TRANSFORMERS, DRY TYPE

In a general sense, transformers are the electrical counterparts of mechanical transmissions. In a very similar way to gear boxes or pulleys, which modify the speed of rotation and the torque of mechanical machines, transformers allow voltages and currents to be altered to suit any particular need. In both cases, energy conversion is achieved with a minimum of losses.

Transformers are one of the most widely used electrical components, and their range of application is virtually endless. They are found in very-low-power electronic circuits and in large power generation and transmission installations. They can handle millivolts to megavolts, milliamperes to kiloamperes, and milliwatts to megawatts. Moreover, they are available for the full spectrum of frequencies used in electrical and electronics applications, from a few hertz to gigahertz. Transformers are usually classified according to their application, such as electronics, audio, video, radio frequency, high frequency, instrument, generator, distribution, and power transformers. Each of these classes can further be subdivided into various categories.

The term *power transformers* refers to a class of transformers whose main function is to supply electrical energy mainly at 50 Hz or 60 Hz. They cover a range from a few watts to hundreds of megawatts. The larger units are used in power systems either in generating stations or distribution substations. At the generation end, three-phase transformers increase voltage from approximately 15 kV to the higher voltage levels required by transmission systems. Power transmission voltages range from 110 kV to 765 kV depending mainly on the length of the transmission lines and the power level. At the receiving end, transformers reduce voltage to distribution levels that vary from 4.6 kV to 36 kV. Large industrial consumers are fed at distribution levels, while for small residential customers, additional transformer banks lower the voltage to levels on the order of 120 V to 600 V (i.e., either single- or three-phase values). Such transformers are usually referred to as distribution or power distribution transformers.

Another approach for classifying transformers is in terms of their cooling and insulating medium. High-voltage units are usually immersed in an oil tank. The use of oil achieves two purposes. First, it absorbs the losses generated in the magnetic core and conductors and transfers the heat to the tank or to an oil-air heat exchanger. Second, oil insulates the high-voltage conductors and other live parts from the core and the tank. In a different type of unit, the dry-type transformer, the primary cooling function is ensured by a gas, usually air, and more rarely fluorocarbons or sulphur hexafluoride. Very often, air constitutes the main insulating medium. Various other solid insulation materials complete the insulation system.

Dry-type transformers are usually subdivided into three categories: electronic, control, and power transformers. The electronic transformer category includes all units found in electronic apparatus either connected to the mains or not, such as high-frequency transformers found in switching mode power supplies. Their capacity varies from a fraction of a voltampere to several hundred voltamperes. Control transformers are used in industrial and commercial installations to feed control circuits (as indicated by their name) and low-power auxiliary circuits. A residential bell transformer and a 120 V to 24 V transformer used to feed control panel pilot lamps are typical examples. They are low-voltage units (less than 600 V), and their capacity varies from a few VA to 3 or 5 kVA. The power transformer category range begins at 1 kVA and is commercially available up to 20 MVA and up to the 36 kV class. There is some overlap at the lower capacity end between power and control categories. However, the short-circuit impedance of a control transformer is lower than its power counterpart. Furthermore, the control transformer windings are more compact, and elaborate cooling arrangements, such as ventilation ducts, are not present. Even if a large part of the present article applies to all dry-type transformers, the main focus is on power dry-type transformers.

POWER DRY-TYPE TRANSFORMERS

Originally limited to low-power and low-voltage applications, advances made in plastic technology during and after World War II made power dry-type transformers commercially viable. Insulating material with higher thermal capabilities enabled less bulky units to be manufactured. The best known of these new materials is probably the Nomex paper, developed by Dupont. In the 1970s, the banning for environmental reasons of polychlorinated biphenyl-based oils (PCBs) opened indoor applications to alternative insulating materials whose fire-retardant properties are an essential characteristic. Advances in such materials allowed higher-voltage units to be brought to the market. Recent insulating material developments and new components, such as vacuum interrupters, have further expanded the field to new areas, such as voltage regulating applications.

At present, dry-type transformers are used extensively for low- and high-voltage applications in commercial, residential, institutional, and industrial buildings. Unlike their oil-filled counterparts, they are not considered a fire hazard and are predominantly installed indoors. While high-voltage units are located in a main substation normally close to the switching apparatus, smaller step-down units are distributed throughout the building in auxiliary electrical rooms to provide lower voltage supply.

Rectifier, converter, and motor-drive transformers represent yet another important sector for dry-type transformers. In such cases, transformers constitute a single component in a larger system. Their role is to adjust the voltage level at the input of the power electronics stage. However, special care should be taken. Indeed, these units usually carry nonsinusoidal currents; therefore, important derating factors must be applied to account for additional losses. Such transformers are heavier and bulkier than standard units.

TRANSFORMER OPERATION

Two fundamental physical laws govern transformer operation: Faraday's and Ampere's laws. The first law states that the voltage e induced in an N-turn winding is proportional to the rate of change of the magnetic flux linking this winding.

$$e = N\frac{d\phi}{dt} \tag{1}$$

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering.* Copyright © 1999 John Wiley & Sons, Inc.

The second law stipulates that the summation of the products of the number of turns and current of each winding is strictly zero:

$$\sum_{i=1}^{n} N_i \cdot I_i = 0 \tag{2}$$

For the two-winding transformer shown in Fig. 1, an ac voltage applied to winding 1 creates a magnetic flux in the core. This flux is seen by winding 2, and a voltage is induced in the second winding. The core channels the flux in a closed magnetic circuit, thus enabling much higher flux densities than in air. Due to the very high relative permeability of the core, fringing is minimal. The induced voltage has the same frequency and the same waveform as the applied voltage. However, its amplitude is proportional to the turns ratio m.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = m \tag{3}$$

A current will flow in winding 2 when a load is connected to its terminal. This current forces a current to flow in the first winding in order to satisfy Ampere's law. Again this current has the same frequency and waveform as the current that induced it. Moreover, its amplitude is inversely proportional to the turns ratio.

