Chapter 13

Design of high voltage power transformers

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13.1 Introduction

The tremendous development and progress in the transmission and distribution of electrical energy during the past 100 years may not have been possible but for the capability of linking the generator, the transmission line, the secondary distribution system and a great variety of loads, each part operating at its most suitable voltage [1]. This linking of systems at different voltages has relied on a simple, convenient and reliable device – the power transformer. This unique ability of the transformer to adapt the voltage to the individual requirements of the different parts of the system is derived from the simple fact that it is possible to couple the primary and secondary windings of the transformer in such a way that their turns ratio will determine very closely their voltage ratio as well as the inverse of their current ratio, resulting in the output and input volt-amperes and the output and input energies being approximately equal.

13.2 Transformer action

A transformer essentially comprises at least two conducting coils having mutual inductance. The primary is the winding which receives electric power and the secondary is the one which may deliver that power as shown in Figure 13.1. The coils are usually wound on a core of laminated magnetic material and the transformer is then known as an iron-cored transformer. The modern iron-cored transformer has so nearly approached perfection that for many calculations it may be considered a perfect transforming device. In the simplest form of the theory of the transformer it is assumed that the resistances of the windings are

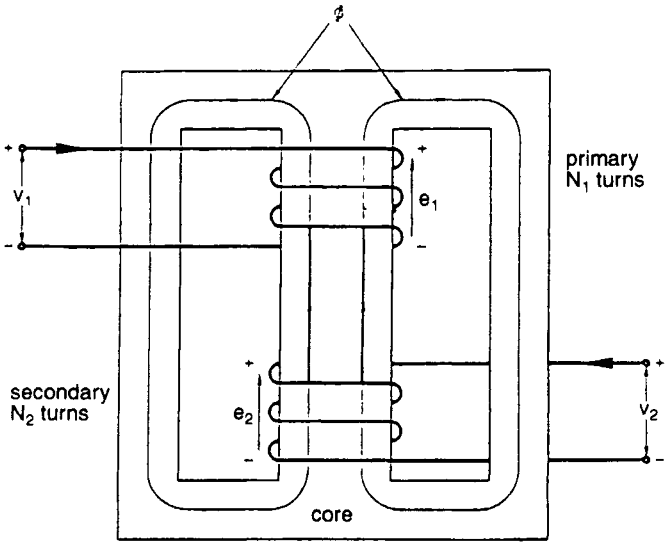


Figure 13.1 Schematic diagram of a transformer showing positive directions of voltages and currents

negligible, that the core loss is negligible, that the entire magnetic flux links all the turns of the windings, that the permeability of the core is so high that a negligible magnetomotive force produces the required flux, and that the capacitances of the windings are negligible. That is, the transformer is assumed to have characteristics approximating to those of an ideal transformer with no losses, no magnetic leakage and no exciting current. Thus, the instantaneous terminal voltage, v_1, is numerically identical to the instantaneous voltage, e_1, induced by the time-varying flux linkages, which in turn is equal to the number of turns in the coil N_1 multiplied by the rate of change of flux linkages. Thus, for the primary,

$$v_1 = e_1 = N_1 \frac{d\varphi}{dt} \tag{13.1}$$

For the secondary circuit similar criteria apply:

$$v_2 = e_2 = N_2 \frac{d\varphi}{dt} \tag{13.2}$$

The parameter φ is the resultant flux produced by the simultaneous actions of the primary and secondary currents, and therefore

$$\frac{v_1}{v_2} = \frac{N_2}{N_1} \tag{13.3}$$

Thus for an ideal transformer the instantaneous terminal voltages are proportional to the number of turns in the winding, and their waveforms are identical.

The net magnetomotive force required to produce the resultant flux is zero and the net magnetomotive force is the resultant of the primary and secondary ampere turns; hence, if the positive direction of both primary and secondary currents are taken in the same direction about the core, then

$$N_1 I_1 + N_2 I_2 = 0 \tag{13.4}$$

that is, for an ideal transformer,

$$\frac{I_1}{I_2} = -\frac{N_2}{N_1} \tag{13.5}$$

The minus sign indicates that the currents produce opposing magnetomotive forces.

The performance of a transformer depends on a time-varying flux and therefore in the steady state a transformer operates on alternating voltage only. The transformer is therefore a device which transforms alternating voltage or alternating current or even impedance. It may also serve to insulate one circuit from another or to isolate direct current whilst at the same time maintaining alternating current continuity between circuits.

13.3 The transformer as a circuit parameter

In the simple theory it may be assumed that the transformer is electrically perfect. In a more comprehensive theory of its electrical characteristics, however, account must be taken of some 'aspects which are not ideal' which occur in iron-cored transformers. First of all the windings have resistance; second, the windings cannot physically occupy the same space and there is magnetic flux leakage between the coils of the transformer; third, an exciting current, albeit small, is required to produce the flux; and fourth, there are hysteresis and eddy current losses in the core. Furthermore, where rapid rates of voltage change occur, then the capacitances relating to the windings can no longer be neglected.

When a transformer is supplied with power through a transmission circuit whose impedance is relatively high, the primary terminal voltage may vary with changes in load over an undesirably large range, because of changes in the impedance drop in the transmission circuit. Therefore, to maintain the secondary voltage at its desired value under varying conditions of load and power factor, it is often necessary to provide tappings to vary the turns in one of the windings (Figure 13.2). Large tap-changing power transformers are also frequently used to control the flow of reactive power between two interconnected power systems or between component parts of the same system, whilst at the same time permitting the voltages at specified points to be maintained at desired levels. Often the tap-changing apparatus is designed so that the ratio of transformation can be adjusted whilst the unit is on-load without interruption of the load current. Various types of on-load tap-changer are available, the most commonly used type being high speed resistor equipment. More will be related on this topic later in this chapter.

The voltage transformation effected by a transformer is accomplished at the expense of an exciting current. This has a power component which corresponds to the no-load loss which is practically all confined within the core, and there is a reactive component which corresponds to the reversible magnetisation of the core and is wattless. At no-load also there is a loss due to current travelling through the copper conductors. This is usually small. There is also a loss in the insulation which is usually minute.

The in-phase and reactive components of the excitation current depend on the quality and thickness of the core steel used, the flux density, the frequency, the quality of the joints and the overall length of the magnetic circuit. It is totally independent of coil design. The

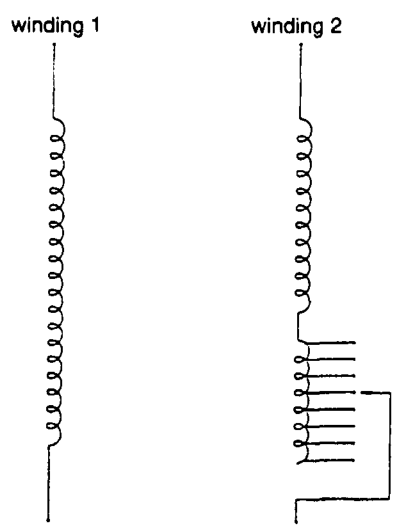


Figure 13.2 Voltages regulation diagram

desirable qualities in a core are minimum values of both the power and reactive components. Of these two, the former is by far the more important consideration.

