Harlow, James H. “Transformers”
The Electric Power Engineering Handbook
Ed. L.L. Grigsby
Boca Raton: CRC Press LLC, 2001

3

Transformers

James H. Harlow
Harlow Engineering Associates

3

Transformers

Harold Moore
H. Moore & Associates

H. Jin Sim
Waukesha Electric Systems

Scott H. Digby
Waukesha Electric Systems

Dudley L. Galloway
ABB Power T&D Company

Dan Mulkey
Pacific Gas & Electric Co.

Paulette A. Payne
Potomac Electric Power Company

Craig A. Colopy
Cooper Power Systems

Richard Dudley
Trench Ltd.

Antonio Castanheira
Trench Ltd.

Michael Sharp
Trench Ltd.

Randy Mulliken
Kuhlman Electric Corp.

Anthony J. Jonnatti
Loci Engineering

Dan D. Perco
Perco Transformer Engineering

James H. Harlow
Harlow Engineering Associates

Robert F. Tillman, Jr.
Alabama Power Company

Jeewan Puri
Square D Company

Loren B. Wagenaar
America Electric Power

Dieter Dohnal
Maschinenfabrik Reinhausen GmbH

Wolfgang Breuer
Maschinenfabrik Reinhausen GmbH

Leo J. Savio
ADAPT Corporation

Ted Haupert
TJ/H2b Analytical Services, Inc.

Shirish P. Mehta
Waukesha Electric Systems

William R. Henning
Waukesha Electric Systems

Alan Oswalt
Waukesha Electric Systems

Philip J. Hopkinson
Square D Company

Andre Lux
ABB Power T&D Company, Inc.

3.1 Theory and Principles

Harold Moore

Transformers are devices that transfer energy from one circuit to another by means of a common magnetic field. In all cases except autotransformers, there is no direct electrical connection from one circuit to the other.

When an alternating current flows in a conductor, a magnetic field exists around the conductor as illustrated in Fig. 3.1. If another conductor is placed in the field created by the first conductor as shown in Fig. 3.2, such that the flux lines link the second conductor, then a voltage is induced into the second conductor. The use of a magnetic field from one coil to induce a voltage into a second coil is the principle on which transformer theory and application is based.

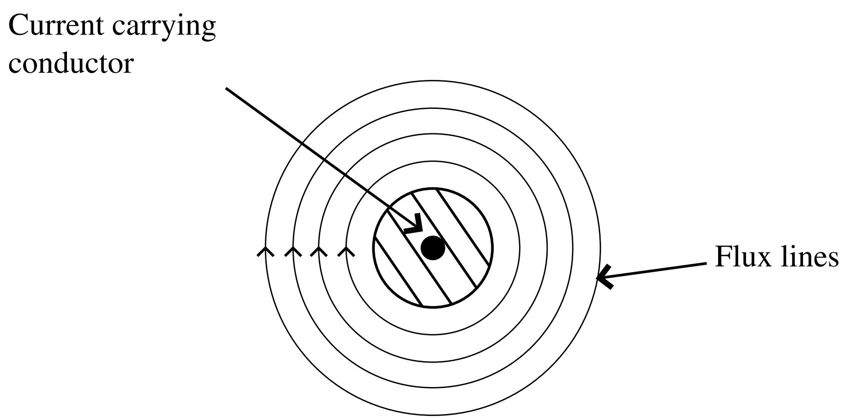


FIGURE 3.1

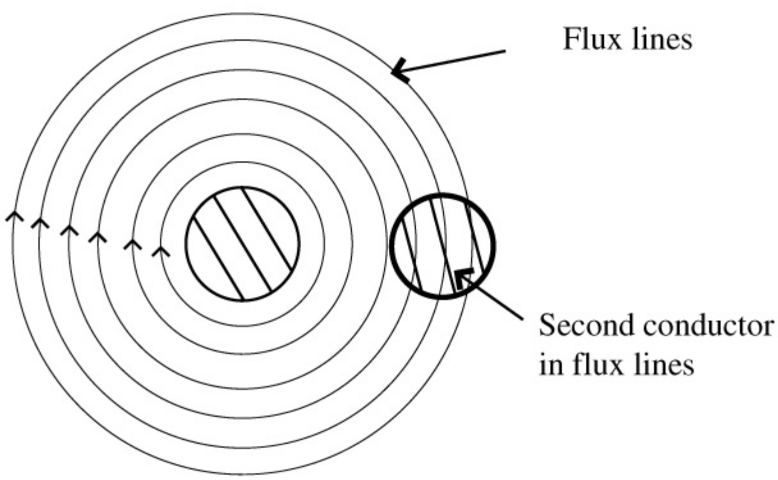


FIGURE 3.2

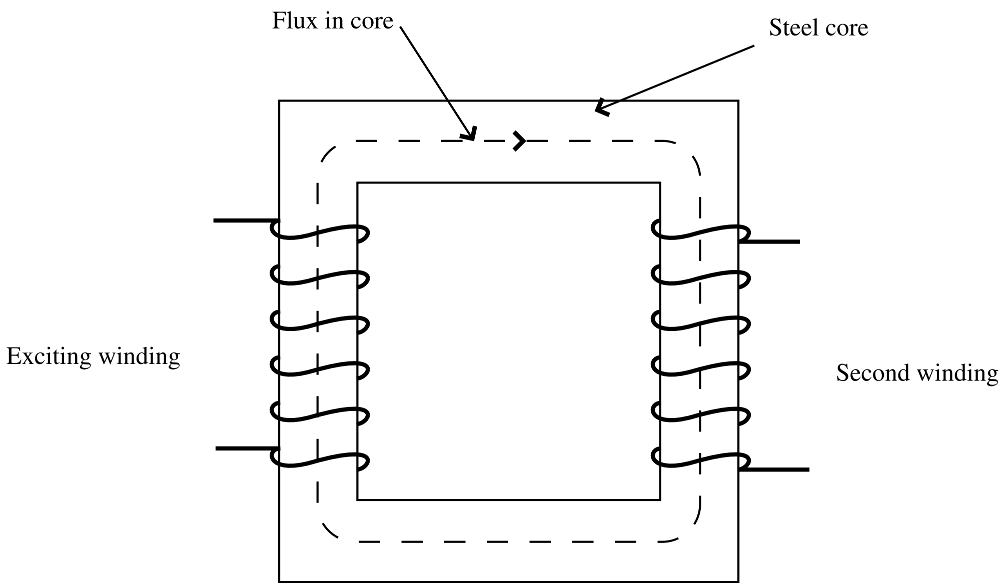


FIGURE 3.3

Air Core Transformer

Some small transformers for low power applications are constructed with air between the two coils. Such transformers are inefficient because the percentage of the flux from the first coil that links the second coil is small. The voltage induced in the second coil is determined as follows.

$$E = N\ d0/dt]10]^{8}$$

where N = number of turns in the coil
d0/dt = time rate of change of flux linking the coil

Since the amount of flux 0 linking the second coil is a small percentage of the flux from coil 1, the voltage induced into the second coil is small. The number of turns can be increased to increase the voltage output, but this will increase costs.

The need then is to increase the amount of flux from the first coil that links the second coil.

Iron or Steel Core Transformer

The ability of iron or steel to carry magnetic flux is much greater than air. This ability to carry flux is called permeability. Modern electrical steels have permeabilities on the order of 1500 compared to 1.0 for air. This means that the ability of a steel core to carry magnetic flux is 1500 times that of air. Steel cores were used in power transformers when alternating current circuits for distribution of electrical energy were first introduced. When two coils are applied on a steel core as illustrated in Fig. 3.3, almost 100% of the flux from coil 1 circulates in the iron core so that the voltage induced into coil 2 is equal to the coil 1 voltage if the number of turns in the two coils are equal.

The equation for the flux in the steel core is as follows:

$$0 = \frac{3.19\,N\,A\,u\,I}{d} \qquad (3.1)$$

where

- 0 = core flux in lines
- N = number of turns in the coil
- u = permeability
- I = maximum current in amperes
- d = mean length of the core

Since the permeability of the steel is very high compared to air, all of the flux can be considered as flowing in the steel and is essentially of equal magnitude in all parts of the core. The equation for the flux in the core can be written as follows:

$$0 = \frac{349\,E\,A}{f\,N} \tag{3.2}$$

where

- A = area of the core in square inches
- E = applied alternating voltage
- f = frequency in cycles/second
- N = number of turns in the winding

It is useful in transformer design to use flux density so that Eq. (3.2) can be written as follows:

$$B = \frac{0}{A} = \frac{349\,E}{f\,A\,N} \tag{3.3}$$

where B = flux density in Tesla.

Equivalent Circuit of an Iron Core Transformer

When voltage is applied to the exciting or primary winding of the transformer, a magnetizing current flows in the primary winding. This current produces the flux in the core. The flow of flux in magnetic circuits is analogous to the flow of current in electrical circuits.

When flux flows in the steel core, losses occur in the steel. There are two components of this loss which are termed “eddy” and “hystersis” losses. An explanation of these losses would require a full chapter. For the purpose of this text, it can be stated that the hystersis loss is caused by the cyclic reversal of flux in the magnetic circuit . The eddy loss is caused by the flow of flux normal to the width of the core. Eddy loss can be expressed as follows:

$$W = K\left[w\right]^2\left[B\right]^2 \tag{3.4}$$

where

- K = constant
- w = width of the material normal to the flux
- B = flux density

If a solid core were used in a power transformer, the losses would be very high and the temperature would be excessive. For this reason, cores are laminated from very thin sheets such as 0.23 mm and 0.28 mm to reduce the losses. Each sheet is coated with a very thin material to prevent shorts between the laminations. Improvements made in electrical steels over the past 50 years have been the major contributor to smaller and more efficient transformers. Some of the more dramatic improvements are as follows:

- Development of grain-oriented electrical steels in the mid-1940s.
- Introduction of thin coatings with good mechanical properties.
- Improved chemistry of the steels.
- Introduction of laser scribed steels.
- Further improvement in the orientation of the grains.
- Continued reduction in the thickness of the laminations to reduce the eddy loss component of the core loss.

The combination of these improvements has resulted in electrical steels having less than 50% of the no load loss and 30% of the exciting current that was possible in the late 1940s.

The current to cause rated flux to exist in the core is called the magnetizing current. The magnetizing circuit of the transformer can be represented by one branch in the equivalent circuit shown in Fig. 3.4. The core losses are represented by [Xr], and the excitation characteristics by [Xm].

When the magnetizing current, which is about 0.5% of the load current, flows in the primary winding, there is a small voltage drop across the resistance of the winding and a small inductive drop across the inductance of the winding. We can represent these voltage drops as Rl and Xl in the equivalent circuit. However, these drops are very small and can be neglected in the practical case.

Since the flux flowing in all parts of the core is essentially equal, the voltage induced in any turn placed around the core will be the same. This results in the unique characteristics of transformers with steel cores. Multiple secondary windings can be placed on the core to obtain different output voltages. Each turn in each winding will have the same voltage induced in it. Refer to Fig. 3.5.

The ratio of the voltages at the output to the input at no load will be equal to the ratio of the turns. The voltage drops in the resistance and reactance at no load are very small with only magnetizing current flowing in the windings so that the voltage appearing at A can be considered to be the input voltage. The relationship $E1/N1 = E2/N2$ is important in transformer design and application.

A steel core has a nonlinear magnetizing characteristic as shown in Fig. 3.6. As shown, greater ampere turns are required as the flux density B is increased. Above the knee of the curve as the flux approaches saturation, a small increase in the flux density requires a large increase in the ampere turns. When the core saturates, the circuit behaves much the same as an air core.