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{m} \tag{4}$$

The last two equations can be combined to show that the power flowing into the load is equal to the power taken from the source:

$$S = E_1 \cdot I_1 = E_2 \cdot I_2 \tag{5}$$

The winding connected to the source is called the primary winding or simply primary, while the winding connected to the load is called the secondary.

If the load impedance is Z_2, the impedance reflected to the primary Z_1 is equal to the load impedance multiplied by the square of the turns ratio:

$$Z_1 = \frac{E_1}{I_1} = \frac{m \cdot E_2}{\frac{I_2}{m}} = m^2 \cdot Z_2 \tag{6}$$

The transformer shown in Fig. 1 constitutes an ideal representation. In fact, several other phenomena should be taken into account to obtain a complete and usable model. Figure 2 shows the general equivalent circuit of a power transformer. This model includes the copper and iron losses, the excitation current, and the leakage inductance.

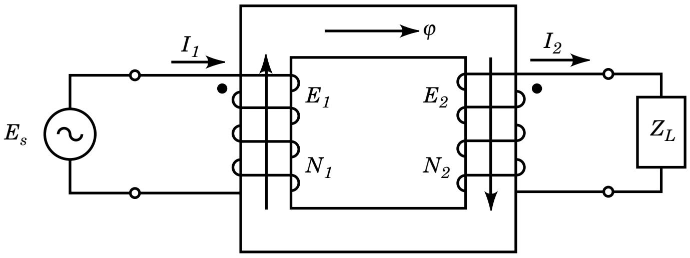

Figure 1. Principle of operation.

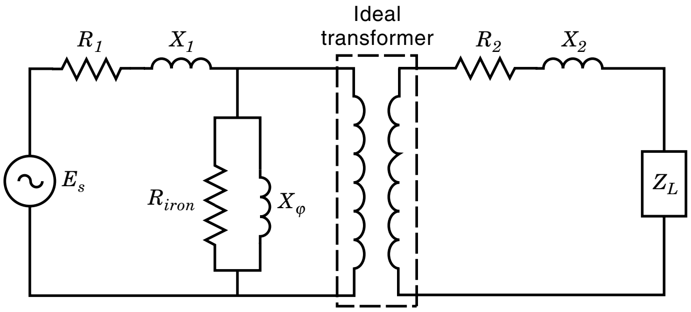

Figure 2. Transformer general equivalent circuit.

When a current flows in a conductor, losses are generated. Such losses are proportional to the square of the current flowing in the windings and are represented by resistors R_1 and R_2. The value of these resistors is usually measured under dc conditions with the transformer at room temperature. Their value is temperature-dependent and increases by approximately 0.4% per degree Celsius. Due to skin and proximity effects and induced currents, this resistance also increases with frequency. The losses due to the latter are usually referred to as stray losses. At power frequency, stray losses cause resistance to increase by 1% to 10%. Larger units are more affected than smaller ones. At 1000 Hz, stray losses can attain two to three times dc losses. Therefore, such losses greatly degrade the performance of transformers that feed nonlinear loads, such as rectifiers, switching power supplies, magnetic ballasts, and variable-speed drives. Such transformers should be derated, often by as much as 30% to 40%, to maintain temperature rises within acceptable limits. When this is not done, the transformer overheats and can fail catastrophically.

In any transformer, the electrical energy consumed by the load is transferred from the primary winding to the secondary winding through magnetic flux linkages. Because of the layers of air that insulate the coils from each other, the magnetic flux lines produced by the primary winding do not completely link the secondary coils. There is, consequently, some magnetic energy trapped in the flux between the windings, more commonly referred to as the leakage flux. This energy being proportional to the square of the currents, leakage flux is modeled by two reactances X_1 and X_2 in series with the winding resistors. Normally, X_1 and X_2 have the same value in per unit or in percent. For usual applications, their value is constant. They are easily determined by short-circuit tests or calculated from the physical dimensions of the coils.

The core losses due to the hysteresis phenomenon and eddy currents in the magnetic material are included in the model by adding the resistor R_{iron}. For a given transformer, eddy current losses P_{eddy} vary with the square of the voltage, while hysteresis losses P_{hyst} depend on both voltage and frequency.

$$P_{\text{eddy}} = K_1 \cdot E_1^2 \tag{7}$$

$$P_{\text{hyst}} = K_2 \cdot E_1^a \cdot f^{1-a} \tag{8}$$

where E_1 is the primary voltage, K_1 and K_2 are constants that depend on magnetic material properties and lamination thickness, f is the frequency, and a is known as the Steinmetz coefficient. For older magnetic materials, the value lies between 1.6 to 1.8. For recent materials, a is closer to or even exceeds 2. For fixed frequency application, iron losses are considered proportional to the square of the voltage. They do not change with temperature.

Finally, the last element of the equivalent circuit is the magnetizing reactance X_φ. When a voltage is applied to the primary winding, this induces a magnetic flux in the core. The flux magnitude $\varphi_{\max}$ depends on voltage, the number of primary turns, and frequency:

$$\varphi_{\max} = \frac{E_1}{\sqrt{2} \cdot \pi \cdot f \cdot N_1} \tag{9}$$

In nonideal transformers, a current must flow in the primary winding for this flux to exist: This is referred to as the magnetizing current. Figure 3 shows that the amplitude of this magnetizing current can be determined from the magnetizing curve. Since this characteristic is highly nonlinear, the current is distorted. For usual magnetic materials, flux density is limited to approximately 1.5 T in order to avoid saturation. In the equivalent circuit, distortion is neglected and the value of X_φ corresponds to the root mean square (rms) value of the magnetizing current.

