C increase in operating temperature halves the life of the insulation, but there is little information available to enable an operator to determine precisely the actual life expectation under any given operating conditions. This obviously depends on other factors, including the incidence and severity of short-circuit forces to which the ageing insulation may be subjected. To some extent also the loss of insulation life due to overload operation during an emergency can be offset, provided that for some further and more protracted period operating temperatures are kept well below the specified limits.

Because of the considerable thermal inertia of the mass of oil and metal in a transformer, appreciable overloads can be carried for short periods without endangering insulation life. IEC 60076-7 gives details of permitted overloads.[10] These allowable overloads are, however, normally regarded as conservative and have been exceeded in service without adverse results. The overload recommendations in IEC 60076-7 are based on a maximum hot-spot temperature of 90°C at rated load and loss of life doubling for each 6°C increase in temperature above 98°C. It is important that the windings are not operated at a temperature above 140°C as air/water vapour bubbles are formed from cellulose insulation at higher temperatures. Bubble formation can lead to dielectric failure of the windings.

33.9 Fittings

The number of fittings and their siting on the transformer tank constitute major problems of transformer standardisation. It is recommended, therefore, that the fittings enumerated in IEC 60076 be used, careful consideration being given to the essential points before any refinements and extras required for satisfactory operation are specified.

Terminals and bushings Transformer terminals must of necessity cover a wide range of voltages, currents and operating conditions. Outdoor type bushings are standardised in Britain and are detailed in ESI Standards 35-1 and 35-2 and BEB Specifications T_1, T_2 and T_3. Some outdoor bushings are fitted with arcing horns which provide a safety gap to discharge an incoming surge which might otherwise damage the transformer windings. It is important that there is the correct correlation between the insulation strength of the transformer winding and the flashover characteristics of the gap. The setting of the gap must be small enough to protect the windings without causing too frequent interruption of the supply due to power arcs following gap flashover due to surges on the system.

Cable boxes These are essential when paper or plastics insulated cables require connection to the transformer. Cable box arrangements depend on the number of cores in the cable and the number of cables connected in parallel. Several factors must be considered in designing a cable box: adequate electrical and mechanical clearances are necessary; the compound must not ooze out of the box nor any transformer oil leak in; and voids must not easily occur in the compound, either during pouring operations or during normal thermal expansion and contraction. In order to make transformers interchangeable the box flanges are standardised (ESI 35-1 and 35-2).

Oil conservator Transformer oil has a coefficient of thermal expansion of 0.000 725 per degree Celsius at 0°C, equivalent to a 7.25% volume change over an oil temperature range of 0–100°C. The expansion may be accommodated in a free-breathing or sealed space at the top of the tank, or in a conservator tank mounted on the tank cover. It is desirable to avoid oxidation of the oil, which causes sludging and acidity to develop. With either the sealed tank or the conservator a nitrogen cushion can be maintained above the surface of the oil, thus preventing oxidation. A free-breathing conservator is preferable to an unsealed tank, as the temperature of the oil in contact with the air is lower and this in itself reduces the rate of oxidation. Some form of oil pressurisation is essential for large transformers and for those working at 33 kV and above; it is desirable also for small transformers, especially those subjected to heavy periodic peak load.

Breather This device allows ingress and egress of air to compensate for changes in oil volume. Except on small transformers, the breather should incorporate either a chemical or a refrigerating system for removing moisture from the air entering the transformer.

Oil gauge This can be a direct-reading glass window, or a dial instrument operated by magnetic coupling from a float on the oil surface. The dial gauge can be fitted with contacts to give a low-oil-level alarm.

Oil temperature indicator Normally of the dial type, oil thermometers can be arranged for remote electrical indication of oil temperature.

Winding temperature indicator The so-called winding temperature indicator is basically an oil temperature thermometer in which the bulb is associated with a heater coil which carries a current proportional to the load on the transformer.

The heater coil introduces an increment of temperature above that of the oil, to correspond to the gradient between winding and oil temperatures. The instrument thus indicates a figure which, although a reasonable analogue of the temperature of the windings, is not a direct measurement thereof.

Important new developments in direct measurement of temperature in high-tension windings are being introduced.[11] This measurement is achieved by the use of fibre-optic strands attached to one of the winding conductors. Two different applications are possible. The first uses a gallium-arsenide based sensor tip at the end of the fibre-optic strand to provide a single-point temperature detector.

The second application is to use the whole length of the fibre-optic strand itself as a distributed sensor. A technique known as optical time domain reflectometry interrogation from a single end enables temperature measurements to be made at points 1 m apart along the full length of a fibre-optic strand up to 4 km long, i.e. at up to 4000 data collection points. These applications may lead to considerable advances in determining safe overloading rules.

Buchholz relay Any electrical fault occurring inside a transformer is accompanied by an evolution of gas. Appreciable quantities of gas may be produced before the fault develops to such an extent that it can be detected by the normal protection equipment. The Buchholz relay, connected between the transformer tank and the conservator, contains two elements: (1) a float which operates a gas alarm device to give warning of gas discharge from within the transformer, and (2) a surge element connected to trip the transformer out of circuit in the event of a massive surge of oil and gas resulting from a major internal fault. In the event of a gas alarm being given, it is sometimes possible to deduce the nature of the defect within the transformer by observing whether the gas emission is at a constant rate (voltage dependent) or varies with load (current dependent).

The Buchholz relay provides sensitive protection against certain types of fault (e.g. flashover between tapping leads) to which the normal protection is relatively insensitive, and may not operate until extensive damage has been caused.

Relief or explosion vents Many users specify relief or explosion vents, which are intended to act as safety valves to reduce internal pressure in the event of a major fault within the transformer and thus to protect the tank from damage. The vents can be spring loaded or fitted with thin non-metallic material to fracture under pressure. Provided that the build-up of pressure is relatively slow, the relief vent can operate satisfactorily and prevent the tank from bursting, but in the event of a violent fault leading to a shock wave of pressure, the tank may be burst before the relief vent has time to operate.

Tapping switches (off-load) Almost every distribution and medium-sized power transformer is fitted with voltage adjusting tappings, usually for five positions corresponding to ±2.5% and ±5% of the supply voltage. To obviate opening up the transformer to change tapping links, a tapping switch is necessary. Such a switch is often fitted on top of the transformer core and is gang operated on all phases by means of a hand wheel on the tank end.