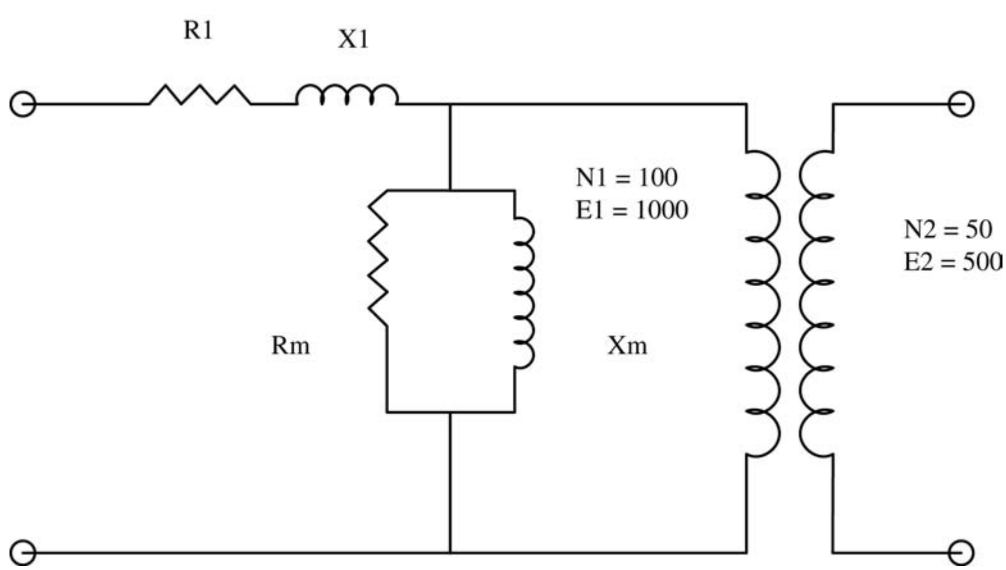


FIGURE 3.4

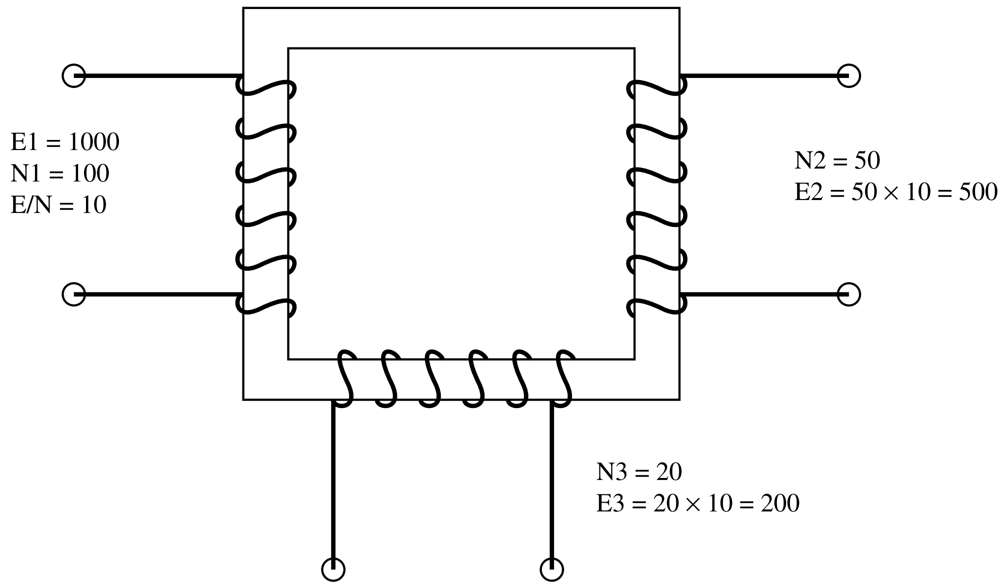


FIGURE 3.5

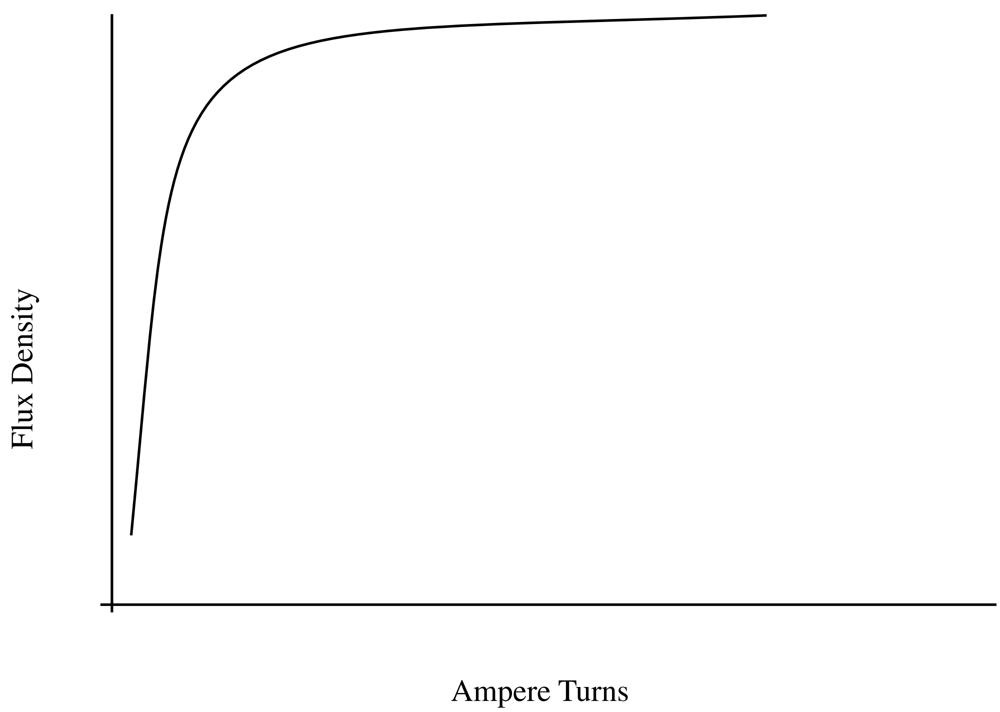


FIGURE 3.6

The Practical Transformer

Magnetic Circuit

In actual transformer design, the constants for the ideal circuit are determined from tests on materials and on transformers. For example, the resistance component of the core loss, usually called no load loss, is determined from curves derived from tests on samples of electrical steel and measured transformer no load losses. The designer will have curves for the different electrical steel grades as a function of induction. In the same manner, curves have been made available for the exciting current as a function of induction.

A very important relationship is derived from Eq. (3.4). It can be written in the following form.

$$B = \frac{349\left[E/N\right]}{f\ A} \tag{3.5}$$

The term [E/N] is called "volts per turn". It determines the number of turns in the windings, the flux density in the core, and is a variable in the leakage reactance which will be discussed below. In fact, when the designer starts to make a design for an operating transformer, one of the first things selected is the volts per turn.

The no load loss in the magnetic circuit is a guaranteed value in most designs. The designer must select an induction level that will allow him to meet the guarantee. The design curves or tables usually show the loss/# or loss/kg as a function of the material and the induction.

The induction must also be selected so that the core will be below saturation under specified over-voltage conditions. Saturation is around 2.0 T.

Leakage Reactance

When the practical transformer is considered, additional concepts must be introduced. For example, the flow of load current in the windings results in high magnetic fields around the windings. These fields are termed leakage flux fields. The term is believed to have started in the early days of transformer theory when it was thought that this flux "leaked" out of the core. This flux exists in the spaces between windings and in the spaces occupied by the windings. See Fig. 3.7. These flux lines effectively result in an impedance between the windings, which is termed "leakage reactance" in the industry. The magnitude of this reactance is a function of the number of turns in the windings, the current in the windings, the leakage field, and the geometry of the core and windings. The magnitude of the leakage reactance is usually in the range of 4 to 10% at the base rating of power transformers. The load current through this reactance results in a considerable voltage drop. Leakage reactance is termed "percent leakage reactance" or "percent reactance". Percent reactance is the ratio of the reactance voltage drop to the winding voltage × 100. It is calculated by designers using the number of turns, the magnitude of the current and the leakage field, and the geometry of the transformer. It is measured by short circuiting one winding of the transformer and increasing the voltage on the other winding until rated current flows in the windings. This voltage divided by the rated winding voltage times 100 is the percent reactance voltage or percent reactance. The voltage drop across this reactance results in the voltage at the load being less than the value determined by the turns ratio. The percentage decrease in the voltage is termed "regulation". Regulation is a function of the power factor of the load, and it can be determined using the following equation for inductive loads:

$$\%\ \text{Reg.} = \%\ R\left[\cos 0\right] + \%X\left[\sin 0\right] + \frac{\left[\%X\left(\cos 0\right) - \%R\left(\sin 0\right)\right]^2}{200}$$

where

- % Reg. = percentage voltage drop across the resistance and the leakage reactance
- % R = % resistance = kilowatts of load loss/kVA of transformer × 100
- % X = % leakage reactance
- 0 = angle corresponding to the power factor of the load. If the power factor is 0.9, the angle is 36.87°.

For capacitance loads, change the sign of the sin terms.

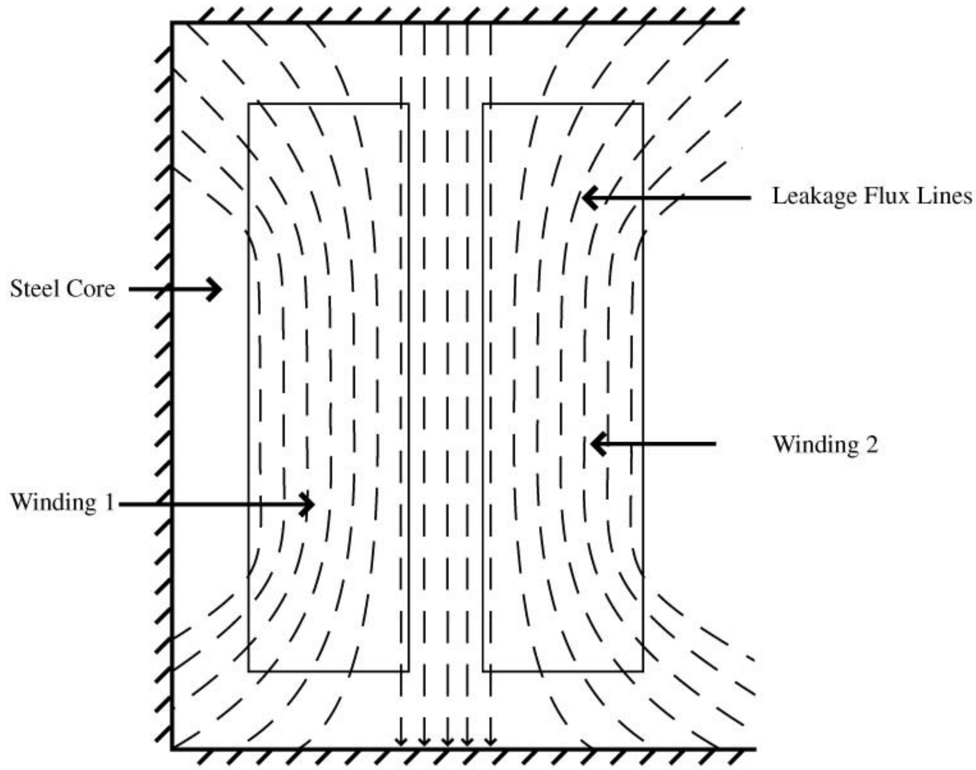


FIGURE 3.7

In order to compensate for these voltage drops, taps are usually added in the windings. The unique volts/turn feature of steel core transformers makes it possible to add or subtract turns to change the voltage outputs of windings. A simple illustration is shown in Fig. 3.8.

Load Losses

This term represents the losses in the transformer that result from the flow of load current in the windings. Load losses are composed of the following elements.

- Resistance losses as the current flows through the resistance of the conductors and leads.
- Eddy losses. These losses are caused by the leakage field, and they are a function of the second power of the leakage field density and the second power of the conductor dimensions normal to the field.
- Stray losses. The leakage field exists in parts of the core, steel structural members, and tank walls. Losses result in these members.

Again, the leakage field caused by flow of the load current in the windings is involved and the eddy and stray losses can be appreciable in large transformers.

