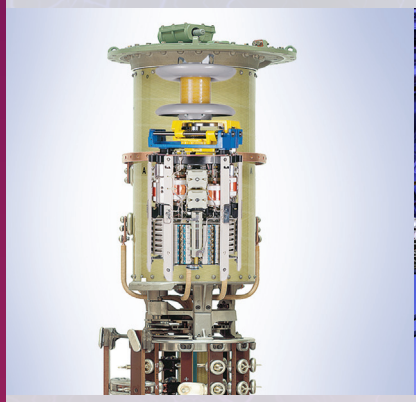
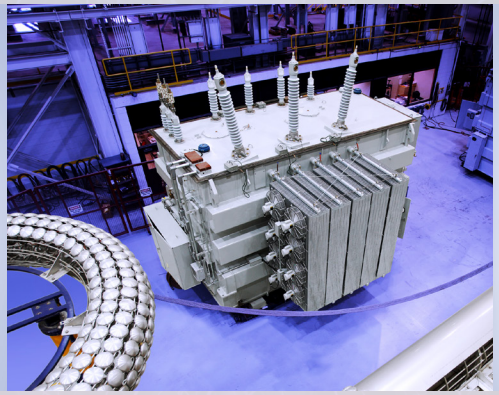
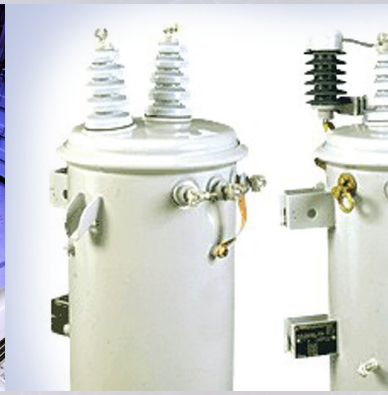
The Electric Power Engineering Handbook

ELECTRIC POWER TRANSFORMER ENGINEERING

THIRD EDITION







EDITED BY **JAMES H. HARLOW**

CRC Press
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Third Edition

Edited by

Leonard L. Grigsby

Electric Power Generation, Transmission, and Distribution, Third Edition

Edited by Leonard L. Grigsby

Electric Power Transformer Engineering, Third Edition

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Electric Power Substations Engineering, Third Edition

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Contents

Preface

It is appropriate that I first acknowledge my appreciation to Professor Leo Grigsby for inviting me to prepare the chapter on power transformers for the first edition (2001) of his now very popular Electric Power Engineering Handbook. From that evolved the recognition that two chapters from the 2001 handbook, those for (1) substations and (2) transformers, could be extracted, expanded, and be offered as stand-alone books while retaining the composite association with Professor Grigsby's overall work. Thus, the first edition of *Electric Power Transformer Engineering* was offered by CRC Press in 2004, the second edition in 2007, and now this third edition.

As editor of the book, my charge to the chapter authors was to direct their messages to engineers who know the basic physics, or applications, or possess a hands-on working knowledge of power transformers. Thus, it is believed that all persons with a power transformer background experience, be they merely curious, seasoned professionals, or acknowledged experts, will find much in the book with which to relate, and that all such readers will glean material appropriate to their individual degree of expertise.

The book is topically structured three parts:

Chapter 1. Theory and principles:

Illustrating to electrical engineers the relevant theories and principles (concepts and mathematics) of power transformers.

Chapters 2 through 11:

Devoting a complete chapter to each of ten particular embodiments of power transformers and closely related apparatus.

- Power transformers
- Distribution transformers
- Phase-shifting transformers
- Rectifier transformers
- Dry-type transformers
- Instrument transformers
- Step-voltage regulators
- Constant-voltage transformers
- Transformers for wind turbine generators and photovoltaic applications
- Reactors

Chapters 12 through 25:

Delving into 14 ancillary topics that are fundamental to the operation or design of the basic transformer.

- Insulating media
- Electrical bushings

- Tap changers and smart intelligent controls
- Loading and thermal performance
- Transformer connections
- Transformer testing
- Load-tap-change control and transformer paralleling
- Power transformer protection
- Causes and effects of transformer sound levels
- Transient-voltage response of coils and windings
- Transformer installation and maintenance
- Problem and failure investigation
- Online monitoring of liquid-immersed transformers
- The United States power transformer equipment standards and processes

While many of these chapter titles remain as in the second edition, the reader will quickly recognize that most have been significantly expanded with new and updated material for this third edition. Each chapter is replete with photographs, equations, and tabular data appropriate to the discussion.

For my part, the manner by which I have been most useful to the production of this book is simply by virtue of the long-standing (and always most enjoyable) association I have had with the experts who comprise the chapter authors. Each author has enthusiastically supported the effort. This offers a peek into the unselfish attitude of the community of power transformer engineers, without which, and without whom, I could never alone have undertaken to produce the work.

James H. Harlow, PE
Editor

Editor

James H. Harlow is self-employed as principal of Harlow Engineering Associates, consulting to the electric power industry since 1996. Prior to this, he had 34 years of industry experience with Siemens (and its predecessor company Allis-Chalmers) and Beckwith Electric. While at these firms, he managed or conducted groundbreaking projects that blended electronics into power transformer applications. Two such projects were the introduction of the first microprocessor-based intelligent electronic device used in quantity in utility substation environments (for the automatic control of load tap changers) and a power-thyristor-based load tap changer to accomplish arc mitigation during the tap change event in step-voltage regulators.

Harlow received his BSEE from Lafayette College, his MBA (statistics) from Jacksonville State University, and his MS (electric power) from Mississippi State University. He joined the IEEE PES Transformers Committee in 1982 serving in various capacities before becoming an officer, culminating as chair of the committee for 1994–1995. In this capacity, he exercised oversight of all power transformer standards that are sponsored by the IEEE. During this period, he served on the IEEE delegation to the ANSI C57 Main Committee (Transformers). As chair of the Transformers Committee, he was a member of the IEEE PES Technical Council, the assemblage of leaders of the various technical committees that comprise the IEEE Power and Energy Society. Continuing involvement led to serving as PES vice president of technical activities and chair of the Technical Council for the years 2001–2002.

Harlow has authored more than 30 technical articles and papers, including serving as editor of the transformer section of the 2001, 2004, and 2007 editions of The Electric Power Engineering Handbook, CRC Press. His editorial contribution within this book is the chapter on his specialty, LTC control and transformer paralleling (Chapter 18). A holder of six U.S. patents, Harlow is a registered professional engineer and a life-senior member of the IEEE.

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1

Theory and Principles

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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 Figure 1.1. If another conductor is placed in the field created by the first conductor such that the flux lines link the second conductor, as shown in Figure 1.2, 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.

1.1 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.

$$E = \frac{N\,d\phi}{dt\,10^8} \tag{1.1}$$

where

N is the number of turns in the coil
$d\phi/dt$ is the time rate of change of flux linking the coil
ϕ is the flux in lines

At a time when the applied voltage to the coil is E and the flux linking the coils is ϕ lines, the instantaneous voltage of the supply is:

$$e = \sqrt{2}E\cos\omega t = \frac{N\,d\phi}{dt\,10^8} \tag{1.2}$$

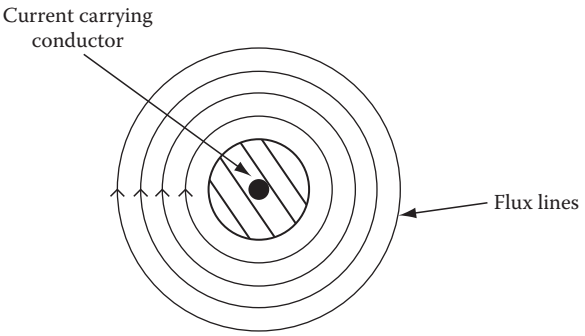

FIGURE 1.1 Magnetic field around conductor.