33.10 Parallel operation

The following information is required when the parallel operation of transformers is considered:

(1) output and temperature rise of the transformers;
(2) polarity for one-phase units; angular displacement for three-phase units-IEC group reference or phasor diagram;
(3) turns ratio on all tappings;
(4) percentage impedance at 75°C; and
(5) percentage resistance drop at 75°C, or the load loss.

The polarity is basically determined by the direction of the primary and secondary windings and the position of the transformer line leads with respect to the start and finish of the windings. British transformers usually have a subtractive polarity. In the case of three-phase units it is the angular phase displacement, i.e. the angle between the primary and secondary phase to neutral voltages, which has to be considered. This angle may be 0°, 180° or ±30° depending on the direction of the windings and the interphase connections.

All groups of transformers having the same angular displacement may be connected in parallel. Those having +30° displacement may be paralleled with −30° units, provided that the line leads are suitably transposed. Parallel operation is not possible between a 0° or 180° group and a ±30° group.

Some typical examples of connections are:

Connection	*IEC ref. no.*	*Displacement* (°)
Delta/star	Dy.11	+30
Star/delta	Yd.1	−30
Star/star	Yy.0	0
Star/inter-star	Yz.11	+30
Delta/inter-star	Dz0	0

From this it will be seen that parallel operation is not possible between star/star and delta/star units. If the turns ratios of the transformers are not identical, a circulating current traverses the transformer windings, increasing the no-load losses. The magnitude of this circulating current for the case of two transformers A and B is

$$I_s = (V_A - V_B)/(Z_A + Z_B)$$

where V is the no-load secondary voltage for a common primary voltage and Z is the leakage impedance, all quantities being complexors.

The relative values of the percentage (or per-unit) impedance determine the proportion of the total load shared by each transformer. Thus, when all the percentage impedances are identical, each transformer will take its fair share of the load. Although it is advisable to have this condition, dissimilar impedance units may be connected in parallel in an emergency, provided that the current carried by any transformer does not exceed its normal rating or an acceptable overload value.

The percentage resistance drops of the transformers need not be the same. A difference in resistance drop, when the percentage impedances are numerically equal, results in an angular displacement of the individual transformer currents and reduces slightly the maximum permissible output. This is not normally of serious consequence.

33.11 Auto-transformers

The great advantage of the autoconnection, as distinct from the usual double-winding arrangement, is that the transformer physical size and losses are much smaller, provided that the primary to secondary turns ratio is not large. The amount of apparent reduction is termed the autofraction

$$n = (V_1 - V_2)/V_1$$

where V_1 is the higher and V_2 is the lower voltage. Thus, the equivalent frame rating of an auto is equal to n times the load or throughput rating. For a 2/1 ratio this means that the auto-transformer is half the size of a double-wound transformer for the same duty. A requirement for tappings can have a marked effect on the apparent economy of using an auto-transformer.

Unfortunately this economy is not obtained without certain liabilities, so that care is required in specifying auto-transformers unless the conditions are known and appreciated.

The calculated reactance of an auto-transformer on a frame kilovolt-ampere base has to be multiplied by n to obtain the reactance on a throughput base, e.g. a 2/1 ratio auto-transformer with a frame reactance of 4% would present an impedance of $4/2 = 2\%$ to through faults. Given a high fault MVA in-feed on the system, this could lead to short-circuit currents of more than the maximum permitted value of 25 times the normal one. System operating conditions must be clearly specified and, if necessary, additional impedance introduced to limit fault currents. It is the joint responsibility of purchaser and manufacturer to ensure that the transformer will not be subjected to excessive stresses.

The common electrical connection between the primary and secondary sides is a potential source of danger. The position of the earth connection with a three-phase star-connected auto-transformer is important and it is normally preferable to connect the supply neutral (assumed earthed) to the auto-neutral, and not to have the auto-neutral floating.

The use of the auto-arrangement on transformers interconnecting different voltage levels (e.g. 400/275 kV) of a transmission system enables significant cost savings to be achieved. Small units are most useful as voltage regulating devices: they lend themselves readily to the provision of tappings, and as the loads generally have constant impedance characteristics, a small unit can control a large load. Consider a 10 kW, 400 V heating load, taking 25 A in an equivalent resistance of 16 Ω. It is required to control the heat in five steps by adjustment of the secondary load voltage E_s, using an auto-transformer. The secondary current for each tap is $I_s = E_s/16$, and the corresponding primary current is $I_p = I_s(E_s/400)$. The winding currents are I_p, in the part corresponding to $(400 - E_s$, and $(I_s - I_p)$ in the remainder. The winding could be graded to carry the maximum current in each portion, and it should be noticed that the 100 V tapping currents are less than those already determined for any portion of the winding. It is an axiom that, for constant impedance auto-transformers, any tappings below half the supply voltage do not influence the transformer size. The equivalent kVA is the sum of the part winding kVA values, divided by 2, and for the example this is 1.65 kVA.

33.11.1 Auto-starters

The principles above are applied to auto-starter transformers for three-phase induction motors. The value of the equivalent motor impedance (assumed constant) is:

$$Z = 1.25V/\sqrt{3}kI = 0.72V/kI$$

where V is the supply voltage, I is the full-load current of the motor and k is its ratio between short-circuit current and full-load current. The winding currents are determined according to the number of tappings. These currents are of short duration.

33.12 Special types

33.12.1 Static balancer

The static balancer is a simple apparatus which in its three-phase form comprises an ordinary three-phase transformer core carrying two windings per limb in zig-zag connection. Normally, when connected to a three-phase line the balancer draws only a small magnetising current. When a load is connected between one line and neutral, however, so that the current balance of the feeders is upset, the load current flows through the balancer windings. This condition is illustrated in *Figure 33.27*, the current distribution being based upon a 100 A line-to-neutral load. Each balancer winding carries one-third of the neutral or out-of-balance current, and has one-third of the line voltage impressed across it. The rating of the balancer as a three-phase transformer is therefore $2(\sqrt{3}V/3)(I/3)(3/2) = 0.58\ VI$, where V is the line-to-neutral voltage, I is the neutral current and VI is the one-phase load being balanced.