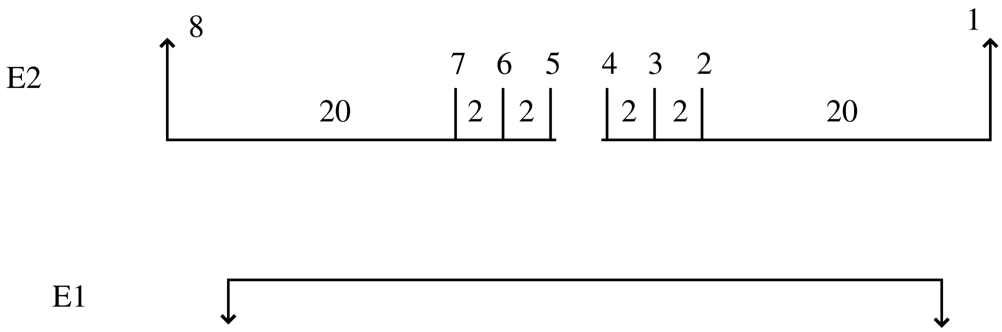
Short Circuit Forces

Forces exist between current-carrying conductors when they are in an alternating current field. These forces are determined using the following equation:

$$F = B\ I\ \sin 0$$

where

F = force density
0 = angle between the flux and the current. (In transformers, sin 0 is almost always equal to 1.)



E1 = 100
N1 = 10
E/N = 10

E2 = E/N X N2

N2	E2
4 to 5 = 48	$E2 = 10 \times 48 = 480$ Volts
4 to 6 = 46	$E2 = 10 \times 46 = 460$ Volts
3 to 6 = 44	$E2 = 10 \times 44 = 440$ Volts
3 to 7 = 42	$E2 = 10 \times 42 = 420$ Volts
2 to 7 = 40	$E2 = 10 \times 40 = 400$ Volts

FIGURE 3.8

Since the leakage flux field is between windings and has a rather high density, the forces can be quite high. This is a special area of transformer design. Complex programs are needed to get a reasonable representation of the field in different parts of the windings. Much effort has gone into the study of stresses in the windings and the withstand criteria for different types of conductors and support systems. This subject is obviously very broad and beyond the scope of this section.

Thermal Considerations

The losses in the windings and the core cause temperature rises in the materials. This is another important area in which the temperatures must be limited to the long-term capability of the insulating materials. Refined paper is still used as the primary solid insulation in power transformers. Highly refined mineral oil is still used as the cooling and insulating medium in power transformers. Gases and vapors have been introduced in a limited number of special designs. The temperatures must be limited to the thermal capability of these materials. Again, this subject is quite broad and involved. It includes the calculation of the temperature rise of the cooling medium, the average and hottest spot rise of the conductors and leads, and the heat exchanger equipment.

Voltage Considerations

A transformer must withstand a number of different voltage stresses over its expected life. These voltages include:

- The operating voltages at the rated frequency
- Rated frequency overvoltages

- Natural lightning impulses that may strike the transformer or transmission lines
- Switching surges that result from opening and closing breakers and switches
- Combinations of the above voltages

This is a very specialized field in which the resulting voltage stresses must be calculated in the windings and withstand criteria must be established for the different voltages and combinations of voltages. The designer must design the insulation system so that it will withstand these various stresses.

3.2 Power Transformers

H. Jin Sim and Scott H. Digby

A transformer has been defined by ANSI/IEEE as a static electrical device, involving no continuously moving parts, used in electric power systems to transfer power between circuits through the use of electromagnetic induction. The term *power* transformer is used to refer to those transformers used between the generator and the distribution circuits and are usually rated at 500 kVA and above. Power systems typically consist of a large number of generation locations, distribution points, and interconnections within the system or with nearby systems, such as a neighboring utility. The complexity of the system leads to a variety of transmission and distribution voltages. Power transformers must be used at each of these points where there is a transition between voltage levels.

Power transformers are selected based on the application, with the emphasis towards custom design being more apparent the larger the unit. Power transformers are available for step-up operation, primarily used at the generator and referred to as generator step-up (GSU) transformers, and for step-down operation, mainly used to feed distribution circuits. Power transformers are available as a single phase or three phase apparatus.

The construction of a transformer depends upon the application, with transformers intended for indoor use primarily dry-type but also as liquid immersed and for outdoor use usually liquid immersed. This section will focus on the outdoor, liquid-immersed transformers, such as those shown in Fig. 3.9.

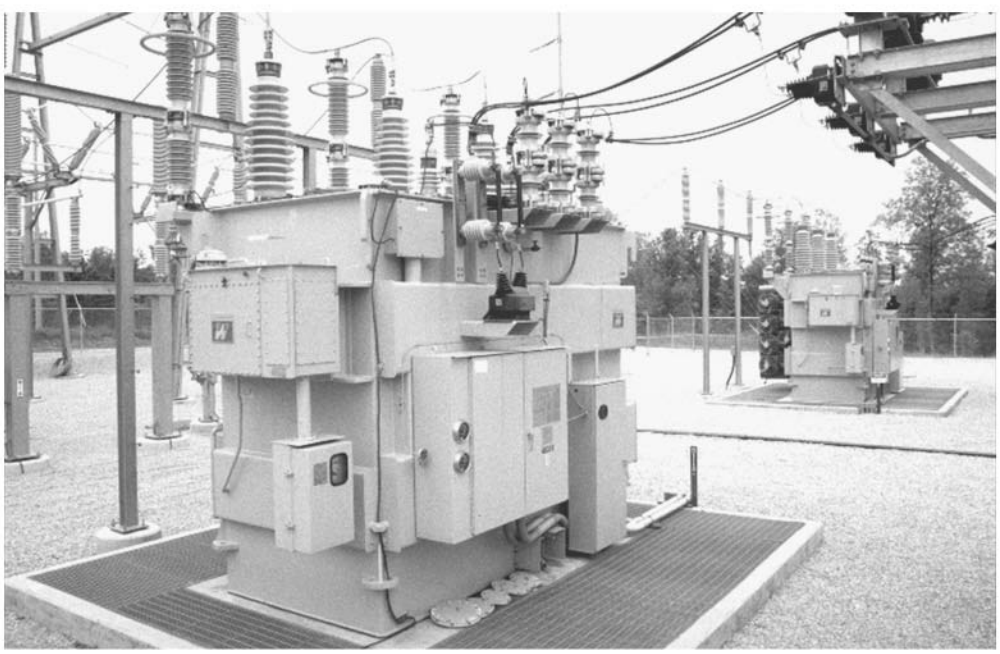


FIGURE 3.9 20 MVA, 161:26.4 × 13.2 kV with LTC, three-phase transformers.

TABLE 3.1 Standard Limits for Temperature Rises Above Ambient

Average winding temperature rise	65°C[a]
Hot spot temperature rise	80°C
Top liquid temperature rise	65°C

[a] The base rating is frequently specified and tested as a 55°C rise.

Rating and Classifications

Rating

In the U.S., transformers are rated based on the power output they are capable of delivering continuously at a specified rated voltage and frequency under "usual" operating conditions without exceeding prescribed internal temperature limitations. Insulation is known to deteriorate, among other factors, with increases in temperature, so insulation used in transformers is based on how long it can be expected to last by limiting operating temperatures.

The temperature that insulation is allowed to reach under operating conditions essentially determines the output rating of the transformer, called the kVA rating. Standardization has led to temperatures within a transformer being expressed in terms of the rise above ambient temperature, since the ambient temperature can vary under operating or test conditions. Transformers are designed to limit the temperature based on the desired load, including the average temperature rise of a winding, the hottest spot temperature rise of a winding, and, in the case of liquid-filled units, the top liquid temperature rise. To obtain absolute temperatures from these values, simply add the ambient temperature. Standard temperature limits for liquid-immersed power transformers are listed in Table 3.1.

The normal life expectancy of power transformers is generally assumed to be about 30 years of service when operated within their ratings; however, they may be operated beyond their ratings, overloaded, under certain conditions with moderately predictable "loss of life". Situations that may involve operation beyond rating are emergency re-routing of load or through-faults prior to clearing.

Outside the U.S., the transformer rating may have a slightly different meaning. Based on some standards, the kVA rating can refer to the power that can be input to a transformer, the rated output being equal to the input minus the transformer losses.

Power transformers have been loosely grouped into three market segments based upon size ranges. These three segments are:

1. Small power transformers — 500 to 7500[1] kVA
2. Medium power transformers — 7500[1] to 100 MVA
3. Large power transformers — 100 MVA and above

It was noted that the transformer rating is based on "usual" service conditions, as prescribed by standards. Unusual service conditions may be identified by those specifying a transformer so that the desired performance will correspond to the actual operating conditions. Unusual service conditions include, but are not limited to, the following: high (above 40°C) or low (below –20°C) ambient temperatures; altitudes above 3300 ft above sea level; seismic conditions; and loads with harmonic content above 0.05 per unit.

Insulation Classes

The insulation class of a transformer is determined based on the test levels that it is capable of withstanding. Transformer insulation is rated by the BIL, or Basic Insulation Impulse Level, in conjunction with the voltage rating. Internally, a transformer is considered to be a non-self-restoring insulation system, mostly consisting

[1]The upper range of small power and the lower range of medium power can vary between 2500 and 10,000 kVA throughout the industry.

of porous, cellulose material impregnated by the liquid insulating medium. Externally, the transformer's bushings and, more importantly, the surge protection equipment must coordinate with the transformer rating to protect the transformer from transient overvoltages and surges. Standard insulation classes have been established by standards organizations stating the parameters by which tests are to be performed.

Wye connected transformers will typically have the common point brought out of the tank through a neutral bushing. Depending on the application, for example in the case of a solidly grounded neutral vs. a neutral grounded through a resistor or reactor or even an ungrounded neutral, the neutral may have a lower insulation class than the line terminals. There are standard guidelines for rating the neutral based on the situation. It is important to note that the insulation class of the neutral may limit the test levels of the line terminals for certain tests, such as the applied potential, or hi-pot, test where the entire circuit is brought up to the same voltage level. A reduced rating for the neutral can significantly reduce the cost of larger units and autotransformers as opposed to a fully rated neutral.

Cooling Classes

Since no transformer is truly an "ideal" transformer, each will incur a certain amount of energy loss, mainly that which is converted to heat. Methods of removing this heat can depend on the application, the size of the unit, and the amount of heat that needs to be dissipated.

The insulating medium inside a transformer, usually oil, serves multiple purposes, first to act as an insulator, and second to provide a good medium through which to remove heat.

The windings and core are the primary sources of heat; however, internal metallic structures can act as a heat source as well. It is imperative to have proper cooling ducts and passages in proximity to the heat sources through which the cooling medium can flow such that the heat can be effectively removed from the transformer. The natural circulation of oil through a transformer through convection has been referred to as a "thermosiphon" effect. The heat is carried by the insulating medium until it is transferred through the transformer tank wall to the external environment. Radiators, typically detachable, provide an increase in the convective surface area without increasing the size of the tank. In smaller transformers, integral tubular sides or fins are used to provide this increase in surface area. Fans can be installed to increase the volume of air moving across the cooling surfaces thus increasing the rate of heat dissipation. Larger transformers that cannot be effectively cooled using radiators and fans rely on pumps that circulate oil through the transformer and through external heat exchangers, or coolers, which can use air or water as a secondary cooling medium.

Allowing liquid to flow through the transformer windings by natural convection is also identified as non-directed flow. In cases where pumps are used, and even some instances where only fans and radiators are being used, the liquid is often guided into and through some or all of the windings. This is called directed flow in that there is some degree of control of the flow of the liquid through the windings. The difference between directed and non-directed flow through the winding in regard to winding arrangement will be discussed further with the description of winding types.

The use of auxiliary equipment such as fans and pumps with coolers, called forced circulation, increases the cooling and thereby the rating of the transformer without increasing the unit's physical size. Ratings are determined based on the temperature of the unit as it coordinates with the cooling equipment that is operating. Usually, a transformer will have multiple ratings corresponding to multiple stages of cooling, as equipment can be set to run only at increased loads.