13.4 The core

One of the most significant improvements in transformer manufacture has been the ongoing development and introduction of higher grade core steels [2]. Prior to the turn of the century, soft magnetic iron materials were used for transformers (Table 13.1). Early in the century, however, silicon steels were produced which gave very much reduced losses. Prior to World War II, metallurgists were able to produce steels in which the grains were oriented in the direction of rolling, making them much easier to magnetise and thus reduce losses. By the early 1970s, Japan was beginning to lead the world in steel production and this included core steels. By clever metallurgical methods they were able to introduce a variety of low-loss steels which are known universally as 'Hi-B'. The technology was licensed to other countries including the UK. 'Hi-B' steel is now in common usage throughout the world. In 1980 various steel companies, led principally by the Japanese, were producing ever thinner core steels. Whereas in 1960 most core steel used in the UK was 0.35 mm thick, the Japanese have perfected 0.18 mm thick materials, and even thinner materials are under development. However, the cost of the very thin materials, together with cutting and handling, becomes almost prohibitive and alternative methods of loss reduction have proved to be more economic. These methods include the use of laser or other scribing methods which break up the long grains of the 'Hi-B' steels, thus allowing easier rotation of those grains, and make the steel much more easy to magnetise.

There was a further benefit noted in respect of the noise level of the transformers which indicated a 2–3 dBA reduction. Such a reduction is extremely important in Japan and is becoming increasingly important in Europe, especially in densely populated areas.

Table 13.1 Core material development

Date	Material
1885	Soft magnetic iron
1900	Nonoriented silicon steel
1935	Grain-oriented silicon steel
1970	Hi-B
1980	Thin Hi-B
1983	Laser scribed Hi-B

The introduction of the grain-oriented materials has certainly reduced both the magnetising current and the loss components of current day cores. However, by making it easier for core materials to be magnetised along the grain, it usually means that it is more difficult to magnetise the materials across the grain. Inevitably, in any transformer design the flux must be persuaded to turn through angles, usually of 90 °. Adjacent to joints between plates, the flux must change direction. This introduces localised power and quadrature components which can be substantially higher than those components which appear away from the joint. The method used to reduce the effects of change of flux direction is to mitre the joint at an angle. The optimum angle for conventional grain-oriented materials is normally recognised as being of the order of 55 °. However, cutting at this angle increases the amount of waste material as the angle on the corresponding plate must be cut at 35 °. The economic optimum angle of mitre is 45 °, as the loss difference between 55 ° and 45 ° is small, and the waste is small.

As has already been stated, change of direction of flux introduces additional losses. Thus if cores are clamped by bolts passing through holes in the core plates, the flux must change direction to circumvent the holes, and this introduces higher local losses in the bolt regions (Figure 13.3). A large proportion of the transformer industry has therefore developed from bolted cores to banded cores. In general, this move has

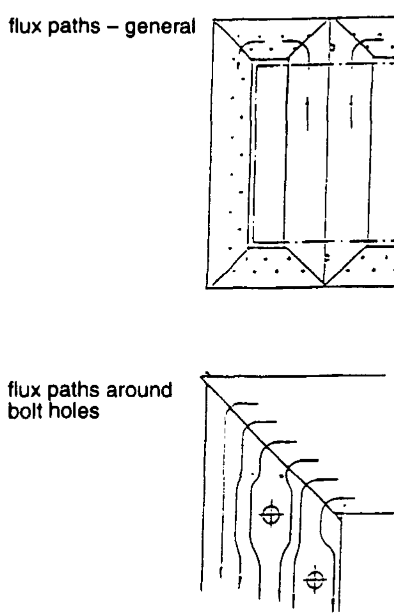


Figure 13.3 Core construction – mitres and bolt holes

tended to reduce noise levels of transformers in addition to about a 3% improvement in the no-load loss.

Thus the transformer designer is faced with a large number of core steel grades (Table 13.2) but the better the grade the higher the price; the choice depends on economics (Table 13.3). When the high grade, thin laser-etched 'Hi-B' material first came onto the market, the author's company manufactured four transformers which were identical in design, with one exception. That exception was that two transformers were produced with high 0.30 mm thick 'Hi-B' steels which up to that time had been widely used, and the other two cores were built from 0.23 mm thick laser-scribed 'Hi-B' material. The test results (Table 13.4) demonstrated reduction of 27% or thereabouts in the no-load loss.

Table 13.2 Grades and losses of electrical steels

Type	Grade	Loss, W/kg 1.7 T, 50 Hz	Relative loss % of that of M103–27P
Conventional	M111–35N	1.41	144
	M097–30N	1.30	133
	M089–27N	1.23	126
	M120–23S	1.11	113
Hi-B	M117–30P	1.12	114
	M105–30P	1.00	102
	M103–27P	0.98	100
	M100–23P	0.92	94
Etched Hi-B	23ZDKH	0.92	94
	27ZDKH	0.84	86

Table 13.3 Typical net worth of core steels for a single phase, 50 Hz generator transformer operating at a flux density of 1.7 Tesla. Base material M103–27P

Type	Grade	Net worth with capitalisation at £3000/kW
Conventional	M111–35N	− 1230
	M097–30N	− 720
	M089–27N	− 460
	M120–23S	− 180
Hi-B	M117–30P	− 330
	M105–30P	− 65
	M103–27P	0
	M100–23P	+ 40
Etched Hi-B	23ZDKH	+ 70
	27ZDKH	+ 180

Table 13.4 Comparison of tested parameters of 45 MVA transformers manufactured from two grades of core steel (Courtesy Alstom T&D Transformers Ltd.)