The general equivalent circuit is very cumbersome to use. The simplified version of Fig. 4 enables currents, losses, efficiency, and voltage regulation to be determined with adequate accuracy. In this circuit, the winding losses and leakage reactances are combined and the magnetizing branch is directly connected across the input terminals. Moreover, in order to made the calculation independent of actual voltage, all the values are expressed in per unit or in percentage of nominal voltage, current, and power. Even in per unit, the value of the four elements of the simplified model varies with the size of the transformers. Winding losses and magnetizing current decrease from 5% for 15 kVA units to 0.5% for 10 MVA units, core losses from 2% to 0.2%. The leakage reactance is designed to vary from 4% to 10% for the same range. The impedance usually provided on the nameplate is the quadrature sum of R_{eq} and X_{eq}:

$$Z_{\text{eq}} = \sqrt{R_{\text{eq}}^2 + X_{\text{eq}}^2} \tag{10}$$

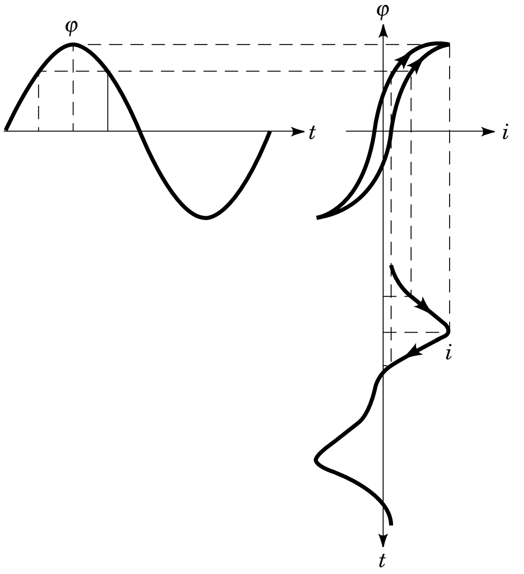

Figure 3. Magnetizing current and hysteresis curve.

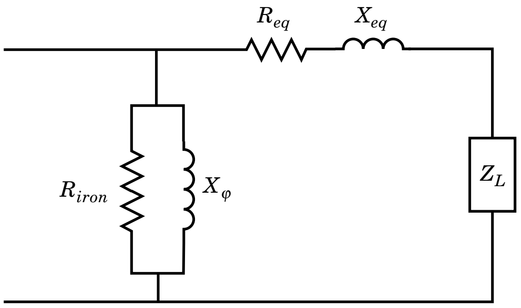

Figure 4. Simplified equivalent circuit.

The efficiency of a transformer is defined as the ratio of the output power to the input power.

$$\eta = \frac{P_{\text{load}}}{P_{\text{load}} + \text{losses}} \cdot 100\% \tag{11}$$

Efficiency η is usually calculated or measured for a resistive load corresponding to the rated capacity of the unit. Under such conditions, efficiency varies from 95% to 99%. In recent years, high efficiency standards have been introduced that bring the lower end to 97%.

Regulation e is defined as the change of the secondary voltage from no-load to full-load conditions expressed in percent of the full-load voltage E_{load}.

$$e = \frac{E_{\text{noload}} - E_{\text{load}}}{E_{\text{load}}} \cdot 100\% \tag{12}$$

Regulation varies with load power factor, being nearly the same in percent as the value of the winding resistance for resistive loads, and approximately 80% of the leakage reactance value for 0.8 lagging (inductive) power factor loads.

The power handling capacity of any transformer is limited by the average and maximum temperature reached by the windings. If the thermal characteristics of insulation is exceeded, its life is shortened. In extreme cases, the unit may fail after only few minutes. The standards specify two limits: the average temperature rise and the maximum temperature reached at any location in the coils. Common values of average rise are 80°C, 115°C, or 150°C. The standards state that the absolute temperature should not exceed the previous values by more than 30°C. Moreover, these values are given for an ambient temperature of 40°C.

MAGNETIC CIRCUIT

A transformer is a device that consists essentially of two or more magnetically coupled windings by means of a common magnetic core. The core is constructed of laminations stacked one on top of the other. The laminations are made of various grades of steel specifically formulated to optimize magnetic properties. Figure 5 shows various types of single-phase and three-phase cores.

The choice of materials having ferromagnetic properties is very large. Though *iron* is the commonly used term when referring to the core, in general core materials are alloys. The magnetic properties of ferromagnetic materials depend not only on their chemical composition but also on the mechanical and heat treatments they have undergone. The magnetic materials described here represent a fraction of all materials available. Other magnetic materials such as ferrite (a ceramic) are widely used in special applications: high-frequency transformers, pulse transformers, and so on.

The most common type of core is a steel composed mainly of iron with a few percent of other elements, notably silicon. This 2% to 4% addition of silicon increases electrical resistivity, thus reducing eddy current losses. Further improvements to this steel have been achieved by means of grain orientation. This takes advantage of the fact that the main direction of magnetization is along the edges of the cube-shaped crystals of which the metal is composed. The material is treated so that the edges of the cubes all lie in the same direction, thus creating a single direction in which the material magnetizes easily, leading to vastly improved magnetic permeability, lower losses, and a higher saturation point.

Grain-oriented silicon steel represents the bulk of the material used in the construction of cores for dry-type transformer. Table 1 gives some of the properties of silicon steel. The material is generally supplied in thin laminate form with insulation on both surfaces to reduce eddy current losses when magnetized with 50 Hz, 60 Hz, or higher-frequency alternating fluxes.