Methods of cooling for liquid-immersed transformers have been arranged into cooling classes identified by a four-letter designation as follows.

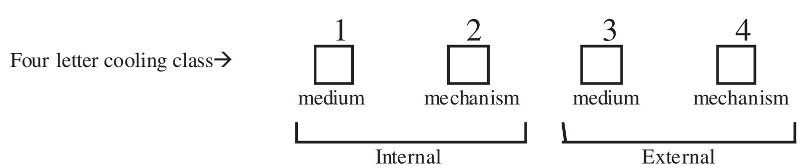


Table 3.2 lists the code letters that are used to make up the four-letter designation.

TABLE 3.2 Cooling Class Letter Descriptions

		Code Letter	Description
Internal	First letter (Cooling medium)	**O**	Liquid with flash point less than or equal to 300°C
		K	Liquid with flash point greater than 300°C
		L	Liquid with no measurable flash point
	Second letter (Cooling mechanism)	**N**	Natural convection through cooling equipment and windings
		F	Forced circulation through cooling equipment, natural convection in windings
		D	Forced circulation through cooling equipment, directed flow in main windings
External	Third letter (Cooling medium)	**A**	Air
		W	Water
	Fourth letter (Cooling medium)	**N**	Natural convection
		F	Forced circulation

This system of identification has come about through standardization between different international standards organizations and represents a change from what has traditionally been used in the U.S. Where OA classified a transformer as liquid-immersed self-cooled in the past, it is designated by the above system as ONAN. Similarly, the previous FA classification is identified as ONAF. FOA could be OFAF or ODAF, depending on whether directed oil flow is employed or not. In some cases, there are transformers with directed flow in windings without forced circulation through cooling equipment.

An example of multiple ratings would be ONAN/ONAF/ONAF, where the transformer has a base rating where it is cooled by natural convection and two supplemental ratings where groups of fans are turned on to provide additional cooling so the transformer will be capable of supplying additional kVA. This rating would have been designated OA/FA/FA per past standards.

Short Circuit Duty

A transformer supplying a load current will have a complicated network of internal forces acting on and stressing the conductors, support structures, and insulation structures. These forces are fundamental to the interaction of current-carrying conductors within magnetic fields involving an alternating current source. Increases in current result in increases in the magnitude of the forces proportional to the square of the current. Severe overloads, particularly through-fault currents resulting from external short circuit events, involve significant increases in the current above rated current and can result in tremendous forces inside the transformer.

Since the fault current is a transient event, it will have the offset sinusoidal waveshape decaying with time based on the time constant of the equivalent circuit that is characteristic of switching events. The amplitude of the basic sine wave, the symmetrical component, is determined from the formula

$$I_{sc} = I_{rated} \Big/ \left(Z_{xfmr} + Z_{sys} \right) \tag{3.6}$$

where Z_{xfmr} and Z_{sys} are the transformer and system impedances, respectively, expressed in per unit, and I_{sc} and I_{rated} are the short circuit and rated currents. An offset factor, K, determines the magnitude of the first peak, the asymmetrical peak, of the transient current when multiplied by the I_{sc} found above and the square root of 2 to convert from r.m.s. value. This offset factor is derived from the equivalent transient circuit; however, standards give values that must be used based upon the ratio of the effective inductance (x) and resistance (r), x/r.

As indicated by Eq. (3.6), the short circuit current is primarily limited by the internal impedance of the transformer, but may be further reduced by impedances of adjacent equipment, such as current limiting reactors, or by system power delivery limitations. Existing standards define the magnitude and duration of the fault current based on the rating of the transformer.

The transformer must be capable of withstanding the maximum forces experienced at the first peak of the transient current as well as the repeated pulses at each of the subsequent peaks until the fault is cleared or the transformer is disconnected. The current will experience two peaks per cycle, so the forces will pulsate at 120 Hz, twice the power frequency, acting as a dynamic load. Magnitudes of forces during these situations can range from several thousand pounds to millions of pounds in large power transformers. For analysis, the forces acting on the windings are generally broken up into two subsets, radial and axial forces, based on their apparent effect on the windings. Figure 3.10 illustrates the difference between radial and axial forces in a pair of circular windings.

The high currents experienced during through-fault events will also cause elevated temperatures in the windings. Limitations are also placed on the calculated temperature the conductor may reach during fault conditions. These high temperatures are rarely a problem due to the short time span of these events, but the transformer may experience an associated "loss of life" increase. This "loss of life" can become more prevalent, even critical, based on the duration of the fault conditions and how often such events occur. It is also possible for the conductor to experience changes in mechanical strength due to annealing that can occur at high temperatures. The temperature at which this can occur will depend on the properties and composition of the conductor material, such as the hardness, which is sometimes increased through cold-working processes, or the presence of silver in certain alloys.

Efficiency and Losses

Efficiency

Power transformers are very efficient pieces of equipment with efficiencies typically above 99%. The efficiency is derived from the rated output and the losses incurred in the transformer. The basic relationship for efficiency is the output over the input, which according to U.S. standards translates to

$$\text{Efficiency} = \left[\text{kVA rating} \big/ \left(\text{kVA rating} + \text{Total losses}\right)\right] * 100\% \tag{3.7}$$

and will generally decrease slightly with increases in load. Total losses are the sum of the no-load and load losses.

Losses

The no-load losses are essentially the power required to keep the core energized, and so are many times referred to as the core losses. They exist whenever the unit is energized. No-load losses depend primarily upon the voltage and frequency, so under operational conditions it will only vary slightly with system variations. Load losses, as the terminology might suggest, result from load currents flowing through the transformer. The two components of the load losses are the I^2R losses and the stray losses. I^2R losses are based on the measured DC resistance, the bulk of which is due to the winding conductors, and the current at a given load. The stray losses are a term given to the accumulation of the additional losses experienced by the transformer, which includes winding eddy losses and losses due to the effects of leakage flux entering internal metallic structures. Auxiliary losses refer to the power required to run auxiliary cooling equipment, such as fans and pumps, and are not typically included in the total losses as defined above.

Economic Evaluation of Losses

Transformer losses represent power that cannot be delivered to customers and therefore have an associated economic cost to the transformer user/owner. A reduction in transformer losses generally results in an increase in the transformer's cost. Depending on the application, there may be an economic benefit to a transformer with reduced losses and high price (initial cost), and vice versa. This process is typically

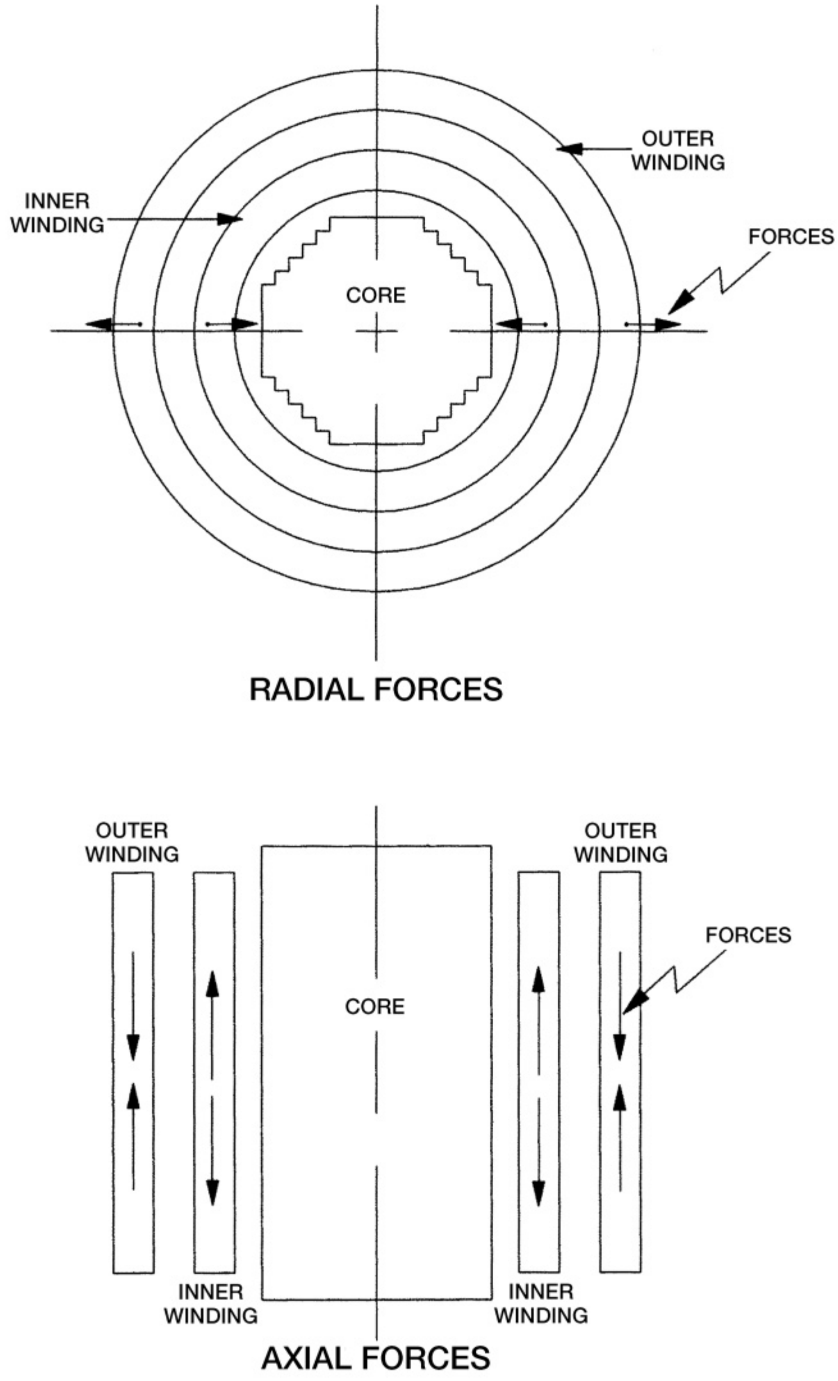


FIGURE 3.10 Radial and axial forces in a transformer winding.

dealt with through the use of "loss evaluations", which place a dollar value on the transformer losses to calculate a total owning cost that is a combination of the price and the losses. Typically, each of the transformer's individual loss parameters, no-load losses, load losses, and auxiliary losses, are assigned a dollar value per kilowatt ($/kW). Information obtained from such an analysis can be used to compare prices from different manufacturers or to decide on the optimum time to replace existing transformers. There are guides available, through standards organizations, for the estimation of the cost associated with transformer losses. Loss evaluation values can range from about $500/kW upwards of $12000/kW for the no-load losses and from a few hundred dollars per kilowatt to about $6000 to 8000/kW for load losses and auxiliary losses. Values will depend upon the application.

Construction

The construction of a power transformer will vary throughout the industry to a certain degree. The basic arrangement is essentially the same and has seen little significant change in recent years, so some of the variations may be discussed here.

The Core

The core, which provides the magnetic path to channel the flux, consists of thin strips of high-grade steel, called laminations, which are electrically separated by a thin coating of insulating material. The strips can be stacked or wound, with the windings either built integrally around the core or built separately and assembled around the core sections. Core steel may be hot or cold rolled, grain oriented or non-grain oriented, and even laser-scribed for additional performance. Thickness ranges from 9 mils (1 mil = 1 thousandth of an inch) upwards of 14 mils. The core cross-section may be circular or rectangular, with circular cores commonly referred to as cruciform construction. Rectangular cores are used for smaller ratings and as auxiliary transformers used within a power transformer. Rectangular cores, obviously, use a single width of strip steel, while circular cores use a combination of different strip widths to approximate a circular cross-section. The type of steel and arrangement will depend on the transformer rating as related to cost factors such as labor and performance.

Just like other components in the transformer, the heat generated by the core must be adequately dissipated. While the steel and coating may be capable of withstanding higher temperatures, it will come in contact with insulating materials with limited temperature capabilities. In larger units, cooling ducts are used inside the core for additional convective surface area and sections of laminations may be split to reduce localized losses.