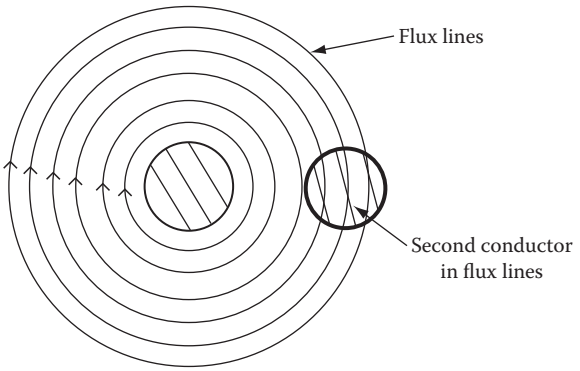

FIGURE 1.2 Magnetic field around conductor induces voltage in second conductor.

$$\frac{d\phi}{dt} = \frac{(\sqrt{2}\cos\omega t 10^{8})}{N} \tag{1.3}$$

The maximum value of ϕ is given by:

$$\phi = \frac{(\sqrt{2}E10^{8})}{(2\pi f N)} \tag{1.4}$$

Using the MKS (metric) system, where ϕ is the flux in webers,

$$E = \frac{N d\phi}{dt} \tag{1.5}$$

and

$$\phi = \frac{(\sqrt{2}E)}{(2\pi f N)} \tag{1.6}$$

Since the amount of flux ϕ linking the second coil is a small percentage of the flux from the first coil, 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.

1.2 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 in the order of 1500 compared with 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 Figure 1.3, 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.

Continuing in the MKS system, the fundamental relationship between magnetic flux density (B) and magnetic field intensity (H) is:

$$B = \mu_0 H \tag{1.7}$$

where μ_0 is the permeability of free space = $4\pi \times 10^{-7}$ Wb A^{-1} m^{-1}.

Replacing B by ϕ/A and H by $(IN)/d$

where

ϕ is the core flux in lines
N is the number of turns in the coil
I is the maximum current in amperes
A is the core cross-section area

the relationship can be rewritten as:

$$\phi = \frac{(\mu NAI)}{d} \tag{1.8}$$

where

d is the mean length of the coil in meters
A is the area of the core in square meters

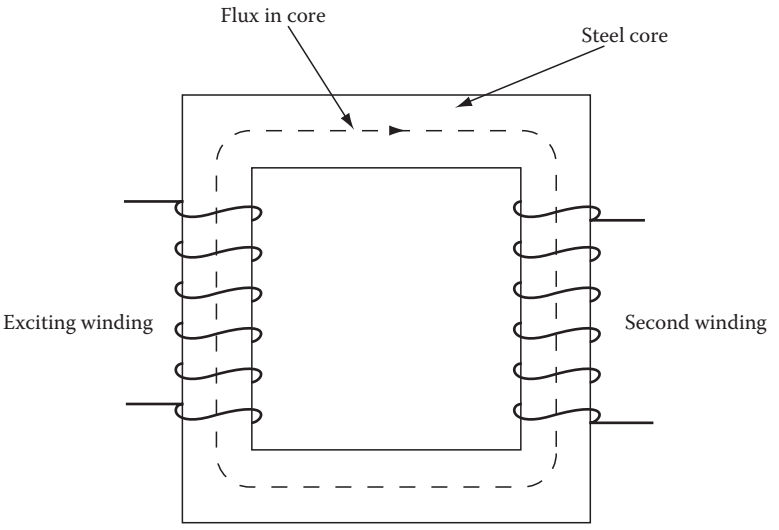

FIGURE 1.3 Two coils applied on a steel core.

Then, the equation for the flux in the steel core is:

$$\phi = \frac{(\mu_0 \mu_r NAI)}{d} \tag{1.9}$$

where, μ_r is the relative permeability of steel ≈1500.

Since the permeability of the steel is very high compared with 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:

$$\phi = \frac{0.225E}{fN} \tag{1.10}$$

where

E is the applied alternating voltage
F is the frequency in hertz
N is the number of turns in the winding

In transformer design, it is useful to use flux density, and Equation 1.10 can be rewritten as:

$$B = \frac{\phi}{A} = \frac{0.225E}{(fAN)} \tag{1.11}$$

where, B is the flux density in tesla (webers/square meter).

1.3 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 "hysteresis" losses. An explanation of these losses would require a full chapter. For the purpose of this text, it can be stated that the hysteresis loss is caused by the cyclic reversal of flux in the magnetic circuit and can be reduced by metallurgical control of the steel. Eddy loss is caused by eddy currents circulating within the steel induced by the flow of magnetic flux normal to the width of the core, and it can be controlled by reducing the thickness of the steel lamination or by applying a thin insulating coating.

Eddy loss can be expressed as follows:

$$W = K[w]^2[B]^2 \text{ Watts} \tag{1.12}$$

where

K is the constant
W is the width of the core lamination material normal to the flux
B is the 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 and 0.28 mm, to reduce the thickness of the individual sheets of steel normal to the flux and thereby reducing 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 include:

- Development of cold-rolled grain-oriented (CGO) electrical steels in the mid 1940s
- Introduction of thin coatings with good mechanical properties
- Improved chemistry of the steels, e.g., Hi-B steels
- Further improvement in the orientation of the grains
- Introduction of laser-scribed and plasma-irradiated steels
- Continued reduction in the thickness of the laminations to reduce the eddy-loss component of the core loss
- Introduction of amorphous ribbon (with no crystalline structure)—manufactured using rapid-cooling technology—for use with distribution and small power transformers

The combination of these improvements has resulted in electrical steels having less than 40% of the no-load loss and 30% of the exciting (magnetizing) current that was possible in the late 1940s.

The effect of the cold-rolling process on the grain formation is to align magnetic domains in the direction of rolling so that the magnetic properties in the rolling direction are far superior to those in other directions. A heat-resistant insulation coating is applied by thermochemical treatment to both sides of the steel during the final stage of processing. The coating is approximately 1-μm thick and has only a marginal effect on the stacking factor. Traditionally, a thin coat of varnish had been applied by the transformer manufacturer after completion of cutting and punching operations. However, improvements in the quality and adherence of the steel manufacturers' coating and in the cutting tools available have eliminated the need for the second coating, and its use has been discontinued.

Guaranteed values of real power loss (in watts per kilogram) and apparent power loss (in volt-amperes per kilogram) apply to magnetization at 0° to the direction of rolling. Both real and apparent power loss increase significantly (by a factor of 3 or more) when CGO is magnetized at an angle to the direction of rolling. Under these circumstances, manufacturers' guarantees do not apply, and the transformer manufacturer must ensure that a minimum amount of core material is subject to cross-magnetization, i.e., where the flow of magnetic flux is normal to the rolling direction. The aim is to minimize the total core loss and (equally importantly) to ensure that the core temperature in the area is maintained within safe limits. CGO strip cores operate at nominal flux densities of 1.6–1.8 T. This value compares with 1.35 T used for hot-rolled steel, and it is the principal reason for the remarkable improvement achieved in the 1950s in transformer output per unit of active material. CGO steel is produced in two magnetic qualities (each having two subgrades) and up to four thicknesses (0.23, 0.27, 0.30, and 0.35 mm), giving a choice of eight different specific loss values. In addition, the designer can consider using domain-controlled Hi-B steel of higher quality, available in three thicknesses (0.23, 0.27, and 0.3 mm).