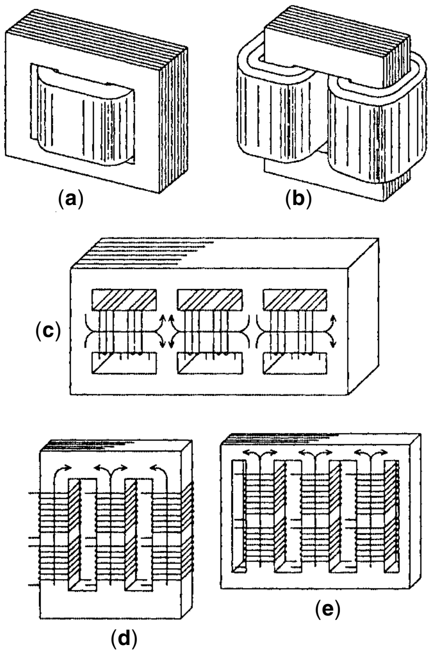

Figure 5. Various types of transformers: (a) single-phase shell type, (b) single-phase core type, (c) three-phase shell type, (d) three-phase three leg, (e) three-phase five leg.

Table 1. Magnetic Properties of Common Steels (in the rolling direction)

Grade of Steel	Flux Density (Tesla)	Core Losses (W/lb @ 60 Hz)	Exciting Power (VA/lb @ 60 Hz)
M0H	1.0	0.185	0.23
	1.2	0.255	0.33
	1.5	0.40	0.58
	1.7	0.57	0.95
M3	1.0	0.19	0.28
	1.2	0.265	0.40
	1.5	0.45	0.70
	1.7	0.67	1.65
M6	1.0	0.26	0.28
	1.2	0.36	0.40
	1.5	0.59	0.70
	1.7	0.83	1.65

The transformer designer uses the preceding figures supplied by steel manufacturers in order to design the core to obtain the best combination of low loss and cost while meeting specification requirements on temperature rise and the ability to meet various abnormal operating conditions.

The different classes of core construction are stacked core and wound core. These two major classifications can further be subdivided according to lamination type. The stacked core can be assembled from L-shaped, E&I-shaped, or C&I-shaped laminations, straight-cut pieces, or miter-cut pieces. The wound core can be a pure toroid or a shaped distributed gap core. Figure 6 illustrates various types of cores.

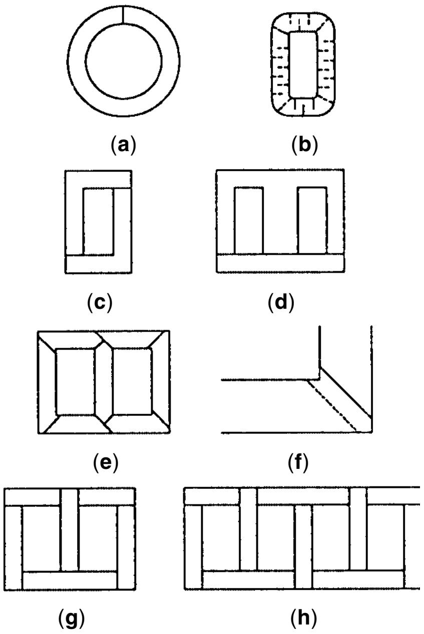

Figure 6. Laminations: (a) wound core toroid, (b) wound core distributed gap, (c) single-phase punched stacked core, (d) core made of E&I-shaped laminations, (e) stacked core with miter-cut laminations, (f) detail of miter-cut lamination joint, (g) three-phase, three-leg, straight-edge core, (h) three-phase, five-leg, straight-edge core.

Table 2. Variation of the Magnetic Properties with the Flux Direction for MOH or M6 Steels

Angle (degree)	Core Losses at 1.5T (W/lb)	Flux Density at 800 AT/m (T)
0	0.4–0.59	1.82
15	0.89–1.05	1.60
30	1.57–1.75	1.43
45	1.78–2.02	1.34
60	2.11–2.34	1.32
90	2.05–2.27	1.47

Magnetic losses increase if flux does not circulate in the direction of grain orientation as it does in the case of wound core. Table 2 shows that losses increase dramatically and that flux density decreases significantly if the magnetic domains are not oriented in the direction of flux circulation. Comparative loss figures on a per kilogram basis at the same flux density and for fully assembled cores are as follows:

Wound core toroid: 1.00

Wound core distributed gap: 1.06

Punched stacked core: 1.63

Stacked straight laminations: 1.48

Stacked miter laminations: 1.32

The preceding figures are intended only to serve as a comparison and can vary with the shape and size of the cores.

Toroids are extensively used in current transformers and punched stacked cores are used in transformers up to 15 kVA when losses are not too important. The majority of dry-type transformers use the other three types. Distributed gap wound core is also used for distribution transformers 15 V and below with rated power up to 750 kVA. This leaves the stacked core with either straight-cut or miter-cut corners as the predominant type of core design used in dry-type transformer construction. This is logical since this type of core gives designers great flexibility in coil design, allowing them to choose rectangular, oval, or round-shaped coils.

The stacked cores are clamped using structural steel frames for the top and bottom yokes. Legs are clamped by steel plates, which are wedged against the inner winding or banded at intervals using synthetic, resin-impregnated glass tapes. Bolts going through the laminations are rarely used since they contribute to increase noise, local heating, and losses. Figure 7 shows the core of a transformer during assembly.