	Original transformer (30M2H)	Duplicate transformer (23ZDKH)
Load loss		
Unit 1	280 kW	280 kW
Unit 2	281 kW	281 kW
No-load loss		
Unit 1	20.1 kW	14.3 kW
Unit 2	19.7 kW	14.2 kW
Noise		
Unit 1	66 dB	64 dB
Unit 2	68 dB	65 dB

Transformers are frequently of 3-phase construction, although track-side transformers and those transformers for which weight or dimensions are critical features of the specification may require single-phase designs. For 3-phase cores, a 3-limb design with each limb carrying windings may be used (Figure 13.4). In this case the leg section and the yoke section areas may be identical. Where transport height becomes critical or where the zero-phase sequence impedance of the transformer is required to be equal to the positive phase sequence impedance, a 5-limb construction is often used. In this case the three inner legs of full section area are equipped with sets of windings and outer legs are provided to recirculate some of the flux. This reduces the magnitude of flux which must be transferred directly between phases and permits reduction in the yoke section areas. Economics provide the control thereafter. Some core designs will have the inner yokes of area 60% of that of the main wound limbs with the outer yokes and outer legs of 40% area. Other variations of 58/44%, 50/50%, 60/60% main to outer yoke section areas are commonly found amongst various manufacturers. For single-phase designs, there are a large number of possible variations. These include a 3-limb construction with only the centre limb wound, a 2-leg construction with both legs wound, a 4-limb construction with two limbs wound, and a complex cruciform core construction with the windings linking one leg on each of the cores forming the cruciform.

The losses in the core materials can be subdivided into two principal groups. First there is the hysteresis loss which is inherent in the material and is a function of the metallurgy and of the flux density. The second component is the eddy loss which results from currents circulating within the laminations due to the flux which is passing through them. This is a function of the resistivity of the material, the dimensions and, of course, the flux density. The core steel manufacturers have worked on the metal-

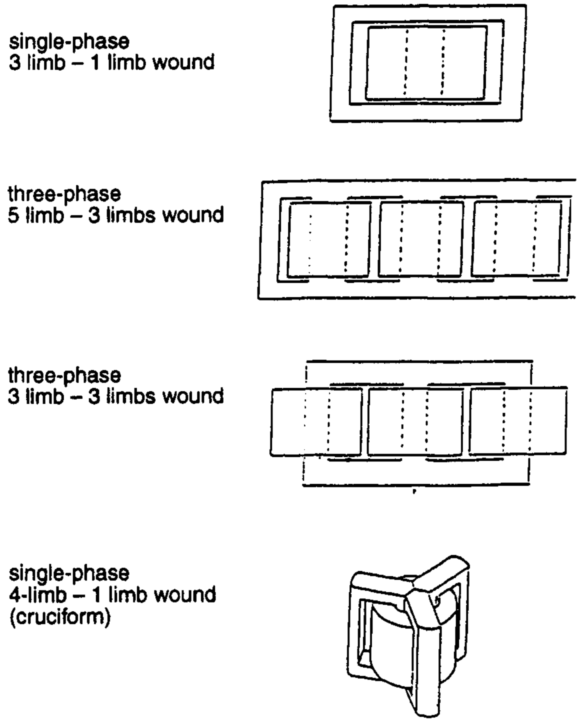


Figure 13.4 Core types

lurgy to reduce the hysteresis components and on the thickness of the material to reduce the eddy components. The ultimate aim is to achieve high permeabilities and low losses at high flux densities.

The coreplates are usually cut on high speed, high accuracy, automatic machines using sharp tools to ensure that burrs and slivers are eliminated so far as is possible. The plates must be built layer by layer, usually no more than two plates at a time, with alternate layers displaced to give a rigid mechanical system when the whole core is fully clamped. Multiple displacement of adjacent layers, using a process known as step-lapping, provides a reduction in the no-load sound pressure level of the transformer by up to 8 dBA and reductions of between 3 and 8 per cent in no-load losses have also been claimed. The core constitutes by far the heaviest component of the transformer.

13.5 The windings

Windings also form an essential feature of any transformer. Various winding constructions may be used and, in the UK, and indeed in most of

Europe, the arrangement used is the core-type transformer with concentric windings. Essentially a core-type transformer is one in which the windings are assembled over a core leg. The second type of transformer is known as the shell-type in which the windings are normally of rectangular pancake construction which are sandwiched and encapsulated by the core. This type of transformer finds its greatest support in the USA, although a number of other manufacturers throughout the world tend to construct to this principle. This chapter will concentrate on the core-type transformer which has virtually exclusive utilisation in the UK.

The type of winding used depends on the current and the voltage. A very high current winding will normally be associated with a low voltage and hence few turns. The principal design intent is to accommodate as much of the conducting medium in the smallest physical space possible. To achieve this, the most straightforward and simple winding is the helical type in which each turn is wound successively against its neighbour (Figure 13.5). As the windings become larger it becomes more difficult to remove the heat generated due to the losses within the winding, and cooling ducts inevitably are required. The so-called spaced spiral winding therefore becomes necessary. This winding type is essentially the same as the helical winding except that cooling ducts are introduced between the turns. As the voltage increases, the current tends to decrease and therefore the windings tend to be of smaller section conductors but of many more turns. Eventually, the economics of space utilisation demand a change from the simple helical or spiral construction to a disc arrangement. As the voltage increases further, the insulation between the conductors, especially the discs adjacent to the line end of the winding, reach the point where additional insulation becomes uneconomic to apply. The dielectric control within the winding may then be achieved by introduction of electrodes of controlled potential inserted within the winding. This latter type is known as the intershielded disc type winding. Ultimately further complications have to be introduced in the design and manufacture of the disc winding, and a feature known as the interleaved disc winding, invented by George Stern of English Electric in the early 1950s, now has worldwide appeal (Figure 13.6). It must be noted that not all of the core-type transformer manufacturers utilise disc windings. A number of companies have continued the principle, once used by some UK manufacturers, of multiple layer construction.

Considering next the conductor material, it is recognised that the best electrical conductor is silver. However, the use of such material in transformers is totally uneconomic, and copper is the next best alternative. There are also certain financial and sometimes technical reasons for the use of aluminium instead. The conductors themselves may be round, particularly where a very large number of turns with low voltages between them are involved. Power transformers, however, tend to use rectangular conductors. These conductors may come in a variety of