The different materials are identified by code names:

- CGO material with a thickness of 0.3 mm and a loss of 1.3 W/kg at 1.7 T and 50 Hz, or 1.72 W/kg at 1.7 T and 60 Hz, is known as M097–30N.
- Hi-B material with a thickness of 0.27 mm and a loss of 0.98 W/kg at 1.7 T and 50 Hz, or 1.3 W/kg at 1.7 T and 60 Hz, is known as M103–27P.
- Domain-controlled Hi-B material with a thickness of 0.23 mm and a loss of 0.92 W/kg at 1.7 T and 50 Hz, or 1.2 W/kg at 1.7 T and 60 Hz, is known as 23ZDKH.

The Japanese-grade ZDKH core steel is subjected to laser irradiation to refine the magnetic domains near to the surface. This process considerably reduces the anomalous eddy-current loss, but the laminations must not be annealed after cutting. An alternative route to domain control of the steel is to use plasma irradiation, whereby the laminations can be annealed after cutting.

The decision on which grade to use to meet a particular design requirement depends on the characteristics required in respect of impedance and losses and, particularly, on the cash value that the

purchaser has assigned to core loss (the capitalized value of the iron loss). The higher labor cost involved in using the thinner materials is another factor to be considered.

No-load and load losses are often specified as target values by the user, or they may be evaluated by the "capitalization" of losses. A purchaser who receives tenders from prospective suppliers must evaluate the tenders to determine the "best" offer. The evaluation process is based on technical, strategic, and economic factors, but if losses are to be capitalized, the purchaser will always evaluate the "total cost of ownership," where:

$$\text{Cost of ownership} = \text{capital cost (or initial cost)} + \text{cost of losses}$$

$$\text{Cost of losses} = \text{cost of no-load loss} + \text{cost of load loss} + \text{cost of stray loss}$$

For loss-evaluation purposes, the load loss and stray loss are added together, as they are both current-dependent.

$$\text{Cost of no-load loss} = \text{no-load loss (kW)} \times \text{capitalization factor (\$/kW)}$$

$$\text{Cost of load loss} = \text{load loss (kW)} \times \text{capitalization factor (\$/kW)}$$

For generator transformers that are usually on continuous full load, the capitalization factors for no-load loss and load loss are usually equal. For transmission and distribution transformers, which normally operate at below their full-load rating, different capitalization factors are used depending on the planned load factor. Typical values for the capitalization rates used for transmission and distribution transformers are \$5000/kW for no-load loss and \$1200/kW for load loss. At these values, the total cost of ownership of the transformer, representing the capital cost plus the cost of power losses over 20 years, may be more than twice the capital cost. For this reason, modern designs of transformer are usually low-loss designs rather than low-cost designs.

Figure 1.4 shows the loss characteristics for a range of available electrical core-steel materials over a range of values of magnetic induction (core flux density).

The current that creates rated flux 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 Figure 1.5.

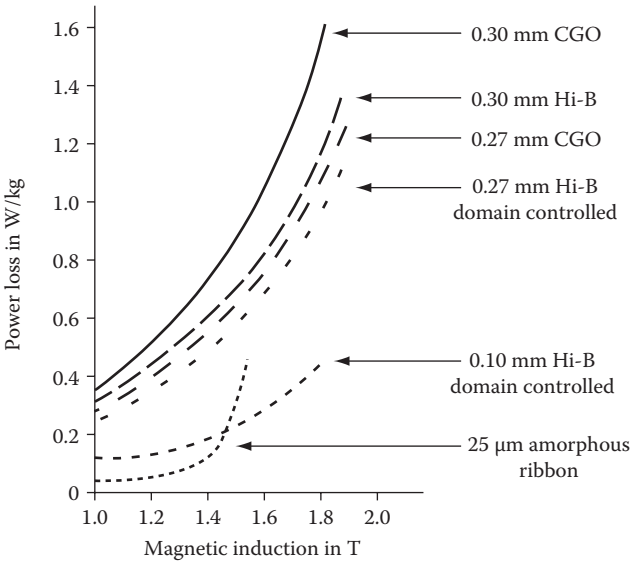

FIGURE 1.4 Loss characteristics for electrical core-steel materials over a range of magnetic induction (core flux density).

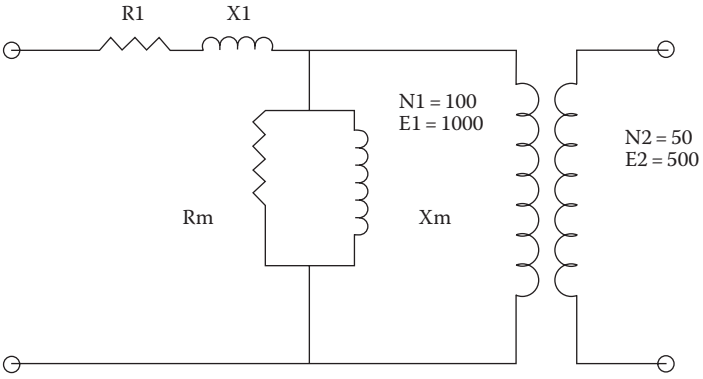

FIGURE 1.5 Equivalent circuit.

The core losses are represented by Rm 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 impedances as R1 and X1 in the equivalent circuit. However, these voltage 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, as seen in Figure 1.6. 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 across the primary winding of the equivalent circuit in Figure 1.5 can be considered to be the input voltage. The relationship E1/N1 = E2/N2 is important in transformer design and application. The term E/N is called "volts per turn."

A steel core has a nonlinear magnetizing characteristic, as shown in Figure 1.7. As shown, greater ampere-turns are required as the flux density B is increased from zero. Above the knee of the curve, as the flux approaches saturation, a small increase in the flux density requires a large increase in the

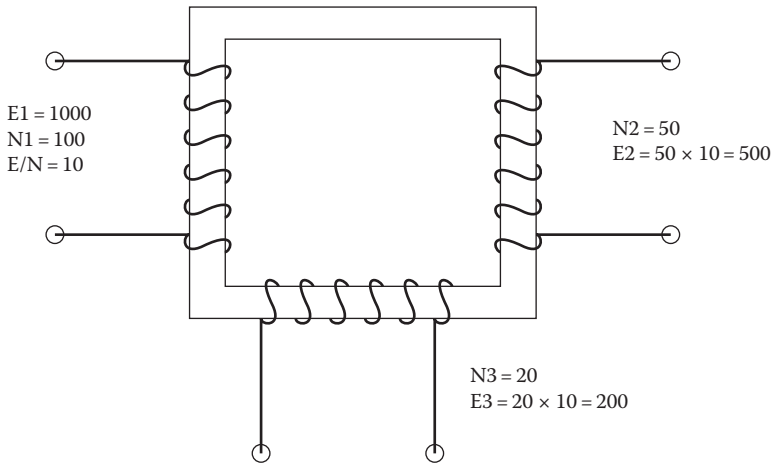

FIGURE 1.6 Steel core with windings.