The core will be held together by, but insulated from, mechanical structures and will be grounded to a single point, usually some readily accessible point inside the tank, but may also be brought through a bushing on the tank wall or top for external access. This grounding point should be removable for testing purposes, such as checking for unintentional core grounds.

The maximum flux density of the core steel is normally designed as close to the knee of the saturation curve as practical, accounting for required over-excitations and tolerances that exist due to materials and manufacturing processes. For power transformers, the flux density is typically between 13 and 18 kG with the saturation point for magnetic steel being around 20.3 to 20.5 kG.

The two basic types of core construction used in power transformers are called core-form and shell-form.

In core-form construction, there is a single path for the magnetic circuit. Figure 3.11 shows a schematic of a single-phase core with the arrows showing the magnetic path. For single-phase applications, the windings are typically divided on both core legs as shown, whereas in three-phase applications, the windings of a particular phase are typically on the same core leg, as illustrated in Fig. 3.12. Windings are constructed separate of the core and placed on their respective core legs during core assembly. Figure 3.13 shows what is referred to as the "E"-assembly of a three-phase core-form core during assembly.

In shell-form construction, the core provides multiple paths for the magnetic circuit. A schematic of a single-phase shell-form core is shown in Fig. 3.14, with the two magnetic paths illustrated. The core is typically stacked directly around the windings, which are usually "pancake" type windings, although some applications are such that the core and windings are assembled similar to core form. Due to advantages in short circuit and transient voltage performance, shell forms tend to be used more frequently in larger transformers where conditions can be more severe. There are variations of three-phase shell-form construction that include five- and seven-legged cores, depending on size and application.

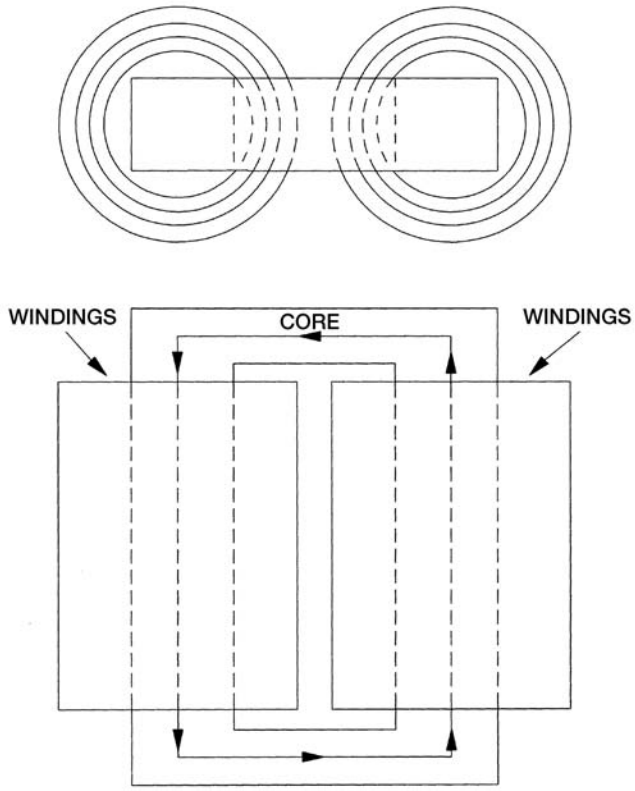


FIGURE 3.11 Schematic of single-phase core-form construction.

The Windings

The windings consist of the current carrying conductors wound around the sections of the core and must be properly insulated, supported, and cooled to withstand operational and test conditions. The terms winding and coil are used interchangeably in this discussion.

Copper and aluminum are the primary materials used as conductors in power transformer windings. While aluminum is lighter and generally less expensive than copper, a larger cross-section of aluminum conductor must be used to carry a current with similar performance as copper. Copper has higher mechanical strength and is used almost exclusively in all but the smaller size ranges, where aluminum conductors may be perfectly acceptable. In cases where extreme forces are encountered, materials such as silver-bearing copper may be used for even greater strength. The conductors used in power transformers will typically be stranded with a rectangular cross-section, although some transformers at the lowest ratings may use sheet or foil conductors. A variation involving many rectangular conductor strands combined into a cable is called continuously transposed cable (CTC), as shown in Fig. 3.15.

In core-form transformers, the windings are usually arranged concentrically around the core leg, as illustrated by Fig. 3.16 of a winding being lowered over another winding already on the core leg of a three-phase transformer. A schematic of coils arranged in this three-phase application was also shown in Fig. 3.12. Shell-form transformers may use a similar concentric arrangement or windings may be stacked into sections or groups as illustrated by Fig. 3.17 and as seen in the picture in Fig. 3.21.

When considering concentric windings, it is generally understood that circular windings have inherently higher mechanical strength than rectangular windings, whereas rectangular coils can have lower associated material and labor costs. Rectangular windings permit a more efficient use of space, but their use is limited to small power transformers and the lower range of medium power transformers where

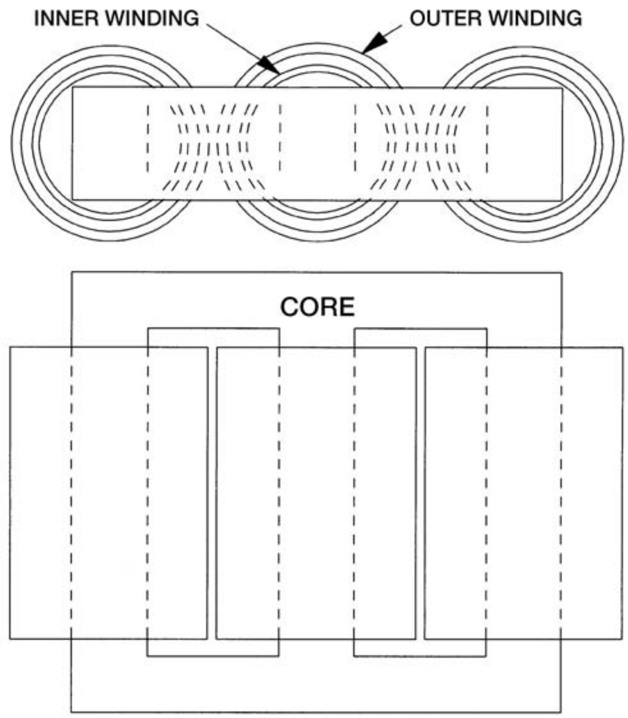


FIGURE 3.12 Schematic of three-phase core-form construction.

FIGURE 3.13 "E"-assembly, prior to insertion of top yoke.

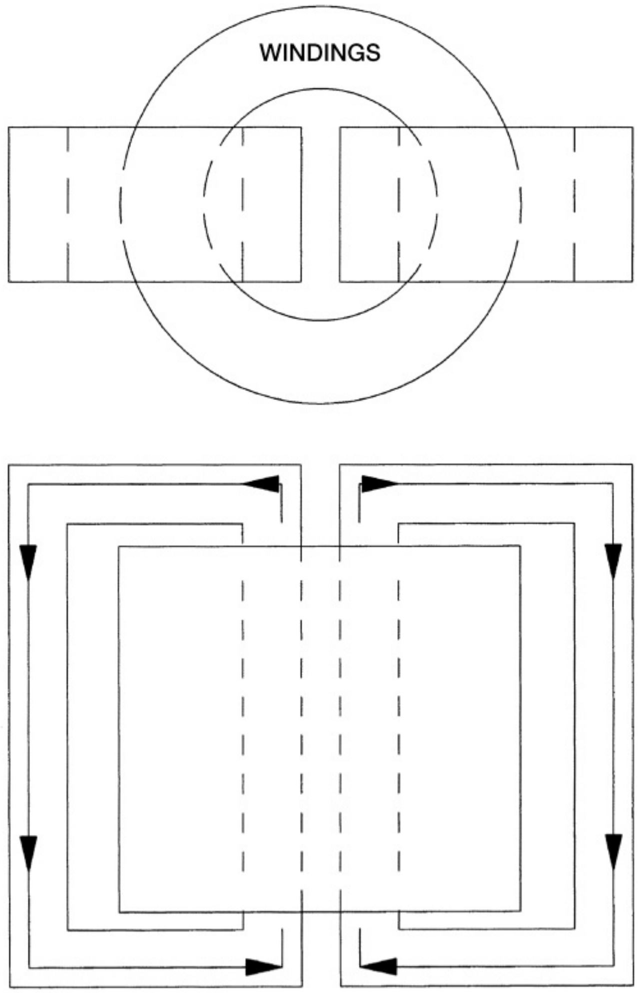


FIGURE 3.14 Schematic of single-phase shell-form construction.

the internal forces are not extremely high. As the rating increases, the forces significantly increase and there is need for added strength in the windings, so circular coils, or shell-form construction, are used. In some special cases, elliptical-shaped windings can even be used.

Concentric coils will typically be wound over cylinders with spacers attached so as to form a duct between the conductors and the cylinder. As previously mentioned, the flow of liquid through the windings can be based solely on natural convection or the flow can be somewhat controlled through the use of strategically placed barriers within the winding. Figures 3.18 and 3.19 show winding arrangements comparing non-directed and directed flow. This concept is sometimes referred to as guided liquid flow.

There are a variety of different types of windings that have been used in power transformers through the years. Coils can be wound in an upright, vertical orientation, as is necessary with larger, heavier coils, or can be wound horizontally and uprighted upon completion. As mentioned before, the type of winding will depend on the transformer rating as well as the core construction. Several of the more common winding types are discussed below.

While it is recognized that several types of windings are sometimes referred to as “pancake” windings due to the arrangement of conductors into discs, the term most often refers to the type of coil that is almost exclusively used in shell-form transformers. The conductors are wound around a rectangular form, with the widest face of the conductor either oriented horizontally or vertically, with layers of

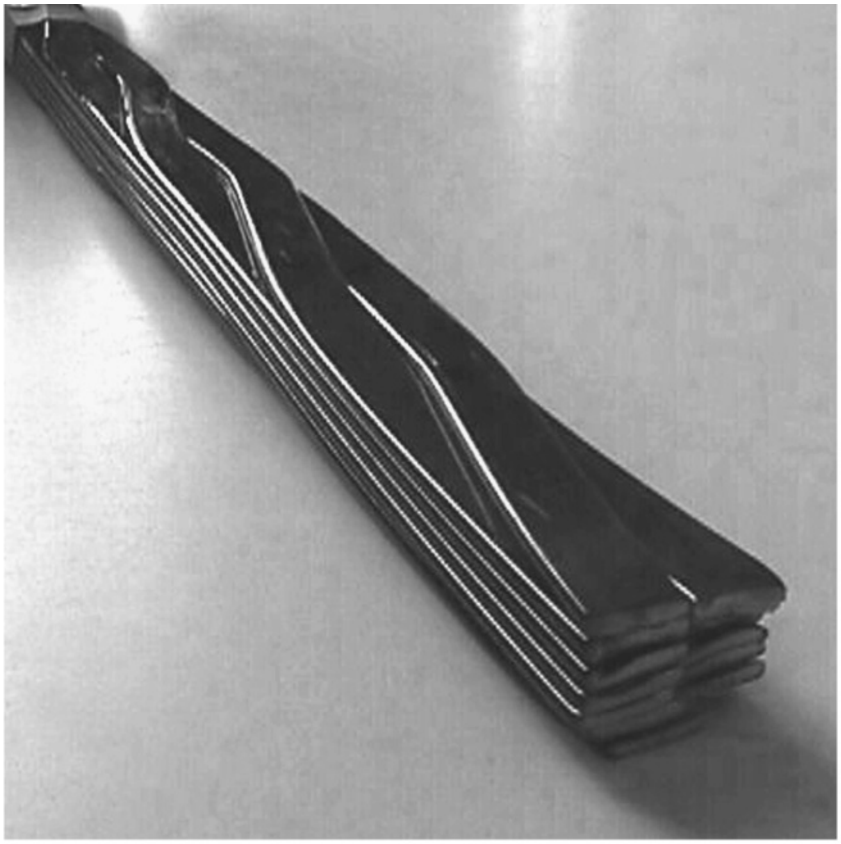


FIGURE 3.15 Continuously transposed cable (CTC).

conductors stacked on top of one another and separated by spacers. Figure 3.20 illustrates how these coils are typically wound. This type of winding lends itself to grouping different windings along the same axial space, as previously shown in Fig. 3.17 and further illustrated in Fig. 3.21.