(1) To supply a one-phase load. A balancer will be found to be cheaper than a one-phase transformer connected across two lines, and much cheaper than a three-to-one phase transformer. Overload protection is provided by a fuse in the load circuit as shown in *Figure 33.27*(*a*), and the balancer neutral current corresponds to the load current.
(2) To improve the voltage regulation of four-wire networks. Balancers have in the past been used chiefly for this application. The improved regulation has been useful on rural distribution systems with isolated one-phase loads. The balancer rating depends upon the out-of-balance current of the system, which usually is taken as 20% of the three-phase line current.
(3) To transform a three-wire system into a four-wire one. Fuses, or even a circuit breaker, must not be employed in the balancer line. If one fuse were to blow, the neutral current would have to flow through the high-impedance paths offered by the sound balancer limbs and there would be a rise in the line-to-neutral voltage on the sound phases.

33.12.2 Welding transformers

Owing to their simplicity, economy and efficiency, transformer welding sets predominate over their rotary machine d.c. counterpart. Stick electrodes have been specially developed

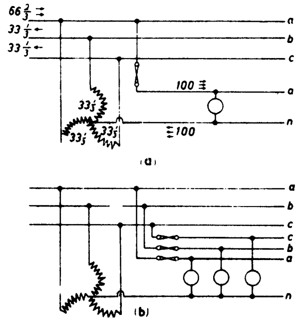

Figure 33.27 A.c. static balancer applications

for a wide range of applications for use on a.c. sources, but even where a d.c. source is imperative, preference is shown for transformer/rectifier equipment over rotary machines.

The basic requirement for a.c. welding is a low-voltage power source (70–100 V), with an adjustable series inductor to ensure stability of welding current and provide phase shift between the source voltage and the welding current, enabling the arc to be re-struck in each half-period after the current has passed through zero.

Power sources are supplied for use either by individual operators when part of the series inductive reactance may be incorporated in the transformer, or by groups of operators when a single multiphase transformer of relatively low impedance provides low-voltage (90 V) supply through a number of separate adjustable inductors. In the latter case advantage can be taken of the diversity factor in minimising the power rating of the transformer. For general-purpose applications standard a.c. single-operator welding sets are also available with inbuilt rectifiers and a smoothing inductor enabling the operator to use a wider range of electrodes.

The inherently high reactance of the source produces a very low p.f. load on the supply which, owing to its variability and intermittent nature, cannot be continuously corrected by capacitors.

However, some correction is both possible and desirable, and most single-operator sets are designed to house a capacitor of a size recommended by the supplier. The performance of welding power sources, specified in BSEN 60638, covers the basic requirements for the majority of applications, but for other uses such as consumable electrode shielded gas systems, the characteristics of the welding set play a fundamental part in determining the quality of the weld. Typically, in transformer/rectifier power sources the internal impedance of the sets is very low and the open-circuit voltage is little more than the arc voltage; this produces a high rate of change of welding current when the arc length varies, and automatically adjusts the burn-off rate. In the past most welding sets supplied for the British market have been oil cooled, and these are most suitable for the onerous conditions found, for instance, in shipyards; but the development of new insulating materials has enabled air cooled dry-type sets increasingly to take their place in less onerous conditions and where light weight and portability are valuable.

33.12.3 Mining transformers

The operating conditions in coal mines impose special requirements on transformers for use underground. There must be no possibility of a defect in the equipment itself causing an explosion of the gaseous atmosphere in the mine, and head-room is normally extremely limited.

Until the early 1950s, special low-height oil filled non-flameproof mining transformers were used underground up to within 300 m of the coal face. The switchgear directly mounted on these transformers was of certified flameproof construction. As the size of the load increased, the problems of voltage drop in the low-voltage cables between the transformer and coal face machinery became greater, leading to the need for a completely flameproof transformer (and associated switchgear) which could be taken close to the coal face. The modern flameproof underground transformer is an air insulated unit constructed with class C insulation and contained in a flameproof case.

33.12.4 Small transformers

Small transformers are made in large numbers for electronic apparatus and similar equipment. The open construction has been superseded by a hermetically sealed arrangement in air filled or oil filled metal containers. The connections are brought out through metal/glass or metal/ceramic seals soldered to the container. Transformers for mobile equipment, which may be operated at 400–1600 Hz for the sake of the saving in weight and size, are made of relatively costly materials to obtain larger magnetic and electric loadings. Thus, very thin cold-rolled silicon steel or thin nickel-iron cores may be used with coils insulated by high-temperature dielectrics such as glass fibre, silicones, etc. In this way a 30 VA, 1.6 kHz, fully sealed transformer weighs about 0.1 kg compared with its open-type equivalent manufactured in 1940 weighing 1 kg or more.

33.13 Testing

The normal practice for testing power and distribution transformers is to carry out a comprehensive set of tests at the maker's works—the number and nature of which depends on whether the transformer is the first of a new design or otherwise—and a few relatively simple tests after installation at site to prove that the transformer is ready for service. The three classes of works tests are referred to as 'type' and 'routine' and 'special'. The first transformer of a particular design or contract is subjected to both type and routine tests, while routine tests only are applied to later units. Special tests are only required at the specific request of the purchaser.

33.13.1 Routine tests

Routine tests consist of:

(1) voltage ratio, polarity and phase displacement checked;
(2) winding resistance measured;
(3) insulation resistance measured;
(4) load loss and short-circuit impedance measured;
(5) no-load loss and magnetising current measured;
(6) dielectric routine tests; and
(7) tests on on-load tap changers, where appropriate.

33.13.1.1 Ratio, polarity and phase displacement

Figure 33.28 shows the type of circuit used for measuring ratio. This involves the use of a 'ratiometer', which basically consists of a multi-ratio transformer from which tappings are taken to coarse and fine adjusting switches. The ratiometer and the transformer under test are connected in opposition. When the ratiometer is adjusted to give a ratio exactly equal to that of the transformer under test, no current will flow in the secondary circuit. The ratio can then be read directly from the dial readings on the ratiometer. Polarity and interphase connections are checked by measuring voltages between various terminals when the transformer is energised at a low voltage.

33.13.1.2 Winding resistance

The d.c. resistance of each phase of each winding is measured separately by the voltammeter method and is recorded together with the temperature of the winding at the time. This information is required for use in connection with later measurements of the load loss and the temperature rise of the transformer under rated load.