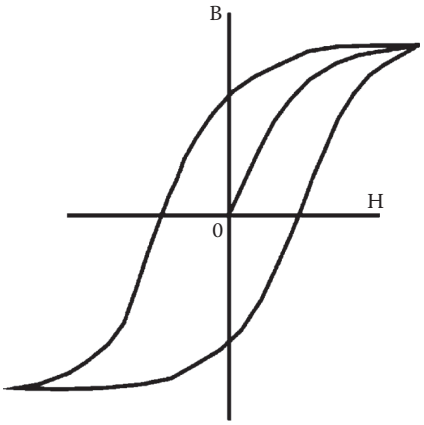

FIGURE 1.7 Hysteresis loop.

ampere-turns. When the core saturates, the circuit behaves much the same as an air core. As the flux density decreases to zero, becomes negative, and increases in a negative direction, the same phenomenon of saturation occurs. As the flux reduces to zero and increases in a positive direction, it describes a loop known as the "hysteresis loop." The area of this loop represents power loss due to the hysteresis effect in the steel. Improvements in the grade of steel result in a smaller area of the hysteresis loop and a sharper knee point where the B-H characteristic becomes nonlinear and approaches the saturated state.

1.4 The Practical Transformer

1.4.1 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 similar to Figure 1.4 for the different electrical steel grades as a function of induction. Similarly, curves have been made available for the exciting current as a function of induction.

A very important relationship is derived from Equation 1.11. It can be written in the following form:

$$B = \frac{0.225(E/N)}{(fA)} \tag{1.13}$$

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 is 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 per unit weight as a function of the material and the magnetic induction.

The induction must also be selected so that the core will be below saturation under specified overvoltage conditions. Magnetic saturation occurs at about 2.0 T in magnetic steels but at about 1.4 T in amorphous ribbon.

1.4.2 Leakage Reactance

Additional concepts must be introduced when the practical transformer is considered. 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, as seen in Figure 1.8. 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%–20% 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," i.e., the ratio of the reactance voltage drop to the winding voltage × 100. It is calculated by designers using the number of turns, the magnitudes 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 × 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," which is a function of the power factor of the load. The percent regulation can be determined using the following equation for inductive loads.

$$\%\text{Reg} = \%\text{R}(\cos\phi) + \%\text{X}(\sin\phi) + \left\{\frac{[\%\text{X}(\cos\phi) - \%\text{R}(\sin\phi)]^2}{200}\right\} \tag{1.14}$$

where

%Reg is the percentage voltage drop across the resistance and the leakage reactance
%R is the percentage resistance = (kW of load loss/kVA of transformer) × 100
%X is the percentage leakage reactance
ϕ is the angle corresponding to the power factor of the load = $\cos^{-1}$ pf

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

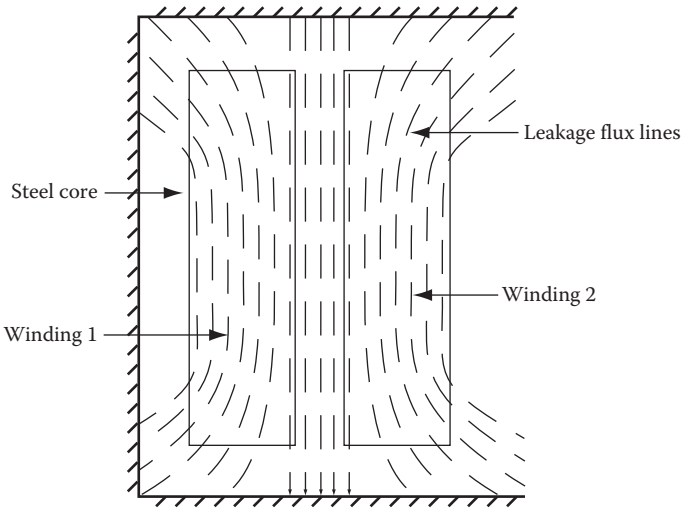

FIGURE 1.8 Leakage flux fields.

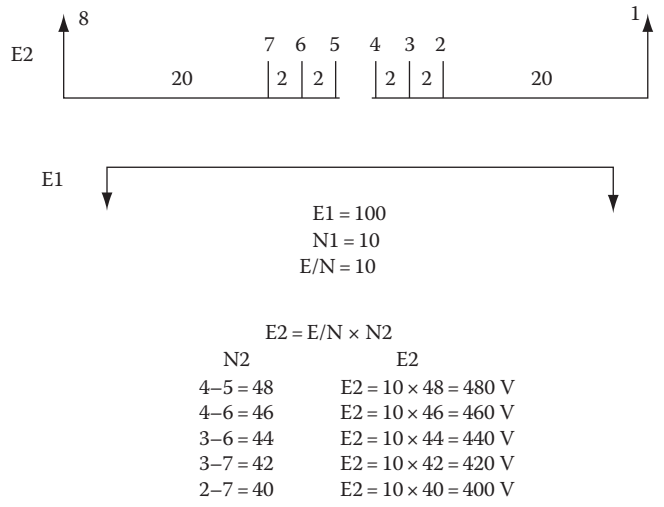

FIGURE 1.9 Illustration of how taps added in the windings can compensate for voltage drops.

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 of this concept is shown in Figure 1.9. The table in the figure shows that when tap 4 is connected to tap 5, there are 48 turns in the winding (maximum tap) and, at 10 V/turn, the voltage E2 is 480 V. When tap 2 is connected to tap 7, there are 40 turns in the winding (minimum tap), and the voltage E2 is 400 V.

1.4.3 Load Losses

The term *load losses* 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 caused by the leakage field. These 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 and heating result in these steel parts.

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. In order to reduce load loss, it is not sufficient to reduce the winding resistance by increasing the cross-section of the conductor, as eddy losses in the conductor will increase faster than joule heating losses decrease. When the current is too great for a single conductor to be used for the winding without excessive eddy loss, a number of strands must be used in parallel. Because the parallel components are joined at the ends of the coil, steps must be taken to circumvent the induction of different electromotive force (EMFs) in the strands due to different loops of strands linking with the leakage flux, which would involve circulating currents and further loss. Different forms of conductor transposition have been devised for this purpose.

Ideally, each conductor element should occupy every possible position in the array of strands such that all elements have the same resistance and the same induced EMF. Conductor transposition, however, involves some sacrifice of winding space. If the winding depth is small, one transposition halfway

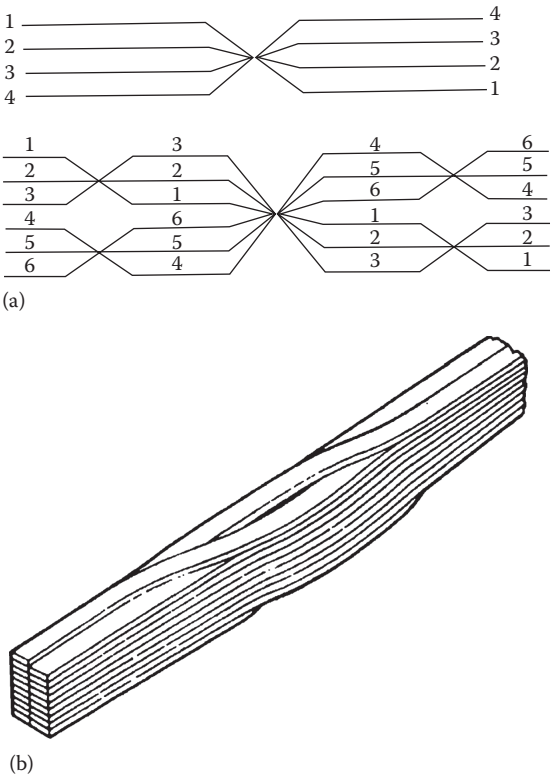

FIGURE 1.10 CTC cable. (a) Forms of transposition. (b) Continuously transposed conductor.

through the winding is sufficient; or in the case of a two-layer winding, the transposition can be located at the junction of the layers. Windings of greater depth need three or more transpositions. An example of a continuously transposed conductor (CTC) cable, shown in Figure 1.10, is widely used in the industry. CTC cables are manufactured using transposing machines and are usually paper-insulated as part of the transposing operation.