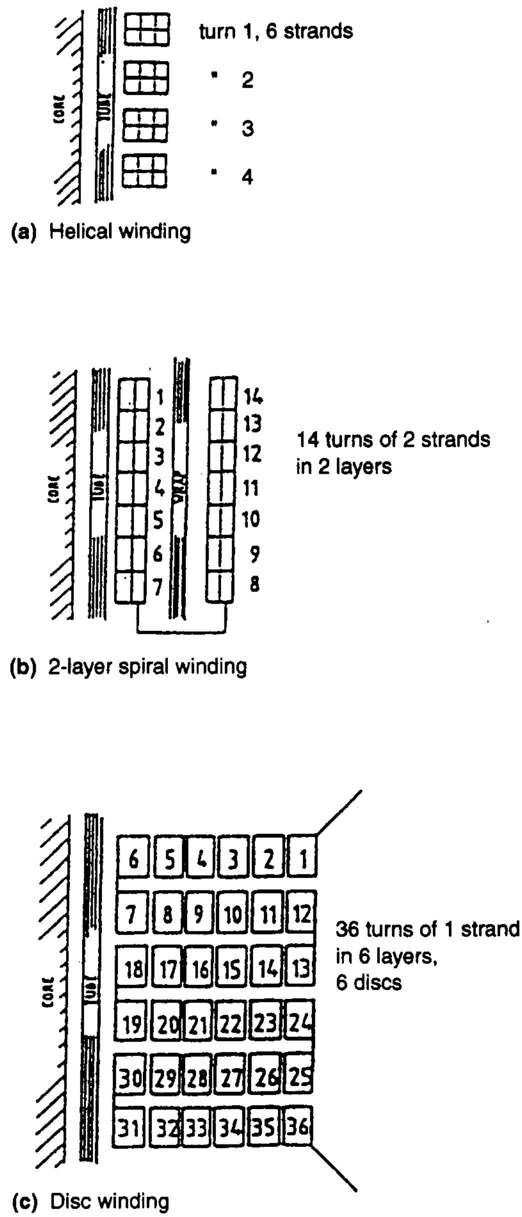


Figure 13.5 Types of transformer windings

forms, either individually as strip conductors, or in paired or triple format with reduced insulation between the individual conductors of the bundle whilst maintaining a high value of insulation between adjacent turns of the winding. The conductors may be laid side by side or end to

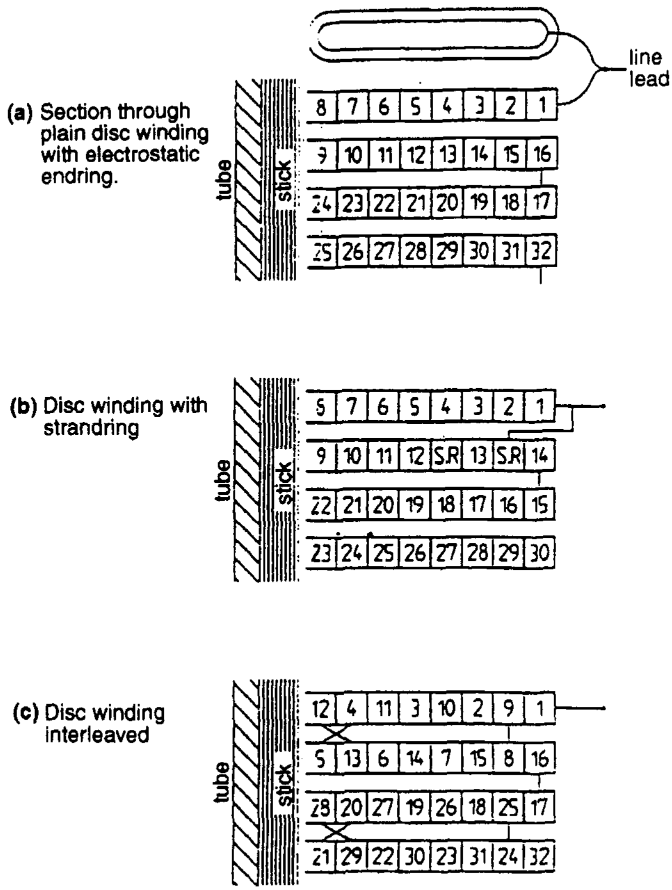
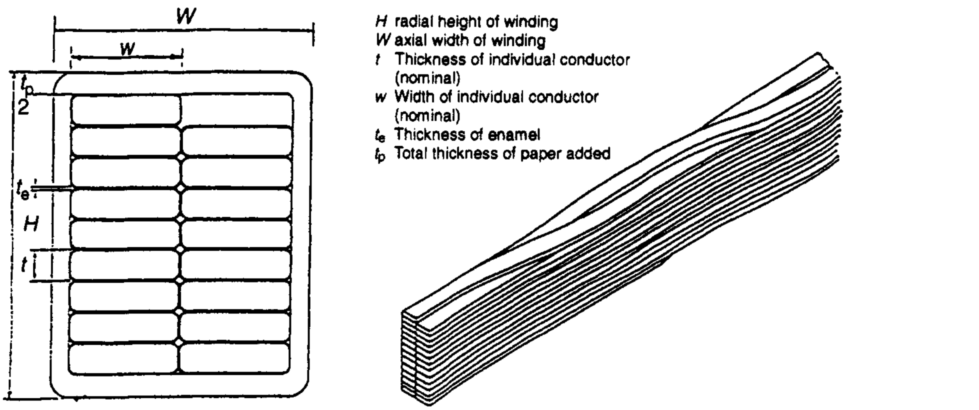


Figure 13.6 Methods of increasing series capacitance in disc windings

end. A further alternative is continuously transposed cable which comprises a number of rectangular copper conductors each insulated with an enamel, transposed with one another at regular intervals along the cable length, and the whole of the bundle wrapped with an insulating material to provide the interturn insulation (Figure 13.7). Where very few turns are involved, the use of foils, either of copper or aluminium, may find preference.

Essentially a transformer requires two windings. However, there are frequently regulating windings which are usually associated with the high voltage winding. These regulating coils may on occasions simply be tappings brought out from the main high voltage winding or alternatively wound as a completely separate winding for reconnection with the high voltage winding at some point outside the winding assembly. Such a separate tapping winding may be wound concentrically outside



Arrangement of winding with continuously transposed conductors

General view of transposed-strip conductor (27 strips in parallel)

Figure 13.7 Continuously transposed conductors

the HV winding or concentrically inside the LV winding (Figure 13.8). In addition, the high voltage winding may be split into two parallel components with the tapping winding also split to permit the high voltage line lead to pass between the two halves. There are sometimes requirements to split the HV into series components to achieve a specific impedance or to reduce some of the force components under short-circuit current flow conditions. This arrangement is known commonly as 'double concentric'. The arrangements may be further complicated by the addition of other windings and a locomotive transformer may typically have four primary high voltage windings, four secondary low voltage windings and five tertiary windings, all having specified impedances between each pair of windings, thus controlling the physical location of each of the many windings with respect to any other [3].

13.6 Cooling systems

A winding carrying current will be subject to a loss in the conductor simply due to the resistance of that conductor. This component of loss is known as the I^2R loss. The current passing through the coil creates a magnetic field, and eddy currents are created in the conductors within that field, giving increased loss. This eddy loss is not uniformly distributed because the field is not uniform. Furthermore, if each conductor does not physically occupy a space in an identical field to that of any

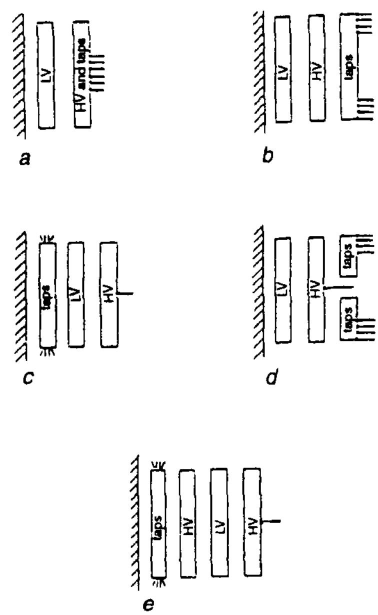


Figure 13.8 Winding arrangements

other conductor to which it is ultimately connected, the voltage induced in each interconnected conductor will be different from its neighbour and circulating currents will result. All of these load and parasitic currents create loss and this loss must be extracted and carried away from the windings to a position at which it can be dissipated. The commonly used cooling medium is transformer oil, although other synthetic fluids, gases or even air, are found in a range of power and distribution transformers.