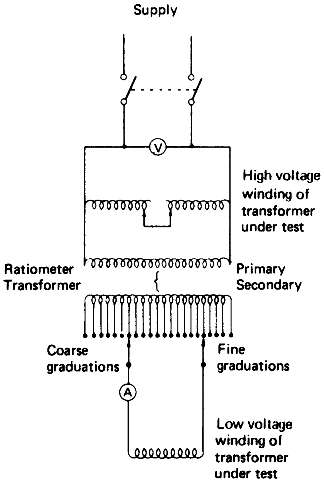

Figure 33.28 Ratio test

Because of the inductive effect of the core, care must be taken to ensure that a steady d.c. value is reached before voltage and current readings are recorded.

33.13.1.3 Insulation resistance

The insulation resistance between windings and from each winding to earth is measured by a special instrument such as the Megger or Metrohm.

The insulation resistance is commonly used as one of the criteria for determining that the transformer has been properly dried out. It varies widely and inversely with temperature, and care is necessary to ensure that the readings are correctly interpreted.

33.13.1.4 Load loss and impedance

Load loss and impedance are measured by short-circuiting the terminals of one winding of the transformer and applying a low voltage to the other winding sufficient to cause rated full-load current to flow. Because the applied voltage, and, hence, the magnetisation of the core, is extremely low, the core loss can reasonably be neglected and the measured input power represents the total load loss at rated load on the complete transformer. The short-circuit is applied to the low-voltage winding and the supply is connected to the high-voltage winding, at which side all readings are taken. In principle, the same result would be obtained if the high-voltage winding were short circuited and the supply connected to the low-voltage winding, but this involves measuring the heavier low-voltage rated currents, which may be too large for convenience.

In the past, a 2-wattmeter method was allowed to measure load loss of smaller transformers, but this method is no longer accepted and three wattmeters are necessary to make the measurement. Alternatively, an Electronic Power Analyser may be used to measure all quantities on a single instrument with higher accuracy.

It is important that the test is performed at normal frequency to ensure the correct proportioning of the PR and stray losses in the windings and structure of the transformer, which are dependent on frequency.

In transformers with exceptionally high reactance the voltage that has to be applied to circulate rated full-load current through the windings, even under short-circuit, may be sufficient to magnetise the core to a level at which the loss therein may be significant. In such cases the core loss during the short-circuit test may be determined by removing the short-circuit and measuring magnetising loss when the transformer is excited on open circuit, at the previously measured voltage required to circulate full-load current. The true load loss is then the difference between the two successive measurements.

It is important that the short-circuiting connections are substantial and applied in such a manner that the loss therein does not represent a significant fraction of the loss within the transformer. It is also important that the temperature is measured at the time that the load loss measurements are made, so that the necessary correction can be made to deduce the copper loss at the temperature (75°C) at which guarantees normally apply. IEC 60076 details the manner in which the load loss measurements at any given temperature can be corrected to the equivalent figure at 75°C.

33.13.1.5 No-load loss and magnetising current

The fundamental principle of this test is that normal rated voltage is applied to one winding while the other is left open circuit. The current flowing in the winding to which the supply is connected is the magnetising current and this is recorded as part of the test records. This magnetising current is normally a small percentage of the full-load current and the I^2R loss is negligible compared with the core loss. To avoid unnecessarily high voltages in the test circuit during the core loss test, it is normal practice to connect the supply to the lower voltage winding of the transformer (see Section 33.2.3).

33.13.1.6 Dielectric routine tests

Dielectric routine tests consist of an applied-high-potential (separate source test), a short duration a.c. test or a long duration a.c. test in combination with a swithing impulse test, dependent on the voltage rating, and a lightning impulse test, dependent on the voltage rating.

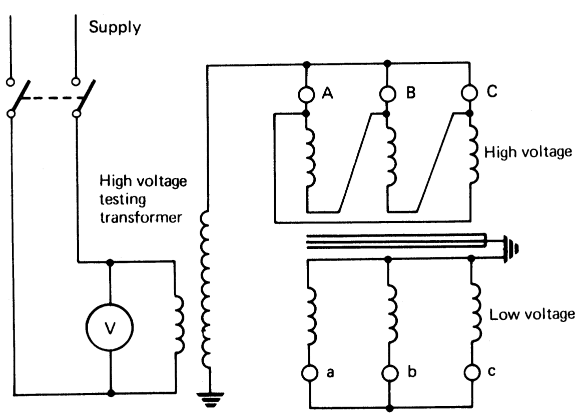

Figure 33.29 Connections for applied-high-potential test

Applied-high-potential tests These tests are normally made, in turn, between each winding, and the core and all other windings connected to earth.

Figure 33.29 shows the arrangement with the high-voltage winding under test and the low-voltage winding and core connected together and to earth. The magnitude of the applied potential test depends on the rated voltage of the winding in question and on whether the major insulation between it and earth is uniform or graded. For a uniformly insulated winding the applied voltage test provides the principal dielectric test of the main insulation. It is usually of the order of $(2E+1)$ kV, where E is the 'highest system voltage' for the winding in question. Full details are given in IEC 60076. On a three-phase transformer an applied voltage test of $2E$ raises the line terminals to 3.46 times their normal operating voltage to earth.

For graded insulation windings the applied voltage test is at a value appropriate to the insulation level at the neutral point and therefore does not adequately prove the strength of the line-end insulation.

Short-duration a.c. test This induced voltage test is a short duration a.c. test that involves exciting the transformer on open circuit at a voltage higher than normal for a short period. This test is a routine test on transformers of up to 170 kV rating and a special test for transformers of higher voltage. For transformers with uniform insulation on which the applied high-potential test provides the principal check on the strength of the major insulation, the purpose of the induced test is to prove the strength of the insulation between turns and between other parts of the transformer operating at different potentials. The magnitude of the test is usually twice rated voltage, and to prevent overexcitation of the core the frequency of supply also has to be increased to at least twice normal.

On transformers up to 170 kV rating, with graded insulation the induced overvoltage test constitutes the main test of the major insulation. The magnitude of the test is fixed so that the potential to earth of each of the high-voltage terminals in turn is raised to the appropriate test voltage for the system on which the transformer is to operate. The magnitude of the test may be as high as 3.46 times normal rated voltage, and the interturn and other insulation is obviously tested to this degree at the same time.