Stray losses can be a constraint on high-reactance designs. Losses can be controlled by using a combination of magnetic shunts and/or conducting shields to channel the flow of leakage flux external to the windings into low-loss paths.

1.4.4 Short-Circuit Forces

Forces exist between current-carrying conductors when they are in an alternating-current field. These forces are determined using Equation 1.15:

$$F = BI\sin\theta \tag{1.15}$$

where

F is the force on conductor

B is the local leakage flux density

θ is the angle between the leakage flux and the load current. In transformers, sin θ is almost always equal to 1

Thus

$$B = \mu I \tag{1.16}$$

and therefore

$$F \propto I^2 \tag{1.17}$$

Since the leakage flux field is between windings and has a rather high density, the forces under short-circuit conditions can be quite high. This is a special area of transformer design. Complex computer programs are needed to obtain a reasonable representation of the field in different parts of the windings. Considerable research activity has been directed toward the study of mechanical stresses in the windings and the withstand criteria for different types of conductors and support systems.

Between any two windings in a transformer, there are three possible sets of forces:

1. Radial repulsion forces due to currents flowing in opposition in the two windings
2. Axial repulsion forces due to currents in opposition when the electromagnetic centers of the two windings are not aligned
3. Axial compression forces in each winding due to currents flowing in the same direction in adjacent conductors

The most onerous forces are usually radial between windings. Outer windings rarely fail from hoop stress, but inner windings can suffer from one or the other of two failure modes:

1. Forced buckling, where the conductor between support sticks collapses due to inward bending into the oil-duct space
2. Free buckling, where the conductors bulge outwards as well as inwards at a few specific points on the circumference of the winding

Forced buckling can be prevented by ensuring that the winding is tightly wound and is adequately supported by packing it back to the core. Free buckling can be prevented by ensuring that the winding is of sufficient mechanical strength to be self-supporting, without relying on packing back to the core.

1.4.5 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 accurate specification of the heat-exchanger equipment.

1.4.6 Voltage Considerations

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

- Operating voltages at the rated frequency
- Rated-frequency overvoltages
- Natural lightning impulses that strike the transformer or transmission lines

- Switching surges that result from opening and closing of breakers and switches
- Combinations of the above voltages
- Transient voltages generated due to resonance between the transformer and the network
- Fast transient voltages generated by vacuum-switch operations or by the operation of disconnect switches in a gas-insulated bus-bar system

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 to withstand all of these stresses.

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2

Power Transformers

H. Jin Sim
Waukesha Electric Systems

Scott H. Digby
Progress Energy

2.1 Introduction

ANSI/IEEE defines a transformer 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 these 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 toward 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 single-phase or three-phase apparatus.

The construction of a transformer depends upon the application. Transformers intended for indoor use are primarily of the dry type but can also be liquid immersed. For outdoor use, transformers are usually liquid immersed. This section focuses on the outdoor, liquid-immersed transformers, such as those shown in Figure 2.1.

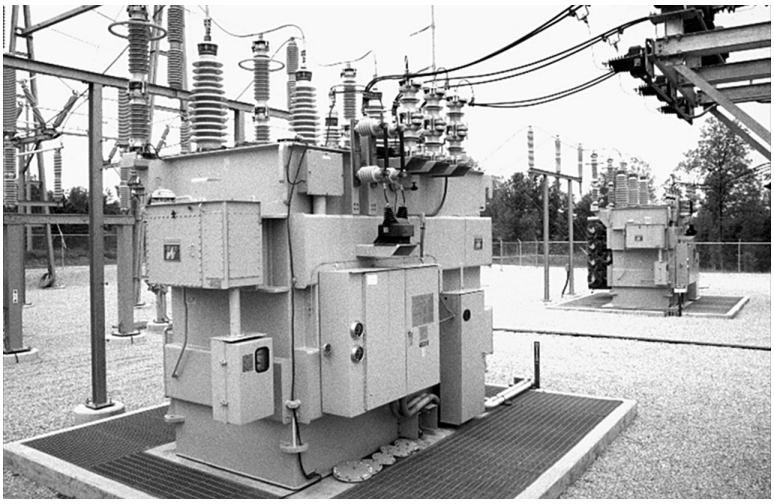


FIGURE 2.1 20 MVA, 161:26.4 × 13.2 kV with LTC, three-phase transformers.

2.2 Rating and Classifications

2.2.1 Rating

In the United States, 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 with increases in temperature, so the insulation chosen for use in transformers is based on how long it can be expected to last by limiting the operating temperature. The temperature that insulation is allowed to reach under operating conditions essentially determines the output rating of the transformer, called the kilovolt-ampere 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 2.1.

The normal life expectancy of a power transformer is generally assumed to be about 30 years of service when operated within its rating. However, under certain conditions, it may be overloaded and operated beyond its rating, with moderately predictable "loss of life." Situations that might involve operation beyond rating include emergency rerouting of load or through-faults prior to clearing of the fault condition.

Outside the United States, the transformer rating may have a slightly different meaning. Based on some standards, the kilovolt-ampere 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.

TABLE 2.1 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.

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

1. Small power transformers: 500–7500 kVA
2. Medium power transformers: 7500 kVA–100 MVA
3. Large power transformers: 100 MVA and above

Note that the upper range of small power and the lower range of medium power can vary between 2,500 and 10,000 kVA throughout the industry.

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 1000 m above sea level, seismic conditions, and loads with total harmonic distortion above 0.05 per unit.

2.2.2 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 impulse insulation level, in conjunction with the voltage rating. Internally, a transformer is considered to be a non-self-restoring insulation system, mostly consisting 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 windings in a three-phase power transformer will typically have the common point brought out of the tank through a neutral bushing. (See Chapter 3 for a discussion of wye connections.) Depending on the application—for example, in the case of a solidly grounded neutral versus 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-voltage or "hi-pot" test, where the entire circuit is brought up to the same voltage level. A reduced voltage rating for the neutral can significantly reduce the cost of larger units and autotransformers compared with a fully rated neutral.

2.2.3 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 the heat.

The windings and core are the primary sources of heat, although internal metallic structures can act as a heat source as well. It is imperative to have proper cooling ducts and passages in the proximity of the heat sources through which the cooling medium can flow so 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 surface area available for heat transfer by convection without increasing the size of the tank. In smaller transformers, integral tubular sides or fins are used to provide this increase

TABLE 2.2 Cooling Class Letter Description

		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

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 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 nondirected flow through the winding in regard to winding arrangement will be further discussed with the description of winding types (see Section 2.5.2).

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 the supplemental cooling 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 2.2 lists the code letters that are used to make up the four-letter designation.

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 United States. Where OA classified a transformer as liquid-immersed self-cooled in the past, it is now designated by the new system as ONAN. Similarly, the previous FA classification is now 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 that the transformer will be capable of supplying additional kilovolt-amperes. This rating would have been designated OA/FA/FA per past standards.