Layer, or barrel, windings are among the simplest of windings in that the insulated conductors are wound directly next to each other around the cylinder and spacers. Several layers may be wound on top of one another, with the layers separated by solid insulation, ducts, or a combination of both. Several strands may be wound in parallel if the current dictates. Variations of this winding are often used for applications such as tap windings used in load tap changing transformers and for tertiary windings used for, among other things, third harmonic suppression. Figure 3.22 shows a layer winding during assembly that will be used as a regulating winding in an LTC transformer.

Helical windings are also referred to as screw or spiral windings with each term accurately characterizing the coil's construction. A helical winding will consist of anywhere from a few to more than 100 insulated strands wound in parallel continuously along the length of the cylinder, with spacers inserted between adjacent turns or discs and suitable transpositions to minimize circulating currents between strands. The manner of construction is such that the coil will somewhat resemble a corkscrew. Figure 3.23 shows a helical winding during the winding process. Helical windings are used for relatively higher current applications frequently encountered in the lower voltage classes.

A disc winding can involve a single strand or several strands of insulated conductors wound in a series of parallel discs of horizontal orientation with the discs connected at either the inside or outside as a "cross-over" point. Each disc will be comprised of multiple turns wound over other turns with the crossovers alternating between inside and outside. Figure 3.24 outlines the basic concept with Fig. 3.25 showing typical crossovers during the winding process. Most windings 25 kV class and above used in

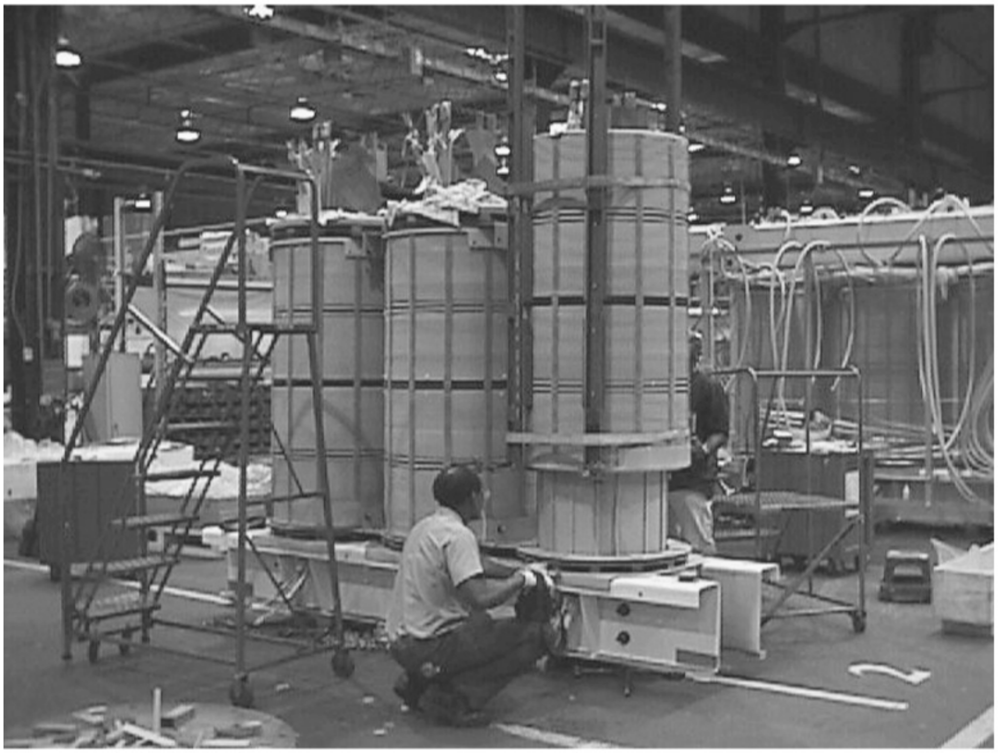


FIGURE 3.16 Concentric arrangement, outer coil being lowered onto core leg over top of inner coil.

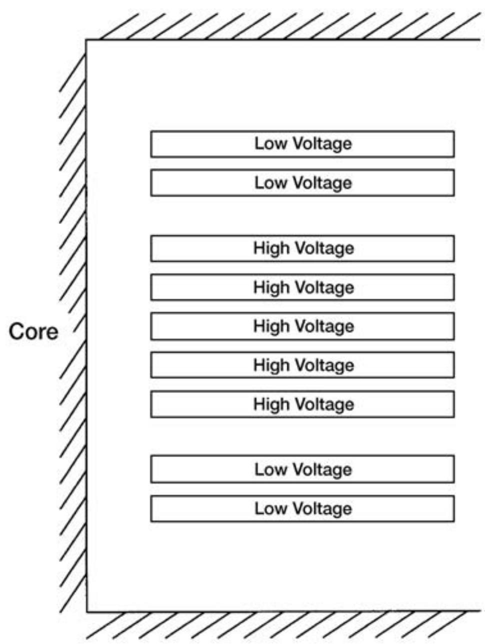


FIGURE 3.17 Example of stacking arrangement of windings in shell-form construction.

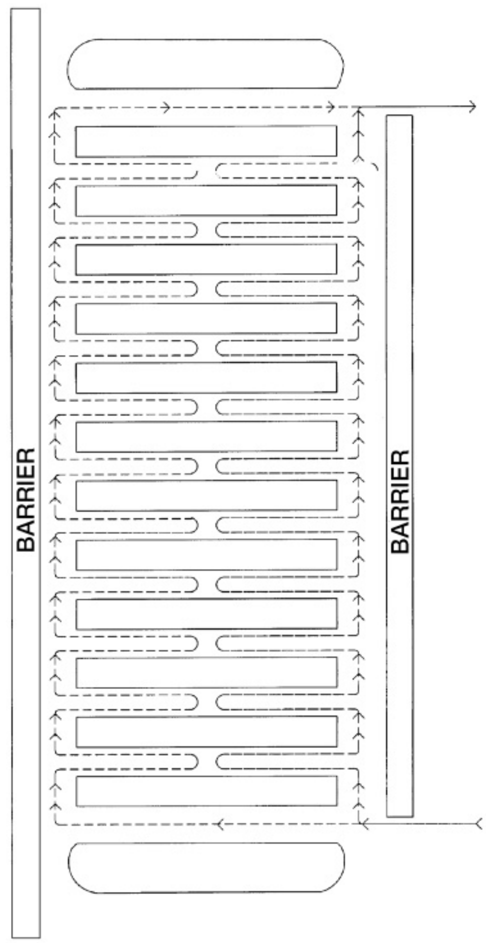


FIGURE 3.18 Non-directed flow.

core-form transformers are disc type so, due to the high voltages involved in test and operation, particular attention must be given to avoid high stresses between discs and turns near the end of the winding when subjected to transient voltage surges. Numerous techniques have been developed to ensure an acceptable voltage distribution along the winding under these conditions.

Taps — Turns Ratio Adjustment

The capability of adjusting the turns ratio of a transformer is oftentimes desirable to compensate for variations in voltage that occur due to loading cycles, and there are several means by which the task can be accomplished. There is a significant difference in a transformer that is capable of changing the ratio while the unit is on-line, referred to as a Load Tap Changing (LTC) transformer, and one that must be taken off-line, or de-energized, to perform a tap change.

Currently, most transformers are provided with a means to change the number of turns in the high-voltage circuit, whereby part may be tapped out of the circuit. In many transformers this is done using one of the main windings and tapping out a section or sections, whereas with larger units a dedicated tap winding may be necessary to avoid ampere-turn voids along the length of the winding that occur in the former case. Use and placement of tap windings vary with the application and among manufacturers. A manually operated switching mechanism, a DETC (De-energized Tap Changer), is normally provided accessible external to the transformer to change the tap position. When LTC capabilities are desired,

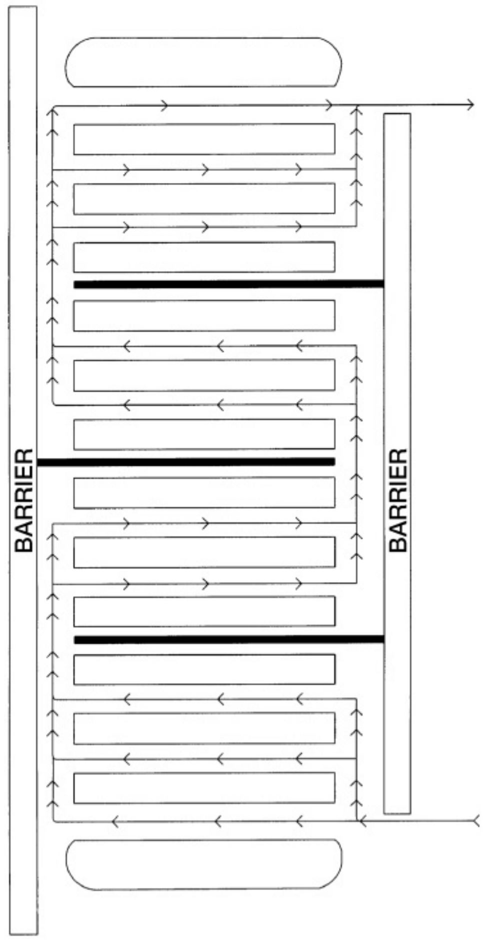


FIGURE 3.19 Directed flow.

FIGURE 3.20 Pancake winding during winding process.

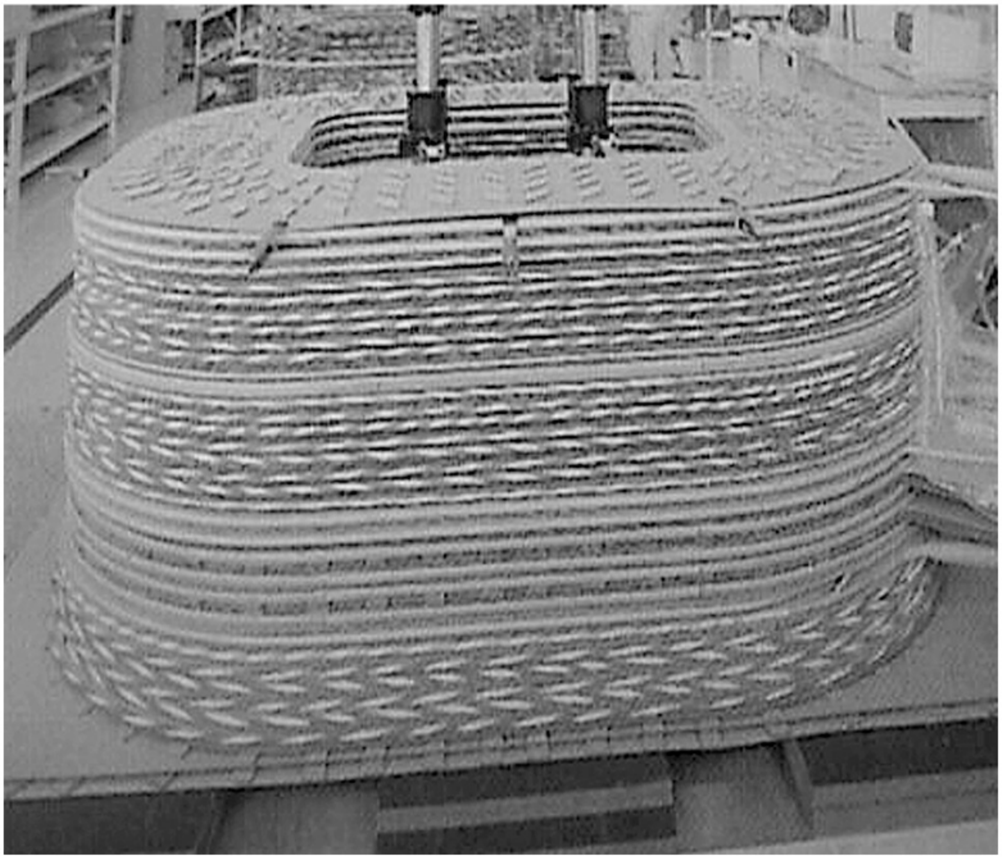


FIGURE 3.21 Stacked pancake windings.

additional windings and equipment are required that significantly increase the size and cost of the transformer.