In fluid systems there is a choice of flow conditions. Flow may be natural, i.e. the oil flow results from convection. Alternatively, a pump may be used to induce a higher rate of flow than simple convection will permit. This forced system will provide greater efficiency of heat transference. Within the winding there is the possibility of having nondirected flow or directed flow.

In the former case the flow is again determined solely by convection, and in the latter case the flow paths are predetermined by the designer to further improve the efficiency of heat transfer from the winding conductors to the fluid. The choice of natural or forced flow lies with the purchaser, who selects the type of flow according to the local conditions. The choice of directed or nondirected flow within the windings of the transformer is usually the choice of the designer.

The oil flow velocities are also usually the choice of the transformer design engineer. There are no mandatory limits on oil velocity, although each manufacturer will impose his own velocity limitations. Very high oil velocities, especially with very dry oil conditions, induce electrostatic charge which may be concentrated in local areas of insulation causing partial discharge and tracking and may ultimately lead to dielectric failure.

13.7 The insulation

The life of transformer insulation is generally determined by the highest temperature which appears within the winding, this highest temperature being known as the hotspot temperature. This usually appears near the top of a winding and probably in the first or second disc from the top. Of course, the actual hotspot position is totally a function of the design and manufacture. Only the transformer manufacturer has access to all the information to determine the position of the hottest spot, at the present time, although direct measurement methods are under consideration.

Just as it has been identified that transformer oil is the most common cooling fluid used in transformer manufacture, it is also an excellent insulant although dielectrically inefficient in large volumes. Conductor insulation is usually paper. Paper itself is not mechanically strong and when dealing with the heavy weights of copper involved in a winding or in the short-circuit forces, a much more substantial insulation in the form of board is required. Major inroads have been made over the years in relation to the quality of insulation materials. The most commonly used insulating board material is made completely from wood. A number of companies, however, mix wood with cotton. By using the relatively long cotton fibres the oil impregnation of the pressboard material is usually easier to accomplish. The conservationists will also argue that cotton is an annual product and therefore its use is environmentally friendly and reduces the rate of depletion of the forests. Unfortunately, however, harvesting the cotton is a very labour-intensive operation and costs are rising. Other systems at lower ratings may use cast resin as the insulant and air as the coolant. Higher temperature systems are available using synthetic fluids which include silicone and are usually associated with higher temperature grade solid insulations such as Nomex and resin or polyester glasses [4, 5]. These materials are very much more expensive than paper and pressboard. In general, however, they are mechanically stable in moist air, whereas paper and pressboard systems are subject to moisture absorption and dimensional changes. Hybrid insulation systems, which utilise high temperature insulation only in the immediate vicinity of the hotter components, principally the conductors and leads, and cellulose materials and transformer oil elsewhere are becoming increasingly common where space is at a premium. These hybrid insulation systems tend to be cheaper than completely high temperature systems and are used typically in transformers used aboard trains.

13.8 The tank

Having considered the core, the windings, the insulation and the cooling fluid, it is obvious that another principal feature of the transformer must be the container used to encapsulate the fluid. As well as being called on to meet the rigours of nature in its allocated environment for periods for 30, 40 or perhaps even 50 years, this tank is required to sustain the vacuum necessary for oil filling, to withstand the pressure exerted by the oil in normal operation, and to withstand the forces imposed during transportation at least twice in its lifetime. In addition, many of the forces which appear within the transformer under short-circuit current conditions are effectively restrained to some degree by the tank. Tanks are therefore usually of mild steel, but on occasions it may be necessary to introduce nonmagnetic steels or other materials to reduce stray losses or the temperatures resulting therefrom.

13.9 The bushings

Connections are required between the system on the primary side and the primary winding of the transformer and between the secondary winding of the transformer and the secondary system. This interconnection requires a device which will permit the high voltage leads to pass through the tank which is normally at earth potential for safety reasons. This interconnection is achieved by the provision of bushings. Lower voltage bushings comprise a through stem which is centrally located in conjunction with an insulating system which has an external surface and which is mechanically coupled to a mounting flange which is then affixed to the tank opening. Such a bushing may be of the noncondenser type and, for in-air use, may have epoxy resin major insulation or alternatively have oil contained within a shedded porcelain.

For higher voltages, a higher level of control of the voltage distribution is often required and condenser bushings are used. The major insulation is either oil impregnated paper or epoxy resin bonded paper, with the oil or the resin being introduced under vacuum. Very thin metallic foils are inserted at regular intervals within the layers of paper making up the major insulation. The inner foil is often the longest and is electrically bonded to the current-carrying conductor. The outer foil is usually the shortest and is electrically bonded to the fixing flange of the bushing. One or two of the intermediate foils may be electrically connected to bushing tappings, which may be used either for check power factor measurements or to drive low power, voltage-measuring circuitry. In normal operation the power factor tapping is connected to earth.

A number of termination possibilities are available – oil/air bushings, oil/SF_6 bushings, oil/oil terminations for ongoing connection to a cable, oil/semi-fluid compound-type terminations or a moulded-type bushing which makes protected but direct connection to a cable.

13.10 On-load tap-changers

On-load voltage regulation has been referred to above. The device which performs this on a transformer is known as an on-load tap-changer. In the USA, reactor-type tap-changing is still available and is frequently used, but the rest of the world uses high speed resistor-type tap-changing. The on-load tap-changer is a device which includes a series of switches which operate in a pre-set sequence to permit the load current to flow throughout the operation [6]. The tapping which is adjacent to the one which is in service is preselected by the tap selector. The service tapping selector switch carries the load current. A switching device transfers the current flow from a direct connection to one which permits the current to be bypassed through a resistor. The switching movement then continues such that the selected and the preselected tapping are both permitted to share the load current, and an additional circulating current created by the voltage difference between the selected and preselected taps is restricted in magnitude by two resistors in the circuit. The switch then continues to move to break contact with that resistor which is connected to the previously selected tapping. Finally, by further switch action, the second resistor is taken out of the circuit. The switch is designed to operate very quickly and the resistors are therefore only required to have short time ratings. It is therefore essential that the operation is not interrupted in order that the tap-changing equipment is fully protected. The complete sequence is therefore actuated by a motor drive mechanism which operates through geneva gears to operate the tap selector switches and simultaneously to wind up an energy spring mechanism which actuates the load current breaking or diverter switch. The diverter switch operating cycle is carried out only when the spring is released, independently of the motor drive mechanism. The actual current transfer time is of the order of 40 to 60 ms, but the total time for one tap-change between initiation of the motor drive mechanism and the completion of the tap-change operation amounts to between 3 and 10s, depending on the type and manufacture of the on-load tap-changing equipment.