The duration of the test is 60 s for any test frequency up to and including twice rated frequency. When the test frequency exceeds twice rated frequency, the duration of the test is for 6000 periods (i.e. 1 min at 100 Hz) or a minimum of 15 s, whichever is the greater. The magnitude of the test voltages for different system operating voltages and conditions are given in IEC 60076.

Long-duration a.c. test For transformers rated above 170 kV, the routine test is a combination of a long duration a.c. test, lasting 60 m and a switching impulse test.

The standard wave shape for a switching impulse test on air insulated equipment is of the order of 250/2500 μs, i.e. a relatively slow rise of front followed by a tail of long duration. The practical difficulty in producing such a wave from an impulse generator connected to a transformer winding (related to the generator capacity and the transformer-core saturation) has led to a relaxation of the requirements for the switching surge wave specified for application to transformer windings. Limiting features are a wavefront rise time of at least 90 μs, a time above 90% of the specified amplitude of at least 200 μs, and a total duration from virtual origin to first zero passage of at least 500 μS.

Partial discharge measurements are made during the long duration a.c. test to give a reliable check on the capability of the insulation in normal service.

Details of the tests and of the specified test levels are given in IEC 60076-3.

Lightning impulse test Although this is a type test for transformers rated up to 72.5 kV, the lightning impulse test is a routine test for all transformers of higher voltage.

The lightning impulse test simulates the conditions that exist in service when a transformer is subjected to an incoming high-voltage surge due to lightning or other disturbances on the associated transmission line.

Lightning impulse tests were introduced originally solely as type tests and, because of fears that they might cause undetected damage to the insulation of a transformer, the tests were largely confined to specially built prototype assemblies and were not applied to production units prior to going into service. Gradually it was realised that with increasing sensitivity of the equipment provided to detect insulation breakdown during the test, there was little risk of a service transformer suffering undetected damage. Still later it was appreciated that the sensitivity of the failure detection equipment was such that it would disclose hitherto unsuspected damage that might have occurred during a preceding power-frequency over-potential test. In Britain, therefore, common practice is for the lightning impulse test to follow the short-duration a.c. test, or the combined long-duration a.c. test and switching surge test.

Details of the lightning impulse test levels are specified in IEC 60076 for transformers for various system voltages. The precise form of a complete impulse test varies with customers' preferences and on whether the test is being applied as a basic type test on the first unit of a new design, or as a routine check on insulation strength following power-frequency test as described above.

The normal sequence for impulse tests in Britain is:

(1) one reduced-level full-wave (voltage between 50% and 75% of the full-wave voltage test level);
(2) one full-wave at specified test level;
(3) two chopped waves with a crest value not less than the specified full-wave test level; and
(4) one full-wave at the test level.

Evidence of insulation failure during an impulse test primarily depends on oscillograph records of the impulse voltage wave and either of the current passing through the winding under test or of the voltage induced by inductive transfer in another winding of the phase under test.

The normal sweep time for the oscillograph recording the voltage wave is 100 μs for a full-wave and a shorter time for a chopped-wave test, e.g. 10 μs. Current oscillograms are taken with the same sweep time, or preferably simultaneous records are taken of current with three different sweep times, e.g. 10, 100 and 500 μs.

It is becoming difficult or impossible to purchase new analogue impulse recording instruments and many laboratories have now installed digital recording equipment. It is important that digital recording equipment used when testing power transformers has at least a 10-bit analogue-to-digital converter in the circuit.

The current and voltage wave shapes as shown on the oscillographic records are carefully compared with each other and particularly with the traces taken during the preliminary reduced voltage shots. Any discrepancy, however slight, in the wave shape of any one of the records compared with the others indicates a change in the conditions either in the test equipment or in the transformer under test. Such discrepancies must be investigated and satisfactorily explained, and any failure to do so involves the risk of a transformer with damaged insulation being put into service. IEC 60722 states that in cases of any doubt as to the interpretation of discrepancies three subsequent 100% full-wave shots shall be applied, and that if the discrepancies are not enlarged by these tests, the impulse test is deemed to have been withstood.[12]

Before the development of the sensitive failure detection techniques now available, the principal criteria for determining whether an impulse test had been successfully withstood were that there should be no noise from within the transformer during the test, and no sign of smoke or bubbles in the oil. These remain as accepted criteria, but are now of secondary significance compared with the oscillographic procedures. The chopped wave test is not usually included when impulse tests form part of the routine tests on a transformer, because of the time involved in setting up the chopping gap and some doubt as to whether the chopped wave test is useful for the detection of defects of workmanship or material. The main purpose of the chopped wave test as part of the impulse-type test series is to increase the stress in the insulation within and between the coils adjacent to the transformer line terminal. This is normally regarded as a feature of the design rather than of the individual unit. The chopped wave test is, nevertheless, representative of the conditions that arise when an incoming surge is suddenly chopped because of a flashover of an insulator in or near the substation, and it is prudent to ensure that the transformer is capable of safely withstanding events of this nature.

33.13.1.8 Tests on on-load tap changers

With the tap changer fully assembled on the transformer the following test sequences are performed:

(1) With the transformer un-energised, eight complete cycles of operation are performed.
(2) With the transformer un-energised, and with the auxiliary voltage reduced to 85% of its rated value, one complete cycle of operation is performed.
(3) With the transformer energised at rated voltage and frequency one complete cycle of operation is performed.
(4) With one winding short-circuited, and rated current in the tapping winding, 10 tap change operations over two tap steps on either side of the middle tapping, or where any reversing switch operates, is performed.

33.13.2 Type tests

Type tests consist of:

(1) dielectric type tests;
(2) a temperature-rise test.

Until the 1950s the distinction between type and routine tests was clearly defined, but operational experience, particularly on very large e.h.v. transformers, seems to be leading towards a compromise arrangement being adopted on transformers other than on the first of a new design. In particular, a simplified impulse test is frequently specified for application to all transformers purchased by certain customers. The logic is that many weaknesses disclosed by impulse test have been found to be due to poor materials or workmanship and not to fundamental errors of design. In the light of this experience it is obviously prudent to adopt the highly sensitive impulse test, even in modified form, as a routine check on materials and workmanship.