2.3 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 asymmetrical sinusoidal waveshape decaying with time based on the time constant of the equivalent circuit that is characteristic of switching events. The amplitude of the symmetrical component of the sine wave is determined from the formula

$$I_{sc} = \frac{I_{rated}}{(Z_{xfmr} + Z_{sys})} \tag{2.1}$$

where

Z_{xfmr} and Z_{sys} are the transformer and system impedances, respectively, expressed in terms of per unit on the transformer base

I_{sc} and I_{rated} are the resulting short-circuit (through-fault) current and the transformer rated current, respectively

An offset factor, K, multiplied by I_{sc} determines the magnitude of the first peak of the transient asymmetrical current. This offset factor is derived from the equivalent transient circuit. However, standards give values that must be used based on the ratio of the effective ac (alternating current) reactance (x) and resistance (r), x/r. K typically varies in the range of 1.5–2.8.

As indicated by Equation 2.1, the short-circuit current is primarily limited by the internal impedance of the transformer, but it may be further reduced by impedances of adjacent equipment, such as current-limiting reactors or by system power-delivery limitations. Existing standards define the maximum 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 hundred kilograms to hundreds of thousands of kilograms 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 2.2 illustrates the difference between radial and axial forces in a pair of circular windings. Mismatches of ampere-turns between windings are unavoidable—caused by such occurrences as ampere-turn voids created by sections of a winding being tapped out, slight mismatches in the lengths of respective windings, or misalignment of the magnetic centers of the respective windings—and result in a net axial force. This net axial force will have the effect of trying to force one winding in the upward direction and the other in the downward direction, which must be resisted by the internal mechanical structures.

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 increase in its "loss of life." This additional "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 the annealing that can occur at high temperatures. The temperature at which this can occur depends on the properties and composition of the conductor material, such as the hardness, which is sometimes increased through cold-working processes and the annealing retarded by the presence of silver in certain alloys.

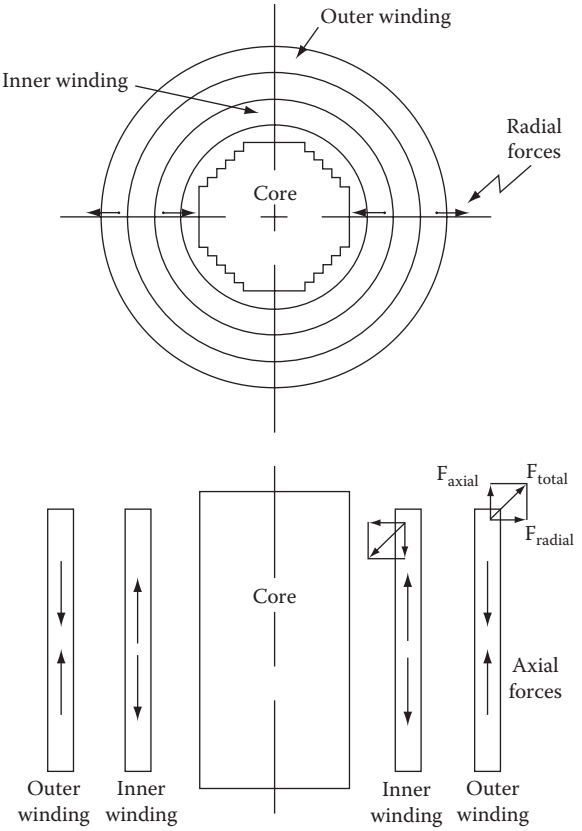


FIGURE 2.2 Radial and axial forces in a transformer winding.

2.4 Efficiency, Losses, and Regulation

2.4.1 Efficiency

Power transformers are very efficient, typically 99.5% or greater, i.e., real power losses are usually less than 0.5% of the kilovolt-ampere rating at full load. 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

$$\text{Efficiency} = \left[\frac{\text{kVA rating}}{(\text{kVA rating} + \text{total losses})}\right] \times 100\% \tag{2.2}$$

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

2.4.2 Losses

The no-load losses are essentially the power required to keep the core energized. These are commonly referred to as "core losses," and they exist whenever the unit is energized. No-load losses depend primarily upon the voltage and frequency, so under operational conditions they vary only 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 (direct current) 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 earlier.

2.4.3 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 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 purchase price and the losses. Typically, each of the transformer's individual loss parameters—no-load losses, load losses, and auxiliary losses—is 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 estimating the cost associated with transformers losses. Loss-evaluation values can range from about $500/kW to upwards of $12,000/kW for the no-load losses and from a few hundred dollars per kilowatt to about $6,000 to $8,000/kW for load losses and auxiliary losses. Specific values depend upon the application.

2.4.4 Regulation

Regulation is defined as the change (increase) in the output voltage that occurs when the load on the transformer is reduced from rated load to no load while the input voltage is held constant. It is typically expressed as a percentage, or per unit, of the rated output voltage at rated load. A general expression for the regulation can be written as follows:

$$\%\,\text{regulation} = \left[\frac{(V_{NL} - V_{FL})}{V_{FL}}\right] \times 100 \tag{2.3}$$

where

V_{NL} is the voltage at no load
V_{FL} is the voltage at full load

The regulation is dependent upon the impedance characteristics of the transformer, the resistance (r), and more significantly the ac reactance (x), as well as the power factor of the load. The regulation can be calculated based on the transformer impedance characteristics and the load power factor using the following formulas:

$$\%\,\text{regulation} = pr + qx + \left[\frac{(px - qr)^2}{200}\right] \tag{2.4}$$

$$q = \text{SQRT}(1 - p^2) \tag{2.5}$$

where

p is the power factor of the load
r and x are expressed in terms of per unit on the transformer base

The value of q is taken to be positive for a lagging (inductive) power factor and negative for a leading (capacitive) power factor.

It should be noted that lower impedance values, specifically ac reactance, result in lower regulation, which is generally desirable. However, this is at the expense of the fault current, which would in turn increase with a reduction in impedance, since it is primarily limited by the transformer impedance. Additionally, the regulation increases as the power factor of the load becomes more lagging (inductive).

2.5 Construction

The construction of a power transformer varies throughout the industry. The basic arrangement is essentially the same and has seen little significant change in recent years, so some of the variations can be discussed here.

2.5.1 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 can be hot- or cold- rolled, grain-oriented or non-grain-oriented, and even laser-scribed for improved performance. Thickness ranges from 0.23 mm to upwards of 0.36 mm. The core cross section can 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 use a single width of strip steel, while circular cores use a combination of different strip widths to approximate a circular cross section, such as in Figure 2.2. The type of steel and arrangement depends 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 is held together by, but insulated from, mechanical structures and is grounded to a single point in order to dissipate electrostatic buildup. The core ground location is usually some readily accessible point inside the tank, but it can 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. Multiple core grounds, such as a case whereby the core is inadvertently making contact with otherwise grounded internal metallic mechanical structures, can provide a path for circulating currents induced by the main flux as well as a leakage flux, thus creating concentrations of losses that can result in localized heating.

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 overexcitations and tolerances that exist due to materials and manufacturing processes. (See Chapter 7 for a discussion of saturation curves.) For power transformers, the flux density is typically between 1.3 and 1.8 T, with the saturation point for magnetic steel being around 2.03–2.05 T.