High speed resistor tap-changers are classified into two groups, the first being the separate tank tap-changer and the second the in-tank tap-changer. As the name implies, the separate tank tap-changer divorces oil of both the selector and diverter tank from the oil in the main tank of the transformer. For the in-tank type tap-changer the selector switch operates within the main tank oil but the diverter oil is maintained in a separate system. Whilst the UK has had a general preference for the separate tank tap-changer, it must be recognised that the in-tank type tap-changer has a very much greater world population. The principle of in-tank tap-changer design offers greater flexibility in matching the tap-changing equipment to the transformer than does the separate tank tap-changer. Furthermore, the number of solid insulation surfaces which are under high dielectric stress in the in-tank design are limited, with the critical surface being associated with the insulating drive tube. The major insulation is thus oil whose quality is easier to maintain and check. With the in-tank tap-changer, however, a certain amount of gas is produced by capacitance current sparking, and many believe that this will disguise any gases which may emerge from the transformer core and windings. Analysis of hydrocarbon gases dissolved in the transformer oil is an important part of condition monitoring.

13.11 Design features

Transformer design is a complex process taking into account dielectric, electromagnetic, thermal and mechanical aspects, many of which are interrelated. The design engineer is, therefore, equipped with a number of calculation tools to confirm the capability of the transformer which he has designed.

13.12 Dielectric design

Dielectrically, the winding is designed to have certain duties. It must be satisfactory for the voltage conditions which appear in normal operation, and must also be capable of meeting any overvoltage conditions which are impressed on it. This capability is demonstrated in the final test of the transformer as an induced overvoltage test at power frequency. Normally, the voltage which is induced in this test is at least twice the normal rated voltage between any parts. The transformer in service also has imposed on it transient voltages in the form of lightning and switching impulses. The lightning impulse, in particular, is of very short duration (Figure 13.9). Because of this, the capacitances of the windings have a much more predominant effect than at power frequencies. The voltage distributions within the winding are therefore determined by capacitance networks, at least for the first 2 or 3 μs of the impulse wave arriving at the terminal. The capacitance network of the transformer winding assembly gives a nonuniform voltage distribution throughout the coils

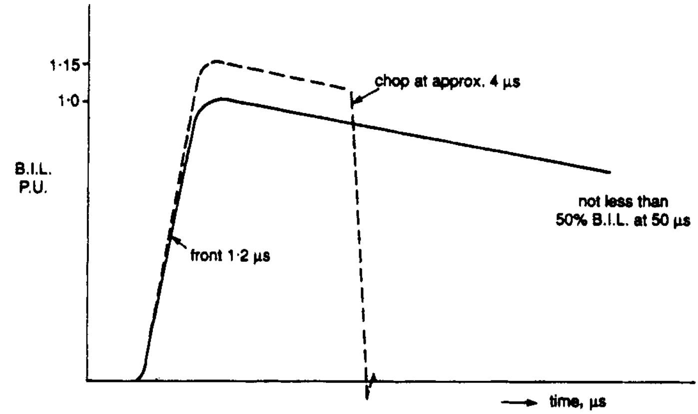


Figure 13.9 Standard impulse waveshape

(Figure 13.10). The highest voltage drops appear at the turns of the winding which are closest to the impinging lightning impulse wave. If the voltage wave was a step function then ultimately a linear voltage distribution would occur. Between the initial distribution and the final distribution, therefore, considerable variations can appear at various parts of the winding. The effect is similar to that which would be achieved by holding a piece of elastic between the live and neutral terminals on a graph and then stretching the elastic to follow the curve of the initial distribution. On letting go of the elastic, oscillations are produced which eventually die to give the linear stretch between the two fixed points. The voltage distributions within the winding under stepped wave application give similar effects.

Usually, control of the amount of insulation on the conductors is determined by the capacitive distribution. Thus, overinsulation of the line end turns may be a cheap and viable solution. However, the feasibility of this method decreases with increasing voltage level. Other solutions then become necessary. The first is the utilisation of shields within the winding. These may either be of the form of covered rectangular conductors inserted between turns of the winding or alternatively as toroids having a metallic coating which are inserted between the discs. By interconnection of the shields with a part of the coil closer to the line end, the capacitance network may be modified and a more linear initial distribution obtained. The distribution is characterised by the value of the square root of the ratio of the shunt to series capacitances in the network. The closer this value is to zero, the more linear is the voltage distribution. In the winding design, variation of the series capacitance is often easier to accomplish than variation of the shunt capacitance. In the intershielded construction, the shields effectively increase the series capacitance, especially at the line end. There are other methods of increasing

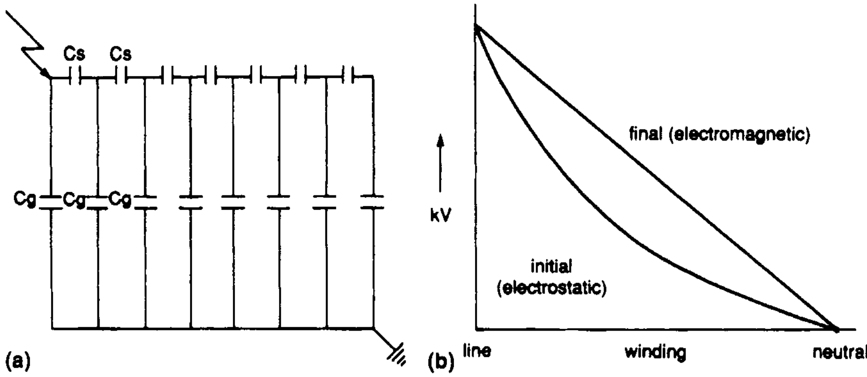


Figure 13.10 **(a)** *Equivalent capacity network;* **(b)** *impulse voltage distribution*

the series capacitance, the most notable of which is the interleaved disc construction to which reference has already been made. The interleaving is accomplished by reconnecting the conductors so that the charge circulates through each disc twice. The interconductor capacitances which act in parallel give a very high series capacitance and improve the degree of nonuniformity of the initial voltage distribution.