33.13.2.1 Dielectric type tests

The lightning impulse test is a type test for transformers rated below 72.5 kV.

The long-duration a.c. test is a special test for transformers rated above 72.5 kV but below 170 kV; it is however, often requested as a type test on new designs.

33.13.2.2 Temperature test

Each new design of transformer should be subjected to a test to determine that the temperature rise at rated load will not exceed the guaranteed values. It is uneconomic, if not totally impossible, to test a large transformer at the maker's works with both full voltage applied and full-load current in the windings, as the total output would have to be supplied and dissipated in some way. On small transformers where the rating of the available test plant is equal to or greater than twice the rating of the transformer under test, it is possible to arrange two units connected back-to-back in the manner shown in *Figure 33.30*. If the ratio of both units is identical, no current will flow in the windings, but if the ratio is deliberately unbalanced (by connecting the two units on different tappings), a circulating current will flow through the two units, of magnitude governed by the out-of-balance voltage and the total impedance of the two units in series. The current is largely reactive (since the reactance of a transformer is normally considerably greater than the resistance), and the net power taken from a supply is equal to the total power loss in the two transformers under test. If tappings are not available, or are unsuitable to circulate approximately rated full-load current, it is possible to inject the requisite circulating current through a small

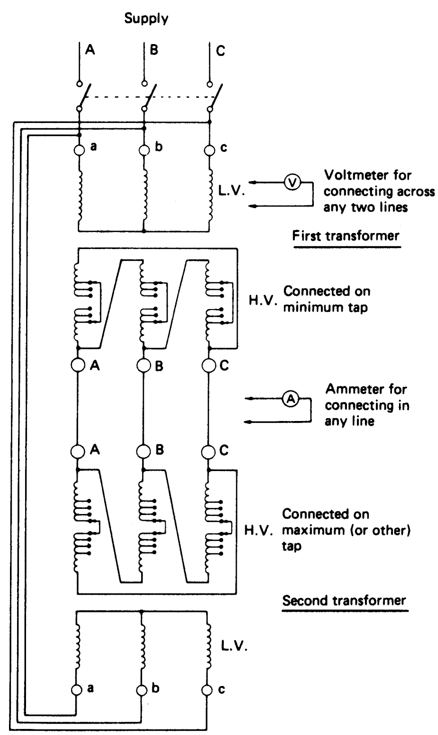

Figure 33.30 Method of connection for a back-to-back heat run

booster transformer connected in the leads running between the two main transformers.

The back-to-back connection, or direct loading, must be employed when making temperature tests on dry-type transformers, because the heat transfers from the core and windings to the cooling medium (air) are largely independent. The test conditions must therefore represent actual conditions in service when the core is heated by the magnetisation loss and the windings are heated by the load current. In oil filled transformers the heat generated in both core and windings is transferred to the oil, and the total heat then has to be dissipated from the oil to the cooling medium. Because the loss in the core is usually appreciably less than the loss in the windings, it is possible to employ the so-called short-circuit method of test.

Under short circuit the loss in the core is almost negligible and the current in the windings is adjusted to a value slightly above the rated figure, so that the total loss in the windings is equal to the sum total of the separately measured load and core losses. The procedure during a short-circuit temperature test is to load the transformer with this increased current until such time as the observed oil temperature rise becomes sensibly constant, or is not rising at more than 1°C/h. This part of the test proves that the cooling equipment of the transformer is adequate to dissipate the total losses under normal full-load conditions and the oil temperature rise is recorded accordingly.

The increased current obviously results in the temperature gradient between windings and oil being higher than when the current is at the rated value. The thermal inertia of the windings is relatively low, however, and any change in current is quickly followed by a corresponding change in the temperature gradient between windings and oil. After the oil temperature rise has been recorded, current is reduced from the increased to the normal rated value and maintained at this level for 1 h. The supply is then disconnected and the d.c. resistance of the windings measured in a manner similar to that employed prior to the loss measurement tests when the transformer was cold. By taking temperature measurements over a period of 10 m plotting a graph against time from shut-down and extrapolating back to the time of shut-down, the resistance of the windings at the instant of shut-down can be determined. The winding temperature rise is then calculated by comparing the cold and hot resistances, with an allowance being made for any fall in oil temperature during the last half-hour at rated current. Full details of the methods are given in IEC 60076.[12]

33.13.3 Special tests

Special tests consist of:

(1) Dielectric special tests.
(2) Determination of capacitances between windings and earth and between windings.
(3) Determination of transient voltage transfer characteristics.
(4) Measurement of zero-sequence impedances on three phase transformers.
(5) Short circuit withstand test.
(6) Determination of sound levels.
(7) Measurement of harmonics in the no-load current.
(8) Measurement of the power taken by the fan and oil pump motors.
(9) Measurement of insulation resistances to earth of the windings, and measurement of the loss angle (tan δ) of the insulation system capacitances.

Special tests are only carried out by agreement between purchaser and manufacturer. The most common special test carried out in Britain is the sound level test.

33.13.3.1 Sound level measurement

Because of the importance of noise as an environmental factor, the specification of a sound level limit for power transformers is increasingly common. The British Electricity Board's Specifications for various sizes of transformer stipulate maximum acceptable sound levels for each size of transformer purchased. The sound level tests, normally carried out at the manufacturer's works, are usually made at times when factory noise (including that of running test plant) can be kept to a level well below that of the noise emitted by a transformer on test. When it is necessary to make sound level tests in a more noisy environment than the noise emitted by the transformer it is necessary to use the sound intensity measurement method. It is also important that the transformer on test is well clear of walls or other large areas which would reflect sound and cause a build-up of noise which would give a false reading.

Sound level measurements made using sound pressure, sound power or sound intensity methods have bee standardised and are described in IEC 60076-10.

33.13.4 Commissioning tests at site

Commissioning tests vary considerably with the size and importance of the installation.

For a small or medium-sized distribution transformer the minimum requirements would be a visual examination for transport damage and an insulation test with a portable instrument. Preferably there should be a check of the ratio (by applying a medium voltage to the high-voltage terminals and measuring the induced voltage at the low-voltage terminals), and on the oil level and condition to confirm that ingress of moisture has not occurred. Measurements of ratio and of polarity are essential if a transformer is to be connected into a circuit where it will operate in parallel with other transformers.