The core section is chosen on the basis of the relation

$$E = 4.44 \cdot f \cdot B \cdot A \tag{13}$$

where E is the induced voltage per turn, f is the frequency, B is the peak flux density, and A is the area of the core. The induced voltage per turn depends on the transformer capacity P; the following empirical expression is often used to select E:

$$E = k \cdot \sqrt{P} \tag{14}$$

where k is a constant based on the manufacturer's experience. The number of turns of each winding is then obtained by dividing the nominal winding voltage by E. The core section is determined by substituting the value of E from Eq. (14) into Eq. (13). B and A being known, the core losses are easily evaluated. The core losses have two components, hysteresis and eddy currents. The hysteresis losses depend on the magnetic material used and vary with frequency and peak flux density $B_{\max}$ raised to the power a. As stated before, a is the Steinmetz coefficient, which varies from 1.6 to more than 2 depending on the material. Eddy losses vary as the square of the frequency, the square of $B_{\max}$, and the thickness of the lamination. The steel manufacturer gives the value of core losses in watts per kilogram. A value of 1 W per kilogram is typical. When the dimensions of the core are known, the losses are easily computed as well as the magnetizing current, which is obtained from the magnetizing curve. The total no-load current I_m is the sum of the magnetising current I_φ and the current required to provide the cores losses I_{iron}. As can be seen from the equivalent circuit of Fig. 4, the two components are in quadrature. I_{iron} is in phase with the primary voltage, while I_φ, being purely reactive, is lagging the voltage by 90 degrees. Therefore,

$$|\text{Im}| = \sqrt{I_{\text{iron}}^2 + I_\varphi^2} \tag{15}$$

The magnetizing current is usually expressed as a percentage of the full load current and varies from 5% for small stacked core distribution transformers down to 0.5% for units in the range of 15 MVA to 20 MVA. Wound core exhibits smaller magnetizing current specially for smaller units. The core

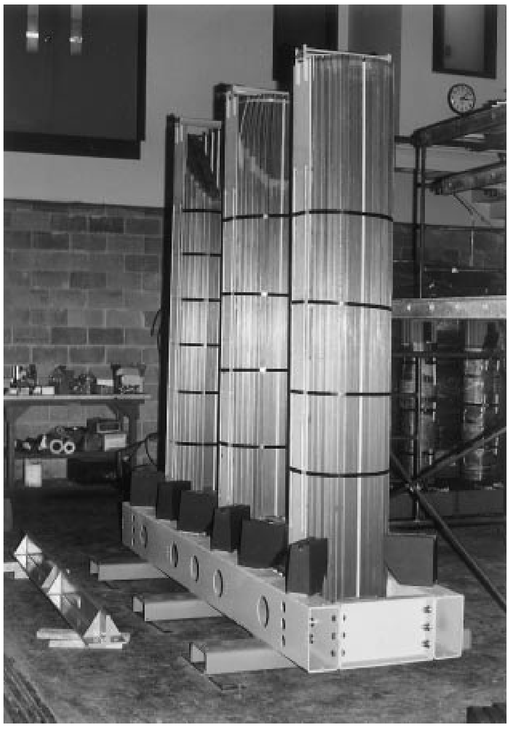

Figure 7. Photograph of a 10 MVA, three-phase stacked core. Courtesy of Megatran Electric Ltd., St-Jean-sur-Richelieu, QC, Canada.

losses also vary in a similar fashion from around 2% to 0.2% for units of 15 MVA to 20 MVA capacity.

Another characteristic of interest is the magnetizing inrush. This phenomenon is caused by three factors: (1) The flux and voltage have a 90 degree phase difference; (2) normal circuit breakers have no precise control of the moment in the cycle at which closing occurs; and (3) the core of a de-energized transformer may have residual flux depending on the actual instant of the previous switching off. The worst-case scenario takes place when a transformer is switched off at current zero, leaving a residual flux on the order of 80%. If this transformer is then re-energized when instantaneous voltage approaches zero, peak flux density reaches 2.8 times its designed maximum value, resulting in severe saturation of the core. The current is limited only by the air core inductance of the energized winding, thus reaching peak values on the order of 10 to 12 times the full load current and greater for lower voltage windings. This peak current decays ultimately to the normal value of exciting current, but the duration may last from a few cycles to few seconds depending on damping factors.

Another factor of importance in the performance of the magnetic circuit is the audible noise produced by magnetostriction in the core. When a strip of steel is magnetized, it contracts slightly. This very small change in dimension occurring 120 times per second is a vibration that creates an audible noise. This is called magnetostriction, and though it varies with flux density, it is not directly proportional to it. The actual noise that affects the surrounding environment is further strongly affected by mechanical resonance of the overall framework and is also influenced by the physical proportions of the window height and leg centers of the core. Experience indicates that noise varies with core loss and flux density according to the following empirical formula:

$$\text{Noise} = K \cdot P_{\text{iron}}^{0.1} \qquad (16)$$

where the noise is expressed in dBA, P_{iron} are the core losses in kilowatts, and K varies from 51 to 55 for the peak flux density increasing from 1.2 to 1.6 T.

WINDINGS AND INSULATING MATERIALS

The third component that enables the transformer to function, aside from the conductors that form the electric circuit (which carries the currents) and the magnetic circuit (which links them), is the insulation system, which isolates the different electrical circuits from each other and from the magnetic circuit, and ensures the safety of its use. In addition to this main function, the insulation system has to be able to withstand and help dissipate the heat generated by the flow of electrical current.

Transformers are classified as liquid filled, dry, or potted based on the primary component of the insulation system, which also serves as the cooling or heat dissipation medium. The potted type is usually used for small transformers generating very little heat. They have totally solid insulation. Heat is transferred by conduction to the surface of the potting material, which may be a grounded metal container or just the potting compound itself. From there, it is taken away by the surrounding medium, usually air. Electronics transformers, voltage transformers, and so on belong to this category. Liquid-filled units constitute the largest portion of all transformers used and have mineral oil, silicon oil, or some other liquid as the primary component of the insulation system. The transformer is immersed in the liquid insulating material, and both are contained in a metallic tank at ground potential. The liquid transfers the heat generated by conduction and convection to the walls of the tank and to cooling radiators, and from these to the surrounding air.