The enhancement may be taken further if there are a number of conductors electrically in parallel. It is then possible to achieve various combinations of capacitance throughout the coil. This is known as grading and by careful grading from fully interleaved through partial interleaving to no interleaving, i.e. continuous disc, the initial distribution may be even further improved.

The windings are required to be separated electrically and often mechanically. This separation is essentially by solid insulation materials but, to introduce cooling oil to the windings, it is common for the insulation to be provided as a combination of solid and oil. In this respect, advantage is taken of the phenomenon whereby a small oil volume is capable of withstanding a greater stress than a large volume. In most major insulation, therefore, the solid insulations serve as barriers to break up the oil spaces into smaller volumes. Nevertheless, it is normally the oil which provides the weakest link. Under power frequency and also lightning impulse conditions, the voltage distribution within the major insulations is controlled by capacitive effects and hence by the relative permittivities of the insulating materials. For transformers which are connected to DC equipment and are therefore subject to DC voltages, it is the relative resistivities of the materials which provide the voltage control. Whereas the permittivity ratio of paper to oil is of the order of 2 to 1, the ratio of resistivities can achieve 100 to 1. The effect of this is that the stress is concentrated within the solid insulation with generally very low stresses appearing in the oil. However, where the solid insulation terminates abruptly, very high stresses may appear at the boundary between the solid and the oil [7]. This could lead to breakdown commencing in the area. The DC field is thus very different from the AC field within a transformer. DC testing in the field on an AC transformer is therefore not a viable alternative to repeating the factory test conditions.

13.13 Electromagnetic design

A transformer is, of course, an electromagnetic device and in operation electromagnetic fields are induced. The effects of these fields are various. Eddy losses are induced in the conductors of the windings when carrying current. Electromagnetic fields exist outside the windings as well as within them and flux is attracted to, and perhaps concentrated within, magnetic materials, whether these be the core structural steelwork, the tank or devices which are deliberately installed to affect the field.

The leakage flux produced by the equal and opposite primary and secondary ampere turns spreads out at the ends of the windings and circulates, some through the core and some between the outer winding and the tank and some through the tank and other metalwork (Figure 13.11). The flux which impinges on or travels within metallic components induces eddy currents and gives rise to loss and temperature increase. To control either temperature rise or the level of loss, or both, knowledge is required of the electromagnetic field. Analogue methods of field solution are possible but are extremely limited in application and inaccurate in operation. Rapid developments in computation have resulted in considerable flexibility, accuracy and improvements in response time. Mathematical solutions may be derived either by finite difference or finite element methods [8]. A number of finite element analysis software packages are currently available for the solution of two- or three-dimensional (Figure 13.12) fields.

Knowledge of the electromagnetic field forms only part of the requirement; the capability of controlling such a field is also extremely important. Control of electromagnetic fields takes two forms. The first is flux attraction and the second is flux rejection. Each plays its part in the manufacture of large power transformers.

It has already been mentioned that the leakage field associated with load currents spreads out at the ends of the winding. The introduction of magnetic shields above and below the windings will effectively straighten the field at the ends (Figure 13.13) and usually give some reduction in the eddy losses within the windings themselves. In addition, as these magnetic flux shunts are located between the windings and the metallic structural framework, they effectively shield the framework from

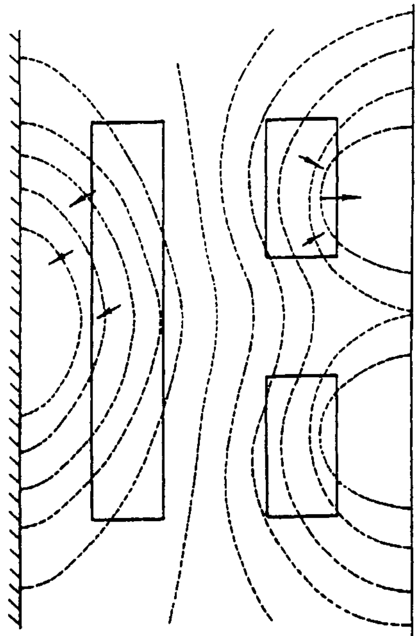


Figure 13.11 *Electromagnetic flux and force distribution (courtesy: Alstom T&D Transformers Ltd, Stafford)*

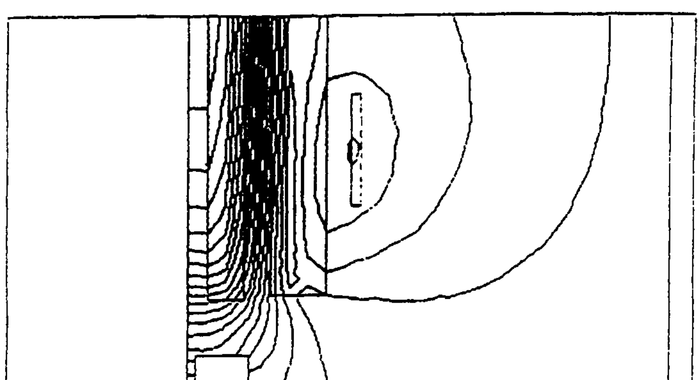


Figure 13.12 *Field plot of a typical transformer without flux shunts or rejectors (courtesy: Alstom T&D Transformers Ltd, Stafford)*

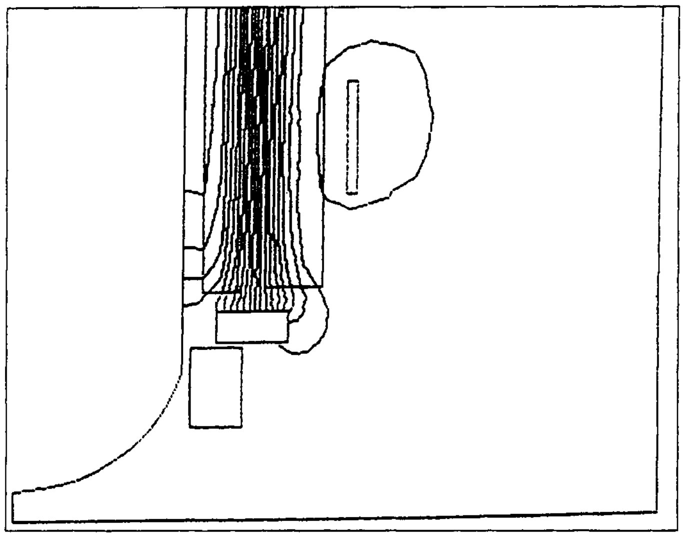


Figure 13.13 Field plot of a typical transformer with winding end flux collectors (courtesy: Alstom T&D Transformers Ltd, Stafford)

impinging flux and reduce stray loss in the structural materials (Figure 13.14). As the shunts provide an attractive sink for the flux, less flux impinges on the tank, with resulting reduction in tank wall loss and tank heating. It is also possible to provide magnetic shunts on the tank wall. This has the purpose of directing the flux through laminated material, giving lower losses than would result from direct impingement on the tank wall.