On large units which are normally despatched either without oil or are only partially filled, checks must be made on the filling procedure and of the condition of the oil prior to filling, in addition to ensuring that the insulation has not become wet during transport.

After filling, a sample of oil may be taken for dissolved gas analysis (see Section 33.14.4) so as to provide a basis for comparison with similar samples taken as part of a routine maintenance procedure when the transformer is in service.

Auxiliary equipment such as on-load tap changing gear and any protective relays and current transformers associated with the main transformer must also be checked for correct operation.

In general, a repetition of high-voltage tests carried out at the works is not considered to be necessary. Where the transformer is subjected to retesting on site at high voltage, the test voltage level is normally restricted to 75% of that applied during tests at the works.

33.14 Maintenance

Maintenance can be described as the measures adopted to ensure that equipment is kept in a fully serviceable and reliable condition. Of necessity it is therefore mainly a routine involving attention at regular intervals to particular features based on service experience and manufacturers' recommendations. In the former, the measures involved tend to be general, whereas the latter tend to cover, in addition to general points, particular measures depending on the constructional characteristics of the individual manufacturer's designs. Consideration here is limited to two particular issues, namely insulating oil and solid insulation.

33.14.1 Insulating oil

Oil forms part of the main insulation of most transformers, but it tends to deteriorate in service owing to (a) operating temperature, (b) atmospheric conditions (applicable to unsealed, non-conservator-type transformers) and (c) presence of moisture or fibres.

In (a) deterioration is accelerated by prolonged high operating temperatures leading to the development of acidity and sludging, which in turn have a deleterious effect on the solid insulation. Poor ventilation in a transformer chamber (b) results in condensation inside the transformer, which similarly is liable to promote acidity and sludging. The electrical strength of the oil is considerably reduced by included moisture or fibres and particularly by a combination of both (c).

Deterioration can be greatly reduced or even arrested by attention to operating conditions and by routine precautions. Samples of the oil should, therefore, be taken from the transformer at regular intervals and the characteristics checked. With large transformers, generally speaking, little trouble is experienced with acidity, mainly owing to the lower operating temperatures. Standard British practice is to specify conservator-type transformers, and apart from one experimental installation associated with a group of generator transformers, it has not been necessary to consider the use of 'inhibited' oil. Similarly, any form of 'sealing' has in the past been considered unnecessary, for the same reasons. More sophisticated oil preservation equipment is now being specified for 400 kV transformers.

In small transformers there is a greater tendency for the development of acidity, but with modern oil (and provided that reasonable precautions are taken) no serious inconvenience should be experienced in this respect. Discharge under oil may result in the flash point of the oil being reduced, although after a relatively short period of time it may recover. Similar reduction in flash point can occur as the result of abnormal local heating such as may be experienced during the development of an incipient fault, e.g. a core fault: involving circulating currents within the core itself due to a breakdown of interlamination resistance or failure of core bolt insulation.

33.14.2 Insulation

The standard method for checking the state of insulation is by measurement of the insulation resistance. It should be noted, however, that a transformer with relatively 'wet' insulation may have a high insulation resistance when the measurement is made with the transformer cold, but the value may drop rapidly as maximum operating temperatures are approached. A hot insulation resistance reading below 1 MΩ per 1000 V rating of the tested windings is generally indicative that drying out is necessary.

When suitable equipment is available, measurement of dielectric loss angle gives a reliable check on the state of the internal solid insulation. As the value of the loss angle will depend on the transformer design, a reference value taken on the actual transformer during works test is necessary for comparison before any useful assessment can be made. A useful method mainly used in the factory for checking the state of dryness in solid insulation is the 'dispersion' test or 'recovery voltage' test, based on the fact that in dry insulation the distribution of elements is such that individual shunt paths of time constant greater than 3 ms are effectively absent and that the presence of moisture introduces time constant within the range 3–300 ms. The method of test involves the application of a 300 ms pulse followed by a 3 ms short-circuiting pulse. Any shunt paths having time constants greater than 3 ms retain their charge, which is measured as a voltage by a suitable measuring device, the measurement indicating the moisture content.

The windings of a transformer should be inspected at long-term intervals. Any slackness due to insulation shrinkage or to the falling out of packing can then be remedied either by the adjustable coil clamping screws or by packing out the winding. This operation is particularly advisable in the case of transformers subject to heavy load surges, such as furnace transformers. Large transformers are usually built with preshrunk windings, so that slackening in service is almost entirely eliminated.

33.14.3 On-load tap changing equipment

From an operational aspect, an important factor is the period of time that can be allowed to elapse before attention to the switch contacts becomes necessary. If practicable, this period should be such that it can be co-ordinated with other outages of plant. This is of particular importance with generator transformers, where outage of the unit means the non-availability of generating plant. Until comparatively recently it was normal practice to carry out maintenance after every 10 000 operations, reasonably corresponding to a normal 12-month period between generator overhauls. The modern high-speed resistor tap changer, however, requires diverter switch maintenance only after 100 000 or more operations, and tap changer maintenance is no longer a limiting factor from the operational point of view.

33.14.4 Reliability and condition monitoring in service

Ignoring short-term outages due to defects in components, the reliability of a transformer depends on the electric strength of the insulation being designed and maintained at an adequate level to withstand the stresses imposed on it by either steady-state or transient voltages.

Although rare, unexpected conditions can arise to cause insulation failure despite an apparently adequate margin of safety. Wagenaar *et al.*, refer to such incidents where discontinuities in the winding arrangement of a large generator step-up transformer responded to critical frequencies arising on the system.[7] Resonant voltages within the windings—particularly in the tapping zone—were significantly higher than those arising during impulse testing and insulation breakdown occurred. The supply authority has increased test voltage levels and introduced further tests to detect critical frequency response within the windings and to prove capability to withstand the consequent stresses.

In the long term, insulation failure can be caused by ageing. This may be due to overheating because of local cooling deficiency or overloading, or simply because of long periods of operation at or near full load. The economics of supply system operation dictate that maximum utilisation is made of installed transformer capacity, by normally loading well up to rated value and accepting some loss of life due to deliberate overloading in an emergency. In these circumstances it is essential to be able to monitor the condition of important units at regular intervals to allow action to be taken to prevent a failure in service.