In dry-type transformers, the liquid is replaced by air and in some cases by nitrogen, sulphur hexafluoride, or some other gas. Unless a gas is used or the surrounding air is very polluted, the enclosure is not sealed and the surrounding air freely circulates through the transformer, thus eliminating the need for secondary cooling circuits. Though air is a very consistent dielectric, has no thermal limitations, and is the least expensive, it has the drawback of low dielectric strength and low thermal capacity. Dry-type transformers thus were limited in their use and bulky right into the 1960s. All this changed with the advent of new insulating materials developed by the growing plastics industry, which developed materials with high dielectric strength, capable of operating continuously without deterioration at temperatures on the order of 250°C. This has enabled dry-type transformers to be produced competitively in capacities up to 20 MVA with insulation levels comparable to liquid-filled units up to the 34.5 kV class, with the additional advantages of nonflammability, close coupling to loads, and low maintenance.

The insulating materials that spearheaded this revolution are polyester, epoxy and polyamide enamels, polyamide paper (such as Nomex, invented by Dupont), polyester film, glass-reinforced plastic boards and sticks, silicon, polyester and epoxy resins for impregnation, and coating and epoxy casting compounds. Of these, enamels and polyamide paper are used to insulate conductors used in winding the coils. Polyamide paper and polyester film are used as layer insulation and as barriers between coils. Glass-reinforced boards are used as phase barriers and coil supports, and the sticks are used to provide ducts inside and between coils to facilitate cooling. Resins are used for dipping and vacuum-pressure impregnation of the finished coils. Resin, sometimes, is also applied between insulation layers in a process called wet winding. This process enables the coating of coils and core to protect them against moisture ingression and other environmental damage. Epoxy casting compounds are used to encapsulate individual coils by casting them in molds to obtain superior protection against the environment.

Since heat is one of the main factors in the aging and deterioration of insulating materials, the transformer designer requires some way to select dielectric materials for continuous operation at anticipated operating temperatures. The temperature index has been developed for this purpose (i.e., to serve as a guide for the relative thermal endurance of the different dielectric materials). As it is impractical to test materials for periods comparable to their expected service life, tests are conducted at elevated temperatures, and the results are used to obtain graphical plots, known as Arrhenius plots. The graph is then extrapolated most commonly to 20,000 h to determine the temperature index of the material. Although temperature classification and temperature index are often used interchangeably, they are not the same. Temperature classification is reserved for insulating systems in specific equip-

Table 3. Properties of Common Insulation Materials

Material → ↓ Property	Casting Epoxy	Polyester Varnish	Epoxy Varnish	Silicone Varnish	Polyester Films	Aramid Paper
Specific gravity	1.73	1.1	1.1	1.05	1.4	0.9
Dielectric strength (V/mil)	400	1700	2300	2000	7000	600
Dielectric constant (60 Hz)	5.0	3.1	5.0	3.1	3.2	2.4
Dissipation factor (60 Hz)	0.01	0.07	0.20	0.01	0.005	0.006
Volume resistivity (Ω cm)	1.00*E* + 13	1.0*E* + 05	1.00*E* + 04	1.00*E* + 14	1.00*E* + 18	1.00*E* + 14
Max. recommended service temperature, °C	180	180	155	220	150	220
Tensile strength at break (psi)	10000				3000	16000

ment. Temperature index is an index that allows comparisons of temperature capability of insulating materials and systems based on specific controlled test conditions.

Insulation materials have other properties, in addition to their insulating and thermal capabilities, that are useful or detrimental to their use in normal or specific conditions of usage. Table 3 compares these properties of the commonly used materials listed previously.

Before describing different types of coils used in dry-type transformers, it must be noted that copper and aluminum are the two materials invariably used in the making of windings. These conductors can be round, rectangular, or sheet in shape and can be bare, enamelled, or wrapped with other insulating material.

The coils used in dry-type transformers can be classified into four major categories according to the way in which they are wound: (1) layer or spiral, (2) sheet, (3) disk, and (4) section or crossover. They can also be classified into two categories according to how they are processed: (1) open type and (2) encapsulated or cast type.

Layer or Spiral

This type of winding is used in low-voltage smaller-capacity units (below 600 V and 1000 kVA) and in medium-voltage higher-capacity transformers (2.4 kV, 5 MVA). An insulated rectangular or square conductor, or a group of conductors in parallel, are wound end to end continuously in a specified number of layers to make this type of winding. The individual layers may be separated by solid insulation or by ducts if cooling requires it, and the starting and finishing ends are extended to serve as leads. Also, at the starting and finishing edges of each layer, insulating sheets of the same thickness as the conductor are shaped and fitted to provide a straight edge in order to facilitate clamping during assembly. If more than one conductor layer is required, transpositions are required to reduce stray losses.

Sheet

Sheet winding constitutes the most popular low-voltage high-current winding used in dry-type transformers. A thin conductor sheet as wide as the height of the high-voltage coil is wound continuously with an insulation sheet of slightly larger width one above the other. Ducts are introduced if required between specified layers. This coil is very simple and fast to wind. The starting and finishing leads are made by brazing bus bars to the sheet. Such a coil has the lowest axial forces under short-circuit conditions. However, its withstand strength in the radial direction is flimsy unless special precautions, like wet winding and winding over a glass-reinforced plastic cylinder, are taken and sufficient radial support provided. The preferred conductor material for this type of winding is aluminum since it is a softer material and does not damage interturn insulation at the edges, as copper is capable of doing.