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

In core-form construction, there is a single path for the magnetic circuit. Figure 2.3 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. In three-phase applications, the windings of a particular phase are typically on the same core leg, as illustrated in Figure 2.4. Windings are

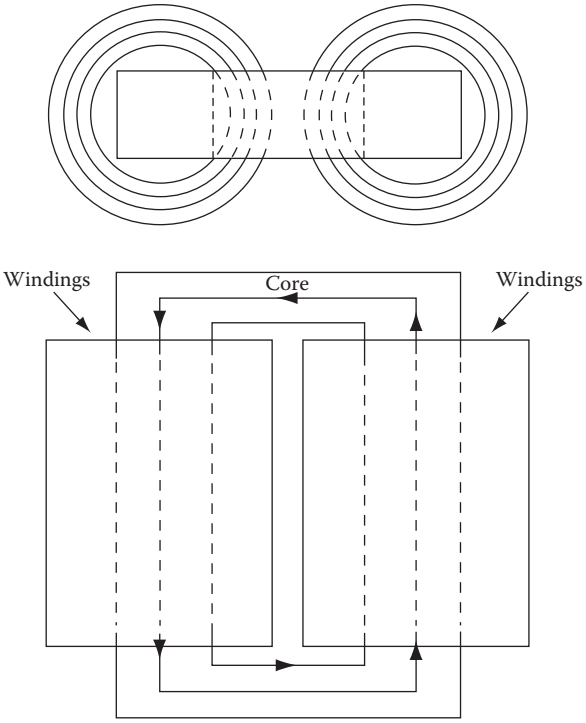


FIGURE 2.3 Schematic of single-phase core-form construction.

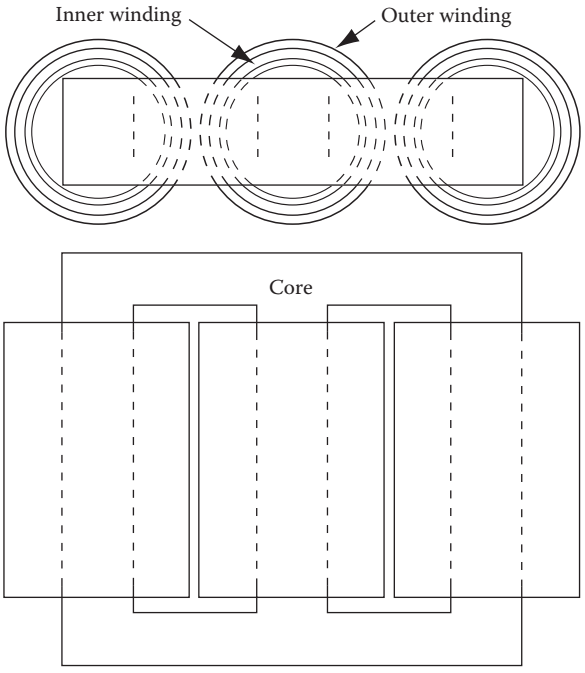


FIGURE 2.4 Schematic of three-phase core-form construction.

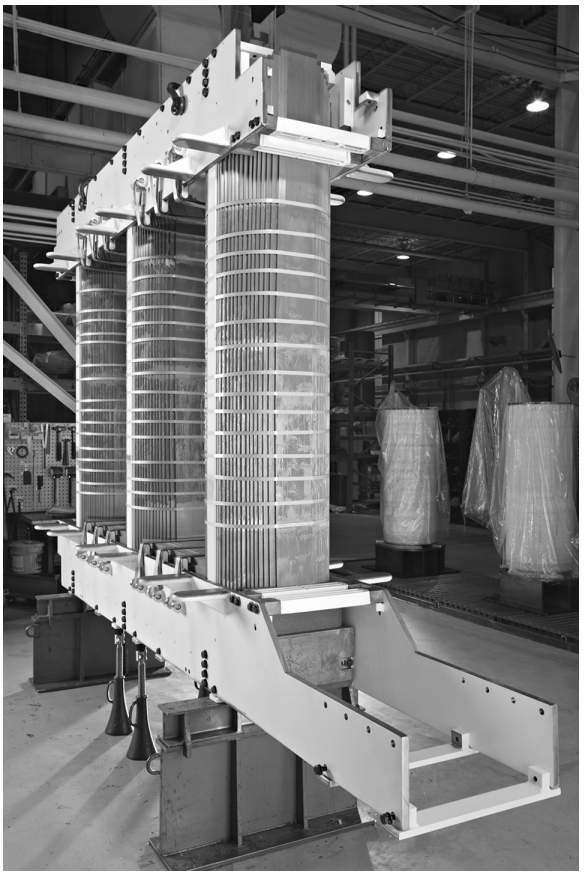


FIGURE 2.5 "E" assembly prior to addition of coils and insertion of top yoke.

constructed separate of the core and placed on their respective core legs during core assembly. Figure 2.5 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. Figure 2.6 is a schematic of a single-phase shell-form core, 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 associated with not having to bring leads out through other windings, i.e., not concentrically arranged windings as in the core form transformers, shell forms tend to be used more frequently for high-current applications and for certain reconnectable winding applications (for cases requiring accommodations to make certain ratio adjustments). Variations of three-phase shell-form construction include five- and seven-legged cores, depending on size and application.

2.5.2 Windings

The windings consist of the current-carrying conductors wound around the sections of the core, and these 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

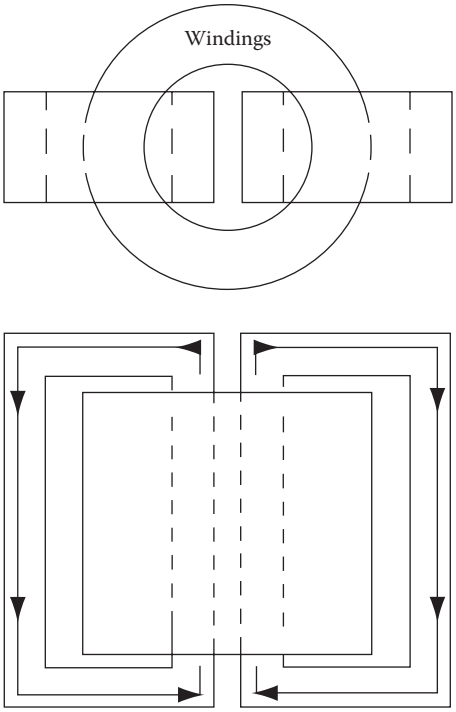


FIGURE 2.6 Schematic of single-phase shell-form construction.

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, copper can be cold worked for even greater strength often with a small amount of silver added to retard the annealing so that this strength is maintained throughout the service life of the transformer. The conductors used in power transformers are typically stranded with a rectangular cross section, although some transformers at the lowest ratings may use sheet or foil conductors. Multiple strands can be wound in parallel and joined together at the ends of the winding, in which case it is necessary to transpose the strands at various points throughout the winding to prevent circulating currents around the loop(s) created by joining the strands at the ends. Individual strands may be subjected to differences in the flux field due to their respective positions within the winding, which create differences in voltages between the strands and drive circulating currents through the conductor loops. Proper transposition of the strands cancels out these voltage differences and eliminates or greatly reduces the circulating currents. A variation of this technique, involving many rectangular conductor strands combined into a cable, is called continuously transposed cable (CTC), as shown in Figure 2.7.

In core-form transformers, the windings are usually arranged concentrically around the core leg, as illustrated in Figure 2.8, which shows 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 Figure 2.4. Shell-form transformers use an interleaved arrangement, as illustrated in the schematic Figure 2.9 and the photograph in Figure 2.13. With an interleaved arrangement, individual coils are stacked, separated by insulating barriers and cooling ducts. The coils are typically connected with the inside of one coil connected to the inside of an adjacent coil and, similarly, the outside of one coil connected to the outside of an adjacent coil. Sets of coils are assembled into groups, which then form the primary or secondary winding.