The simplest and cheapest diagnostic technique available for on-line tests is by laboratory analysis of dissolved gases (DGA) in samples of oil taken from the transformer while in service. DGA can be used to diagnose the type of fault causing gas to be produced, e.g. arcing, intense local heating of conductor joints or other metal parts, with or without involvement of cellulose insulation.

IEC 60599 gives guidance for fault diagnosis which involves determining the concentration of the various hydrocarbon gases and calculating the ratio of the concentration of different pairs of gases.[14]

Table 33.3 provides a useful summary of the key gases produced by different types of fault.

A very important development has been to determine the amount of furfuraldehyde present in the oil samples.[15] Furfuraldehyde is the liquid residue of the breakdown of paper by molecular chain scission and is the only non-destructive indication of the thermal ageing of paper. It enables an assessment to be made of the 'amount of life' left in the insulation before total ageing has occurred and can be used to determine whether a transformer should be replaced.

33.15 Surge protection

Any transformer connected to an overhead transmission line must be protected against surges resulting from lightning striking the line conductors. National and international standards exist for the insulation level of lines, switchgear and transformers at all usual transmission voltages, in the context of *insulation coordination*.

Transformers are protected against lightning surges by discharge gaps which may be in the form of simple arcing horns attached to the transformer bushings, or more sophisticated surge arresters. The minimum spacing of the gap electrodes, is chosen to ensure that a flashover will not occur under normal steady state or transient power-frequency operating conditions. The voltage at which the gap will flashover following a lightning surge is known, and the insulation level of the transformer is chosen to withstand this gap voltage together with a margin of safety. (The nominal margin is 20%, but in practice it is somewhat higher, owing to the fact that the actual strength of the transformer insulation is necessarily greater than its specified level.)

Modern surge arresters are based on metal oxide technology. Under normal service conditions the arrester draws only a very small current, but under surge or overvoltage conditions the non-linear characteristics of the material allow it to draw a much larger current to supply a discharge path to the surge or overvoltage.

Whether surge arresters are used instead of the simple discharge gap depends on such factors as the severity of lightning in the area and the importance of ensuring that the individual supply circuit remains intact. A lightning surge that causes a gap discharge with either form of protection is inevitably followed by a power arc sustained by normal operating voltage. With surge arresters the non-linear characteristic causes the resistance to rise immediately the lightning discharge current (which may amount to several kiloamperes) ceases to flow. With simple arcing horns, however, a flashover of the gap due to lightning is followed by a power arc which is not self-extinguishing and which forms a direct earth fault on the phase in question. This leads to disconnection by the normal earth fault protection, although if the associated switchgear is arranged for automatic reclosing, there is only a momentary interruption.

In Britain it has been found that, in general, surge arresters are unnecessary largely because of the relative freedom from severe lightning storms and the small statistical probability of a lightning strike close to a transformer. Open-type gaps (usually referred to as 'co-ordinating gaps') give perfectly adequate protection against lightning surges with relatively slow 'fronts' (of the order of 5 μs or greater), although necessarily with the disadvantage described above in respect of continuity of supply following a gap flashover. In other parts of the world where lightning storms are intense, it is normal practice to provide surge arresters because of the better protection that they provide.

Lightning arresters are used in Britain on certain lower-voltage lines (as an alternative to the use of automatic reclosing circuit-breakers) and on some 132 kV wood pole lines without earth wires. Such lines have an inherently high insulation level to ground (compared with a steel tower line, in which a lightning surge is usually immediately discharged by a flashover of a line insulator on the nearest tower) which results in high-amplitude surges travelling along the line to the transformer.

Surge arresters are also used in certain special cases (e.g. in association with shunt inductors) where circuit characteristics are such that it is desirable to limit the magnitude of switching surges by installing an arrester to provide a discharge path. Conversely, some circuit configurations (e.g. the complex bus-bar system of a main switching station) are such as to reduce to an insignificant level any likelihood of a co-ordinating gap flashover being caused by lightning. In such cases surge arresters may be found unnecessary, even on such important installations as main generator step-up transformers.

Table 33.3 Sources of 'key gases' from decomposition of cellulose and oil

Material	*Condition and temperature*	*Key gases*	*Symbol*
Cellulose	Overheated >150°C	Carbon monoxide Carbon dioxide (Water)	CO CO_2
Cellulose	Excessive heat >1000°C	Carbon monoxide Carbon dioxide (Carbon/tar)	CO CO_2
Oil	Overheated >150°C	Methane Ethane Ethylene (Organic acids)	CH_4 C_2H_6 C_2H_4
Oil	Electrical stress (partial discharges and arcing to 1000 °C)	Hydrogen Acetylene (Waxes and water)	H_2 C_2H_2

33.16 Purchasing specifications

The essential basic information to be given is the following:

(1) standard (national or international);
(2) rated winding voltages;
(3) frequency;
(4) cooling medium (external);
(5) cooling medium (internal);
(6) ambient temperature of cooling media;
(7) transport limitations (weight, dimensions);
(8) nominal rating;
(9) number of phases;
(10) phase connection;
(11) phase relation;
(12) terminal arrangement;
(13) altitude (if >1000 m);
(14) impulse levels for lightning and switching surges (if applicable);
(15) impedance (with acceptable minimum or maximum values for limitation of fault level or voltage regulation);
(16) characteristics of transformers with which parallel operation is required;
(17) tapping range (number and size of steps, whether on-load or off-load, restriction of impedance variation over tap range);
(18) performance requirements for cyclic or emergency overloading; and
(19) special requirements (fittings, paint finish, etc.).

In addition to the technical information, listed above, the manufacturer should be advised on the basis of purchase (minimum first cost, maximum efficiency or capitalised loss). If a loss-capitalising formula is to be used, details should be provided to minimise the work of preparing and evaluating bids.

A working group within CIGRE Study Committee 12 has prepared a guide for customers' specifications for transformers 100 MVA and 123 kV and above.[16]

Specifications should set down a clear definition of technical requirements and operating conditions, and exclude detailed clauses on constructional points better left to the maker. The highly competitive transformer market, together with the normal practice of buying on the lowest tender that complies with the specification, means that the manufacturer must put forward the minimum-cost design with no extra capability not specified. It is thus important to specify every abnormal requirement.

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