Disk

This type of winding is used almost exclusively for high-voltage coils when the required basic insulation levels (BIL) exceed 60 kV. This is very similar to the continuous disk winding used in oil-filled transformers, with two basic differences. First, the winding is performed over winding combs made out of glass-reinforced material with slots to accommodate the wire. This comb provides the necessary interdisk space. Second, due to the fixed spacers between disks, the winding, though continuous, does not use the collapsing and building up of alternate disks used in continuous disk winding, with the crossovers occurring at the top and bottom alternately. Instead, at the end of each disk, the conductor is bent and insulated and brought down to the bottom of the next slot, and the next disk is wound exactly as the previous one. This reduces the voltage appearing across each spacer to that of one disk and is less time-consuming to wind than the traditional continuous disk.

Section or Crossover

This is really a combination of layer and disk winding, and is widely used for high-voltage windings of low-capacity units when the conductor may have to be round or small rectangular strip. Insulated conductors are wound similar to the layer or spiral winding with solid interlayer or with ducts, but only of a length equal to the total axial height divided by the number of sections less the intersection spacer length. The sections can be wound continuously like a disk, or each section can be prewound and assembled and the interconnections made at assembly. This type of winding is very popular, even on larger kVA high-voltage coils when the coils have to be encapsulated. Another advantage is the possibility of using thin aluminum foils for high-voltage coils in this multiple-section manner and automating the winding process.

The finished windings are processed in different ways depending on the whether the unit is ultimately an open-type unit or an encapsulated type. In the case of the open type, the coils are invariably wound one over the other with all the insulation barriers in place. For the plain dip process, they

Figure 8. Photograph of two coils of a 10 MVA, 25 kV/6.9 kV transformer after impregnation. Courtesy of Megatran Electric Ltd., St-Jean-sur-Richelieu, QC, Canada.

are then preheated and simply immersed in a varnish bath. They can also be vacuum impregnated, or vacuum impregnated followed by a pressurization period. This last method is called the vacuum-pressure impregnation or VPI process. After this impregnation, the coils are baked in an oven to cure the varnish. If multiple dips are specified, then the coils are only half-baked between immersions until the last dip. Figure 8 shows two coils at the end of the impregnation process while Fig. 9 shows a 2.5 MVA, 13.8 kV voltage regulator made of two vacuum impregnated transformers. The high-voltage disk windings are clearly visible.

For the encapsulated type of unit, coils are wound separately and placed in specially made molds and preheated. The casting or encapsulating resin is mixed and introduced under vacuum into this mold and, once filled, the mold is placed in an oven and baked as specified. The coils are taken out of the molds after the baking period and assembled on the core. Figure 10 shows a 5 MVA, 25 kV to 600 V three-phase transformer with cast coils.

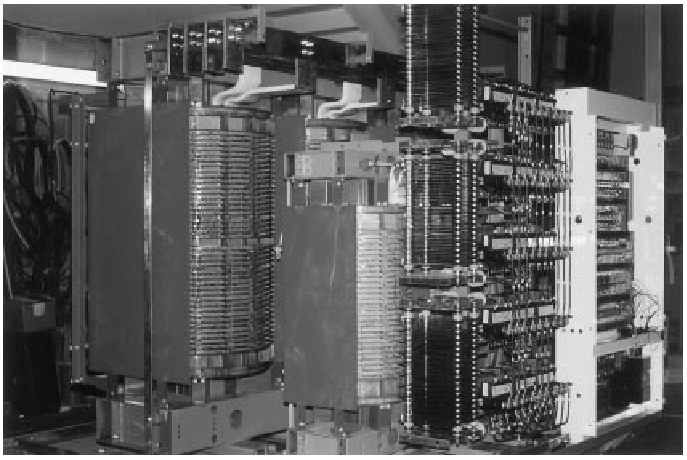

Figure 9. Photograph of a 2.5 MVA, 13.8 kV/600 V voltage regulator made of two vacuum-pressure-impregnated transformers with high-voltage disk windings. Courtesy of Megatran Electric Ltd., St-Jean-sur-Richelieu, QC, Canada.

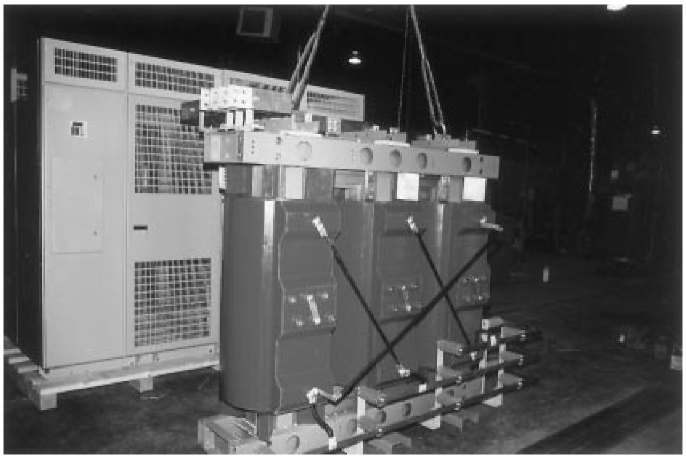

Figure 10. Photograph of the core and enclosure of a 5 MVA, 25 kV/600 V cast-coil transformer. Courtesy of Megatran Electric Ltd., St-Jean-sur-Richelieu, QC, Canada.

The coils of the dry-type transformer are designed to work under specified system conditions and meet certain performance criteria. Under the specified system conditions, in addition to the working voltage and the continuous load current, certain abnormal conditions that occur at rare intervals have to be withstood successfully by the unit. The two such main conditions are surge voltages and short circuits at the load terminals.

Surge voltage to be withstood are based on the voltages of the system in which the transformer works and are specified by national standards like Canadian Standards Association (CSA) standard C9 and American National Standards Institute (ANSI) C57 standards series. Surge or transient voltages are, by their nature, distributed along the winding in a nonuniform fashion dependent on the capacitance of the winding to ground and its inherent series capacitance between turns, disks, layers, and so on. Since nonlinearity and hence higher stresses are reduced if ground capacitance is lower and series capacitance higher, it stands to reason that the types of coil that use solid material for interlayer, intersection, and interdisk insulation (encapsulated or cast coils) have a better capability to withstand surge voltages. Indeed, relative to the series capacitance, the ground capacitance is reduced due to the dielectric constant of air being lower than that of solid insulation.