It is also possible for a transformer to have dual voltage ratings, as is popular in spare and mobile transformers. While there is no physical limit to the ratio between the dual ratings, even ratios (for example, 24.94 × 12.47 kV or 138 × 69 kV) are easier for manufacturers to accommodate.

Accessory Equipment

Accessories

There are a great many different accessories used for the purpose of monitoring and protecting power transformers, some of which are considered standard features and others which are used based on miscellaneous requirements. A few of the basic accessories will be discussed briefly.

Liquid Level Indicator

A liquid level indicator is a standard feature on liquid-filled transformer tanks because the liquid medium is critical for cooling and insulation. This indicator is typically a round-faced gauge on the side of the tank with a float and float arm that moves a dial pointer as the liquid level changes.

Pressure Relief Devices

Pressure relief devices are mounted on transformer tanks to relieve excess internal pressures that might build up during operating conditions to avoid damage to the tank itself. On larger transformers, several pressure relief devices may be required due to the large quantities of oil.

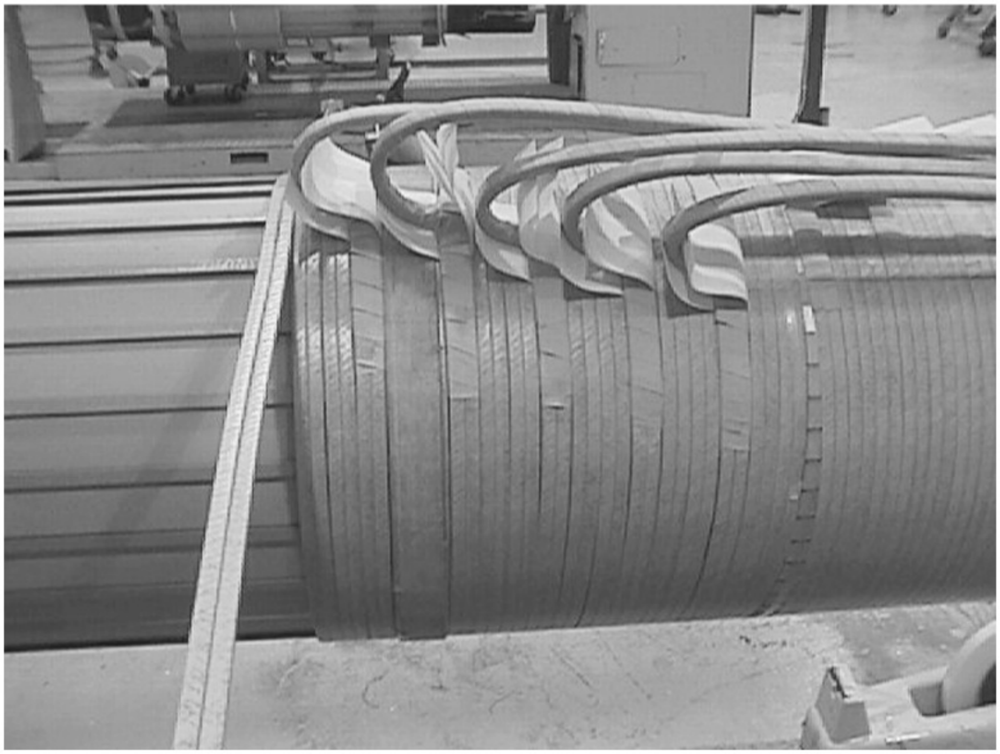


FIGURE 3.22 Layer windings (single layer with two strands wound in parallel).

Liquid Temperature Indicator

A liquid temperature indicator will measure the temperature of the internal liquid at a point near the top of the liquid through a probe inserted in a well mounted through the side of the transformer tank.

Winding Temperature Indicator

A winding temperature simulation method is used to approximate the hottest spot in the winding because of the difficulties involved in direct winding temperature measurements. The method applied to power transformers involves a current transformer which will be located to incur a current proportional to the load current through the transformer. The current transformer feeds a circuit that essentially adds heat to the top liquid temperature reading to give an approximate reading of the winding temperature. This method relies on design or test data of the temperature differential between the liquid and the windings, called the winding gradient.

Sudden Pressure Relay

A sudden (or rapid) pressure relay is intended to indicate a quick increase in internal pressure that can occur when there is an internal fault. Varieties are used that can be mounted on the top or side of the transformer or that operate in liquid or gas space.

Desiccant (Dehydrating) Breathers

Desiccant breathers use a material such as silica gel to allow air to enter and exit the tank which removes moisture as the air passes through. Most tanks will be somewhat free-breathing and such a device, if properly maintained, allows a degree of control over the quality of air entering the transformer.

Liquid Preservation Systems

There are several methods in practice to preserve the properties of the transformer liquid and associated insulation structures that it penetrates. Preservation systems attempt to isolate the transformer's internal environment from the external environment (atmosphere) while understanding that a certain degree of

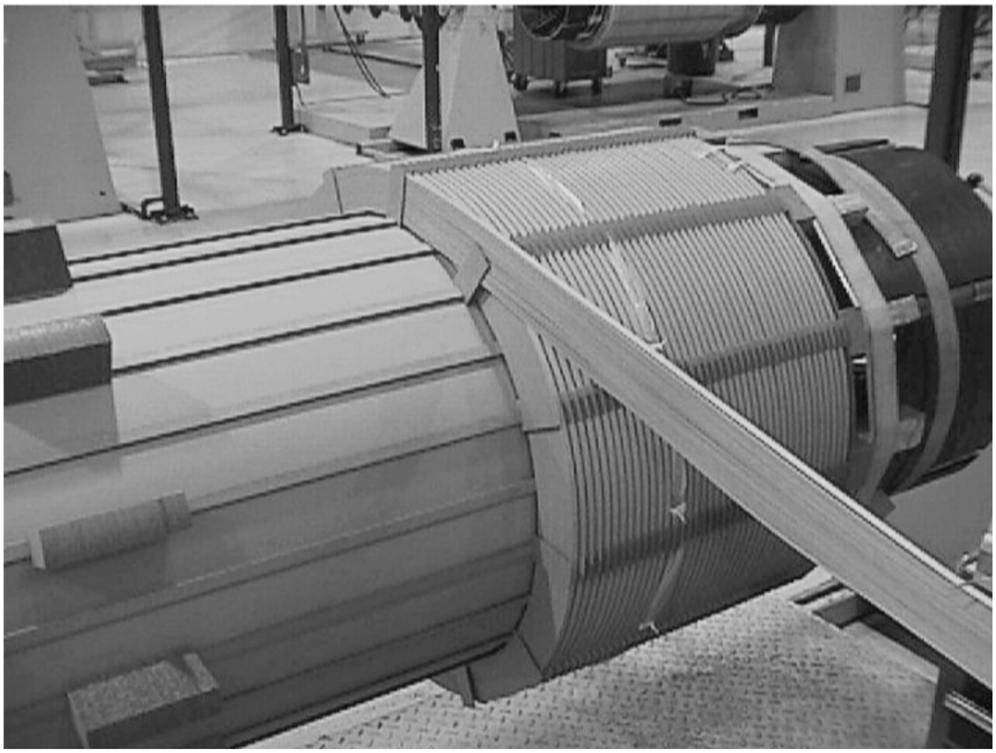


FIGURE 3.23 Helical winding during assembly.

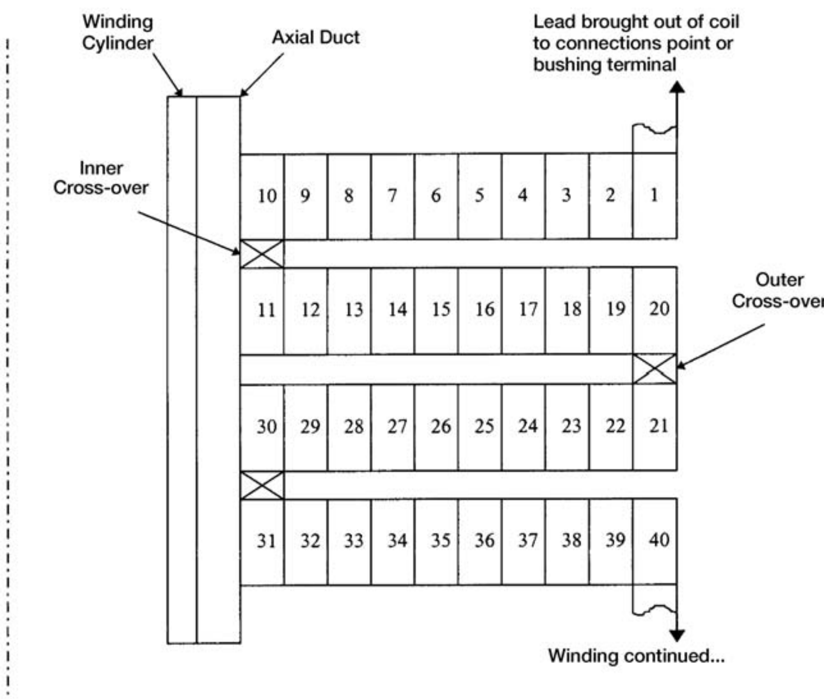


FIGURE 3.24 Basic disc winding layout.

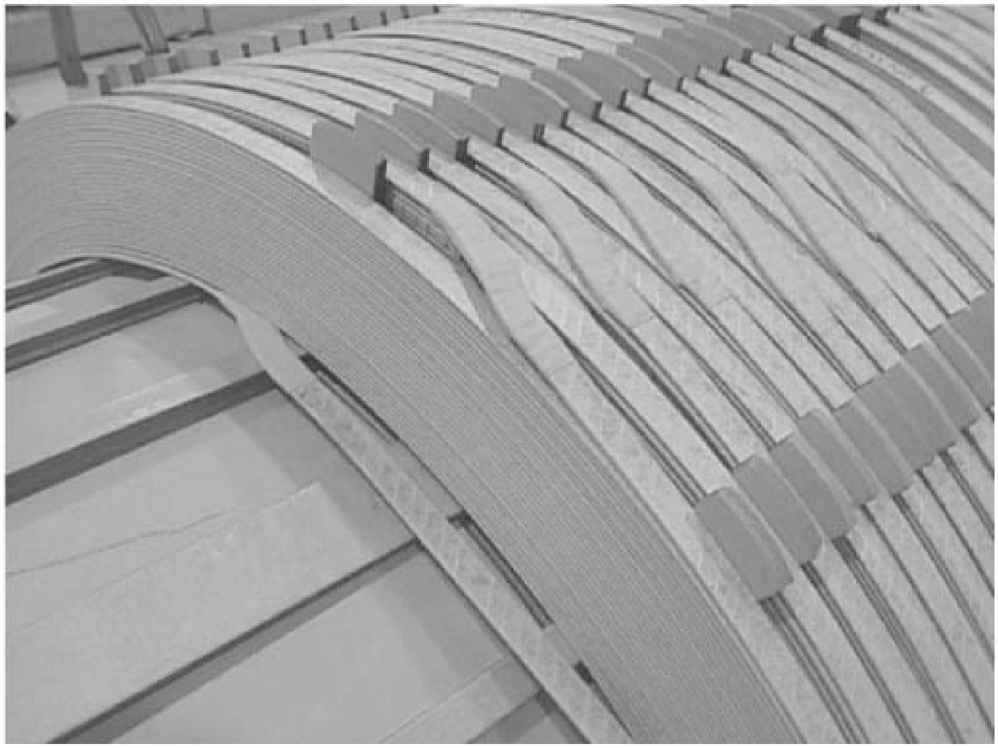


FIGURE 3.25 Disc winding inner and outer crossovers.