The second method of electromagnetic flux control is by rejection. The provision of conducting shields, usually of aluminium or perhaps copper, has the effect of preventing flux penetration, provided a sufficient thickness of material is available. Before the advent of sophisticated finite element modelling software, the use of rejectors presented the difficulty of determining where the rejected flux was actually transferred and consequential effects.

13.14 Short-circuit forces

As every electrical engineer knows, when a conductor which is carrying current lies within a changing magnetic field, it experiences a force. This force is proportional to the square of the current. The transformer is required to be capable of withstanding through fault currents and hence the forces resulting from the peak value of those currents must be resisted and the design prepared accordingly. The action of the forces is complex but, for simplicity, they may be resolved into axial and radial

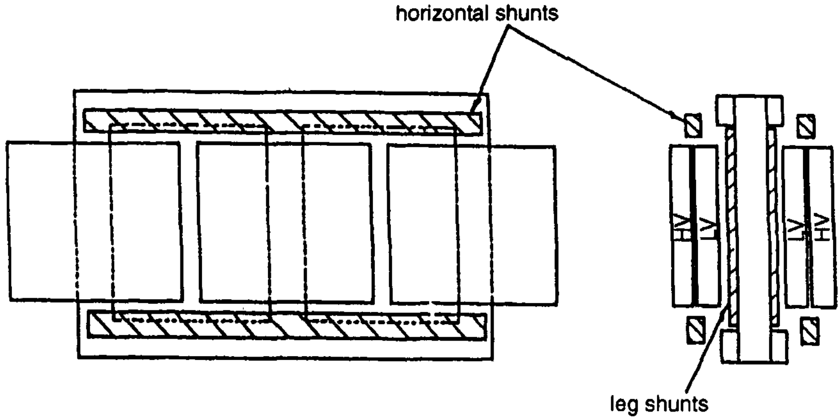


Figure 13.14 Leakage flux shunts

components. The axial component of the force results from the radial component of the flux and vice versa. It may be shown that for a simple two-winding transformer the axial force on a conductor is greatest at the ends of the coil and acts towards the centre of that coil. The summation of the forces gives rise to a compressive stress which is maximised at the coil centre. The radial component of the force acts on the inner winding radially inwards and is greatest at the centre of the coil. On the outer winding, it acts outwards, thereby imposing a hoop stress on the conductors. Furthermore, any imbalance of the ampere turns of the two windings, either by design intent or by manufacturing tolerances, will give rise to forces on the ends of the windings. Mechanical engineering takes over from electrical engineering in the design of the transformer in these respects.

13.15 Winding thermal design

The heat generated by the currents passing through the winding conductors must be extracted and transferred to some other part of the cooling system for dissipation. To achieve this, the winding is equipped with a labyrinth of channels which permit oil to come in contact with the covered conductors, extract the heat and, by induced convection or forced flow, carry it from the winding assembly (Figure 13.15). The heat flow is affected by the proximity or otherwise of conductors to a cooling oil duct, the thermal conductivity through the paper and the oil velocity over the exposed surfaces of the winding. For disc-type winding constructions, the bulk of the exposed surface of a coil usually lies in the horizontal plane. To achieve greater efficiency of heat removal, it is

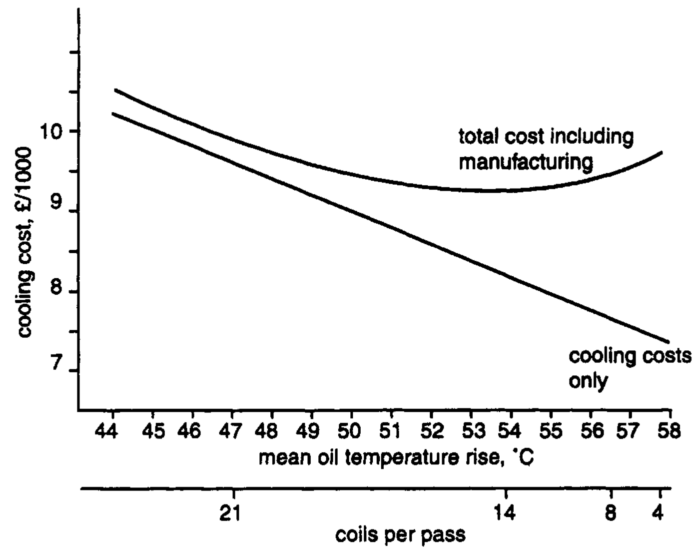


Figure 13.15 Relationship between cost of cooling a typical transformer and the number of disc coils between oil restriction washers

necessary, especially under forced oil conditions, to persuade the oil to flow past these surfaces. This is achieved by inserting oil restriction washers alternately at the inside and outside diameters of the coil. The number of horizontal ducts which are located between these restriction washers has an effect on the winding to local oil gradient (Table 13.5). For forced oil flow conditions, the rate of flow also has an effect on the gradient. Increasing the flow beyond a certain level (which depends on the particular design) has little effect on the gradient (Table 13.6).

High oil flow rates, as stated previously, may give rise to charge build-up with a phenomenon known as streaming electrification [9].

13.16 Conclusion

The power transformer is a device which has been in use for more than 100 years. Its principles have not changed in that time, but the efficiency of material utilisation and the quality of those materials most certainly have. Core steels, solid insulation materials and insulating fluids have shown considerable strides in their development to fulfil the demands of the market which requires a very high level of reliability, more power per unit volume and weight and economy in operation. Transformer design has kept in step with these developments, increasing the efficiency of material utilisation by a more accurate and more effective calculation for every aspect of transformer manufacture, test and service. Continued

Table 13.5 Temperature effects of varying the number of disc coils per pass

Coils per pass	9	18
Winding hot spot rise above ambient air, °C	55.4	59.6
Winding average rise above ambient, °C	45.7	47.0
Hot spot to average difference	9.7	12.6
Winding oil rise difference	4.4	4.4
Winding over local oil	5.3	8.2

Table 13.6 Temperature effects of varying oil flow rates in a typical transformer

Oil flow	+ 20%	Nominal	- 20%	- 50%
Average winding rise above ambient, °C	45.4	45.7	46.1	47.1
Hot spot winding rise above ambient, °C	54.1	55.4	56.9	61.5

investigation into transformer features and the wider application of sophisticated calculation methods [10] confirm that transformer design is not a mystic art but a science. Experience is vital in leading the ongoing development, but the benefits of new ideas emanating from unopinionated minds is essential in stepping up the gearing to produce ever more reliable units in shorter times and at reduced prices. Transformers may be an old idea but new brains will always be needed and welcomed in the industry.

13.17 References

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