Short-circuit strength, meaning the ability of the unit to withstand the mechanical forces created by a short circuit at the output terminals due to the heavy currents limited only by the impedance of the unit and the systems feeding it, is inherently better in a dry-type transformer due to the materials and the resins used to impregnate them compared to liquid-filled units. But this advantage disappears if the coils are not properly designed.

The other unusual condition to be met by transformers is the short-time overload capability. This capability depends on the time constant or the time taken by a unit to reach its steady-state temperature if the initial rate of rise were maintained. This time constant depends on the sum of the thermal capacities of the materials to be heated. Dry-type transformers do not have high time constants in general compared to liquid-filled units, and thus have lower short-time overload capability since their time constants are on the order of one hour, while that of liquid-filled units is in the neighborhood of 2.5 h.

VOLTAGE REGULATION

It is a general practice to have some means of adjustment to maintain constant voltage at the output terminals by compensating for the variations of the input voltage. This is done by tapping out or adding turns to the primary or input winding and maintaining the volts per turn, and thus the output voltage.

This operation is usually performed when the transformer is de-energized; this is called off-circuit tap changing. In dry-type transformers, the usual method is to bring out the tap terminals on the outer surface of the coil or on a terminal board, where the linking to obtain the required turns is done manually with the unit de-energized. It is possible, though not usual, to have tap switches similar to those used in liquid-filled units.

Until recently, dry-type transformers were never supplied with under-load-tap-changing equipment. This was due to the fact that under-load tap changing involves breaking of load current at full voltage, thereby requiring switching equipment with capabilities comparable to those of circuit breakers. To do this in air was cumbersome, bulky, and extremely expensive. But with the increased capacities and voltages of dry-type transformers, the demand for such equipment has increased, and recently voltage regulators became commercially available. Two different approaches are used to provide under-load voltage regulation. One takes the traditional approach of the liquid-filled units by providing motor-driven selector switches combined with a spring-activated vacuum-diverter switch. The other approach uses a separate regulator winding feeding a buck/boost transformer connected in series with the primary winding. Voltage regulation is achieved by means of low-voltage vacuum contactors that modify the tap settings of the regulating winding of the buck/boost transformer, circumventing high-voltage switching equipment. The contactors are usually controlled by programmable logic controllers (PLC). These contactors can clearly be seen on the right side of Fig. 9. In cases where high-speed response is required, the second approach has successfully used thyristors in place of vacuum contactors, thereby achieving sub-cycle switching.

LOSSES AND CONVERTER TRANSFORMERS

Aside from the magnetic circuit losses discussed earlier, the units generate losses in the electric circuit by the flow of load currents. These currents, being ac, produce, in addition to the basic losses due to the dc resistance in the conductors and leads, other losses (comprising eddy losses in the conductors and stray losses in the structural material in proximity to the flux path). Since transformer leakage flux path is fairly linear, the eddy losses are fairly accurately calculated using the formula developed by Professor H. Dwight. An empirical formula used by manufacturers allows the eddy losses in the coils to be expressed as a fraction of the basic losses. These losses are proportional to the square of the frequency, the dimension of the conductor at right angles to the leakage flux path, and the conductor weight. These losses seldom exceed 5% of basic losses for a 60 Hz sinusoidal current but can be significant with nonlinear loads having large high-frequency components since they are almost proportional to the square of the frequency. These extra losses must be taken in consideration when the transformer feeds rectifiers, converters, computer equipment, or motor drives. A special type of transformer, referred to as K-factor transformers, is available for such applications. The stray losses are more difficult to calculate and are usually taken as a watts per kilovolt-ampere capacity of the transformer from experience with the test results of past units. These windings plus stray losses are usually known as the load losses and vary from a high of 5% for units in the 5 kVA to 10 kVA capacity range to as low as 0.5% for units in the 10 MVA to 15 MVA capacity range.

IMPEDANCE

The concept of leakage inductance has been presented before, and the unit impedance consists of this leakage inductance and the load losses added in quadrature. Though the negative aspects of high impedance are well known, since they affect the efficiency and regulation, there is a positive aspect from a protection point of view: Indeed, it is the impedance that restricts the available short-circuit current at the load terminals. This is of great importance, especially in the case of dry-type transformers, since those tend to be the final units in the chain leading to the consumer. National standards recommend values depending on the capacity of the units, and customers usually specify their exact needs, taking into account system rigidity and protection requirements.

FITTINGS AND ACCESSORIES

Since dry-type transformers, especially the encapsulated ones, can be operated without an enclosure, the first accessory that can be had is an enclosure. These can be ventilated for free air circulation or louvered with air filters to remove dust from the air. They can also be sealed with separate cooling equipment in the case of extremely polluted environmental conditions. The accessory that is most commonly asked for is a temperature indicator with contacts for operating protective equipment in case of overheating. Since most dry-type transformers have low-voltage class secondaries, the temperature is sensed directly on the hottest coil surface in the low-voltage coil using a bulb-type sensor or resistive temperature detector (RTD). The next most commonly required accessory is the fan cooling package. In this, fans are placed under each coil in such a way as to blow air up the ducts and enhance the cooling. Very simple fan placement can get up to 33% extra rating and, with directed flow, rating increases up to 50% are possible. These fans are usually controlled by the thermometer contacts to switch on and off at preset temperatures.

Accessories such as current transformers and surge arrestors similar to those installed in liquid-filled units, are available and frequently installed in higher-capacity units.

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