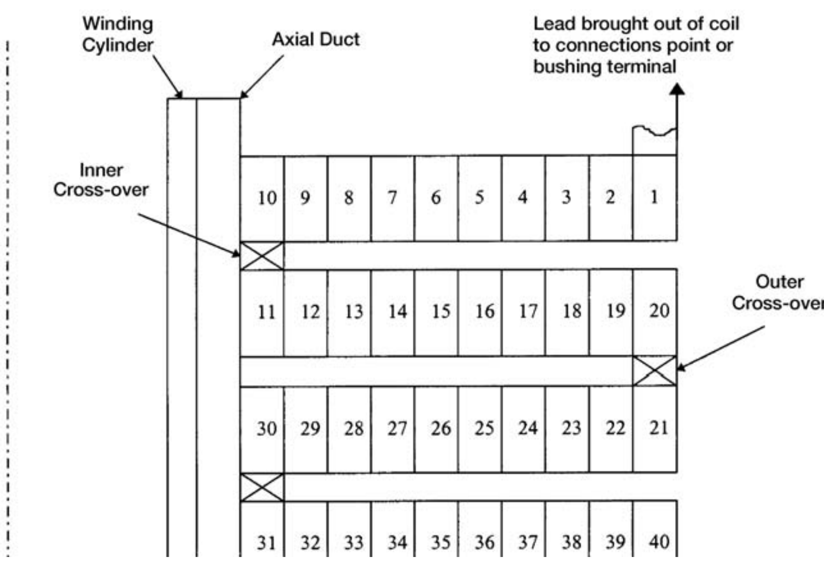


FIGURE 3.26 General arrangements of liquid preservation systems.

interaction or "breathing" is required due to variations in pressure that occur under operational conditions, such as expansion and contraction of liquid with temperature. The most commonly used methods are outlined as follows and illustrated in Fig. 3.26.

1. Sealed tank systems have the tank interior sealed from the atmosphere and will maintain a layer of gas, a gas space or cushion, that will sit above the liquid. The gas plus liquid volume will remain constant. Negative internal pressures can exist in sealed tank systems at lower loads or temperatures with positive pressures existing as load and temperatures increase. A pressure-vacuum bleeder is used to limit operating pressures in transformers over a certain size.
2. Positive pressure systems involve the use of inert gases to maintain a positive pressure in the gas space. A source of inert gas, typically a bottle of compressed nitrogen, will be injected incrementally into the gas space when the internal pressure falls out of range.
3. Conservator (expansion tank) systems are used both with and without air bags, also called bladders or diaphragms, which involve a separate auxiliary tank. The main transformer tank will be completely filled with liquid, the auxiliary tank will be partially filled, and the liquid will expand and contract within the auxiliary tank. The auxiliary tank will be allowed to "breath", usually through a dehydrating breather. The use of an air bag in the auxiliary tank can provide further separation from the atmosphere.

Inrush Current

When a transformer is taken off-line, there will be a certain amount of residual flux that can remain in the core due to the properties of the magnetic core material. The residual flux can be as much as 50 to 90% of the maximum operating flux, depending on the type of core steel. When voltage is reapplied to the transformer, the flux introduced by this source voltage will build upon that which already exists in the core. In order to maintain this level of flux in the core, which can be well into the saturation range of the core steel, the transformer can draw current well in excess of the transformer's rated full load current. Depending on the transformer design, the magnitude of this current inrush can be anywhere from 3.5 to 40 times the rated full load current. The waveform of the inrush current will be similar to a sine wave, but largely skewed towards the positive or negative direction. This inrush current will experience a decay, partially due to losses, which will provide a dampening effect; however, the current can remain well above rated current for many cycles.

This inrush current can have an effect on the operation of relays and fuses located in the system near the transformer. Decent approximations of the inrush current require detailed information regarding the transformer design which may be available from the manufacturer but is not typically available to the user. Actual inrush currents will also depend upon where in the source voltage wave the switching operations occur, the moment of opening effecting the residual flux magnitude, and the moment of closing effecting the new flux.

Modern and Future Developments

High-Voltage Generator (Powerformer)

Because electricity is currently generated at voltage levels that are too low to be efficiently transmitted across the great distances that the power grid typically spans, step-up transformers are required at the generator. With developments in high-voltage cable technology, a high-voltage generator, called the powerformer, has been developed that will eliminate the need for this GSU transformer and associated equipment. This powerformer can reportedly be designed to generate power at voltage levels between 20 and 400 kV to directly feed the transmission network.

High-Temperature Superconducting (HTS) Transformer

Superconducting technologies are being applied to power transformers in the development of what are being referred to as high-temperature superconducting (HTS) transformers. In HTS transformers, the copper and aluminum in the windings would be replaced by superconductors. In the field of superconductors, high temperatures are considered to be in the range of –250 to –200°F, which represents quite a significant deviation in the operating temperatures of conventional transformers. At these temperatures, insulation of the type currently used in transformers would not degrade in the same manner. Using superconducting conductors in transformers requires advances in cooling, specifically refrigeration technology directed toward use in transformers. The predominant cooling medium in HTS development has been liquid nitrogen, but some other mediums have been investigated as well. Transformers built using HTS technology would reportedly be of reduced size and weight and capable of overloads without experiencing "loss of life" due to insulation degradation, instead using an increased amount of the replaceable coolant. An additional benefit would be an increase in efficiency of HTS transformers over conventional transformers due to the fact that resistance in superconductors is virtually zero, thus eliminating the I^2R loss component of the load losses.

References

American National Standard for Transformers — 230 kV and Below 833/958 through 8333/10417 kVA, Single-Phase, and 750/862 through 60000/80000/100000 kVA, Three-Phase Without Load Tap Changing; and 3750/4687 through 60000/80000/100000 kVA with Load Tap Changing — Safety Requirements, ANSI C57.12.10-1997, National Electrical Manufacturers Association, 1998.

Bean, R. L., Chackan, N. Jr., Moore, H. R., and Wentz, E. C., *Transformers for the Electric Power Industry*, McGraw-Hill, New York, 1959.

Goldman, A. W. and Pebler, C. G., *Power Transformers*, Vol. 2, Electrical Power Research Institute, Inc., Palo Alto, CA, 1987.

Hobson, J. E. and Witzke, R. L., Power transformers and reactors, in *ElectricalTransmission and Distribution Reference Book,* 4th ed., Central Station Engineers of the Westinghouse Electric Corporation, Westinghouse Electric Corporation, East Pittsburgh, PA, 1950, chap. 5.

IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers, IEEE C57.12.00-1993, The Institute of Electrical and Electronics Engineers, Inc., 1993.

IEEE Standard Terminology for Power and Distribution Transformers, ANSI/IEEE C57.12.80-1978, The Institute of Electrical and Electronics Engineers, Inc., 1998.

Mehta, S. P., Aversa, N., and Walker, M. S., Transforming transformers, *IEEE Spectrum*, p. 43, 1997.

3.3 Distribution Transformers[2]

Dudley L. Galloway

Historical Background

Long-Distance Power

In 1886, George Westinghouse built the first long-distance alternating current electric lighting system in Great Barrington, Massachusetts. The power source was a 25-hp steam engine driving an alternator with

[2]Figures 3.31, 3.32, 3.33, and 3.35 adapted or reprinted from IEEE Std. C57.105-1978 "IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems", Copyright © 1978 by the Institute of Electrical and Electronics Engineers, Inc. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner. Information is reprinted with the permission of the IEEE.

Figure 3.36 adapted from IEEE Std. C57.12.90-1993 "IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short Circuit Testing of Distribution and Power Transformers", Copyright © 1993 by the Institute of Electrical and Electronics Engineers, Inc. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner. Information is reprinted with the permission of the IEEE.

Figure 3.37 adapted from IEEE Std. C57.12.00-1993 "IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers", Copyright © 1993 by the Institute of Electrical and Electronics Engineers, Inc. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner. Information is reprinted with the permission of the IEEE.

All others, by permission of ABB Power T&D Company Inc., Raleigh, NC, and Jefferson City, MO.

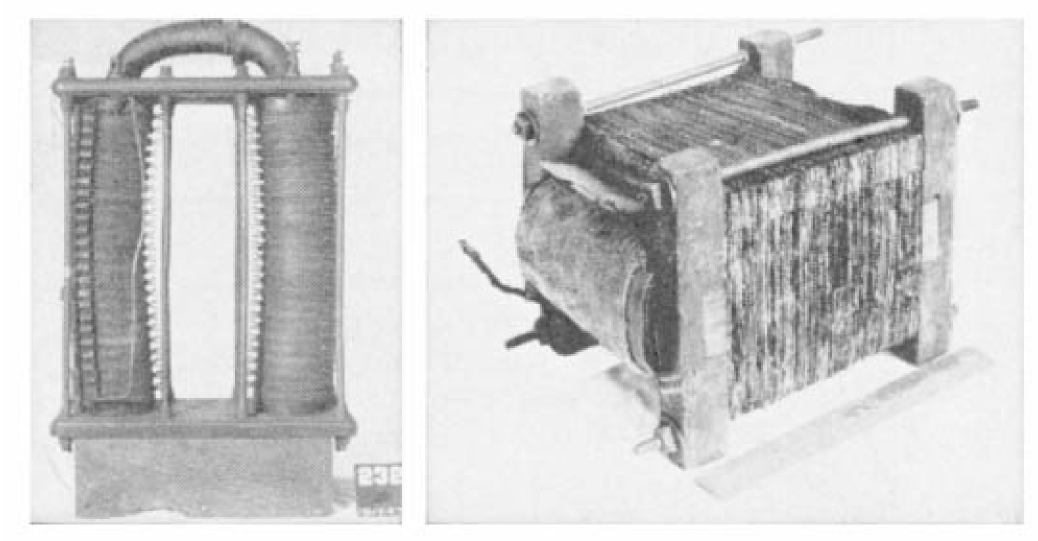


FIGURE 3.27 (a) The Gaulard and Gibbs transformer. (b) William Stanley's early transformer.

an output of 500 V and 12 A. In the middle of town, 4000 ft away, transformers were used to reduce the voltage to serve light bulbs located in nearby stores and offices (Powel, 1997).

The First Transformers

Westinghouse realized that electric power could only be delivered over distances by transmitting at a higher voltage and then reducing the voltage at the location of the load. He purchased U.S. patent rights to the transformer from Gaulard and Gibbs, shown in Fig. 3.27a. William Stanley, Westinghouse's electrical expert, designed and built the transformers to reduce the voltage from 500 to 100 V on the Great Barrington system. See Fig. 3.27b.

What Is a Distribution Transformer?

Just like the transformers in the Great Barrington system, any transformer that takes voltage from a primary distribution circuit and "steps down" or reduces it to a secondary distribution circuit or a consumer's service circuit is a distribution transformer. Although many industry standards tend to limit this definition by kVA rating (e.g., 5 to 500), distribution transformers can have lower ratings and can have ratings of 5000 kVA or even higher, so the use of kVA ratings to define transformer types is being discouraged (IEEE, 1978).

Construction

Early Transformer Materials

From the pictures, the Gaulard–Gibbs transformer seems to have used a coil of many turns of iron wire to create a ferromagnetic loop. The Stanley model, however, appears to have used flat sheets of iron, stacked together and clamped with wooden blocks and steel bolts. Winding conductors were most likely made of copper from the very beginning. Several methods of insulating the conductor were used in the early days. Varnish dipping was often used and is used for some applications today. Paper tape wrapping of conductors has been used extensively, but has now been almost completely replaced by other methods.

Oil Immersion

In 1887, the year after Stanley designed and built the first transformers in the U.S., Elihu Thompson patented the idea of using mineral oil as a transformer cooling and insulating medium (Myers et al., 1981). Although materials have improved dramatically, the basic concept of an oil-immersed cellulosic insulating system has changed very little in well over a century.