FIGURE 2.7 Continuously transposed cable.

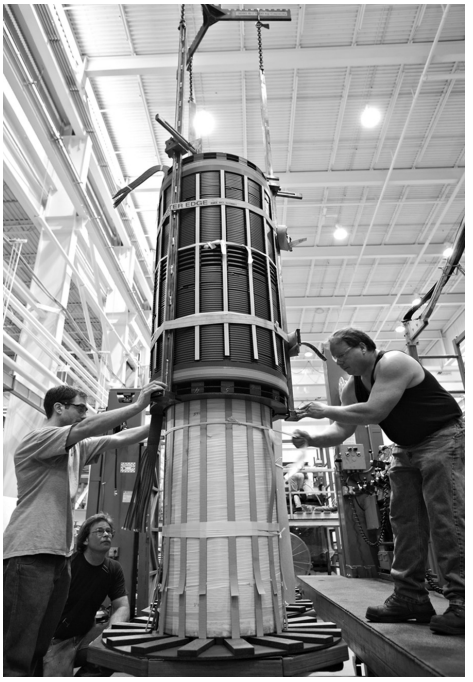


FIGURE 2.8 Concentric arrangement, outer coil being lowered onto core leg over top of inner coil.

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 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, elliptically shaped windings are used.

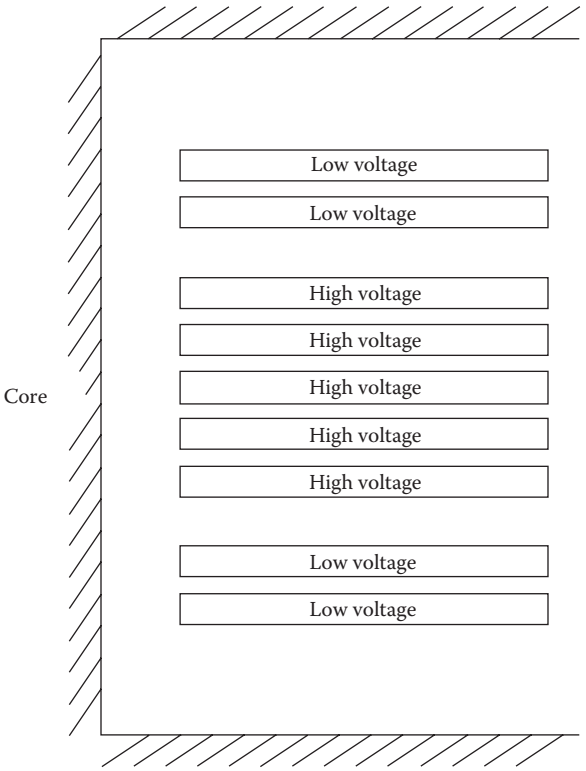


FIGURE 2.9 Example of stacking (interleaved) arrangement of windings in shell-form construction.

Concentric coils are typically 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 2.10 and 2.11 show winding arrangements comparing nondirected and directed flow. This concept is sometimes referred to as guided liquid flow.

A variety of different types of windings 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 they can be wound horizontally and placed upright upon completion. As mentioned previously, the type of winding depends on the transformer rating as well as the core construction. Several of the more common winding types are discussed here.

2.5.2.1 Pancake Windings

Several types of windings are commonly referred to as "pancake" windings due to the arrangement of conductors into discs. However, the term most often refers to a coil type that is used almost exclusively in shell-form transformers. The conductors are wound around a rectangular form, with the widest face of the conductor oriented either horizontally or vertically. Figure 2.12 illustrates how these coils are typically wound. This type of winding lends itself to the interleaved arrangement previously discussed (Figure 2.13).

2.5.2.2 Layer (Barrel) Windings

Layer (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 can be wound on top of one another, with the layers separated by solid insulation, ducts, or a combination. Several strands can be wound in parallel if the current magnitude so dictates. Variations of this winding are often used for

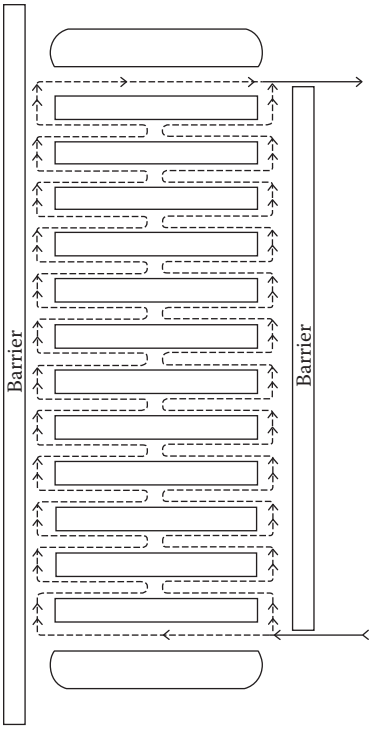


FIGURE 2.10 Nondirected flow.

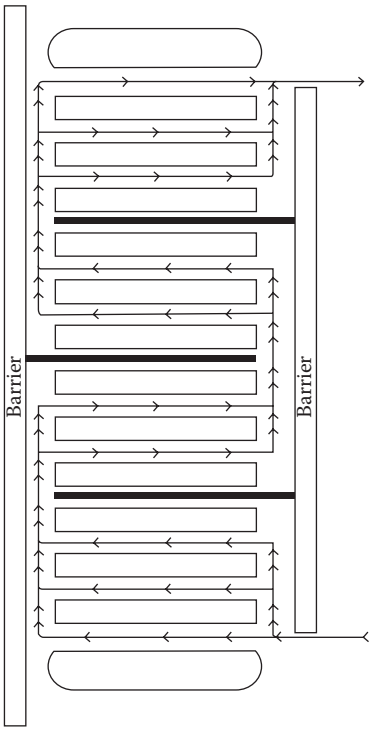


FIGURE 2.11 Directed flow.

FIGURE 2.12 Pancake winding during winding process.

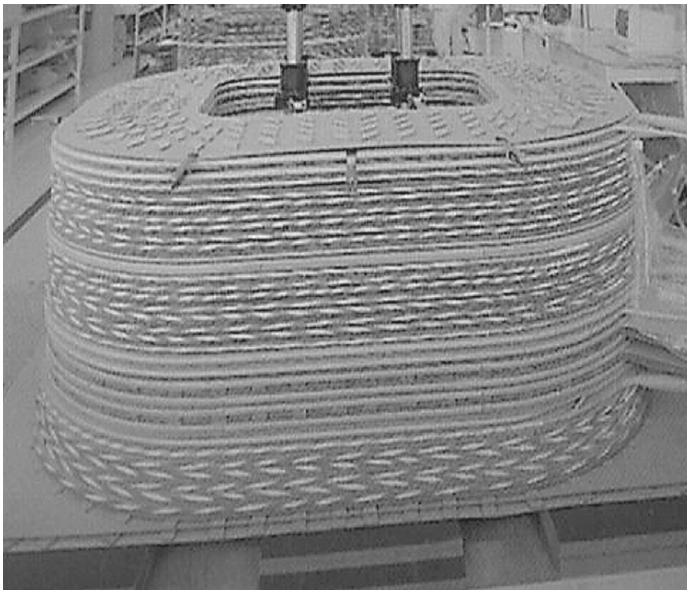


FIGURE 2.13 Stacked pancake windings.

applications such as tap windings used in load-tap-changing (LTC) transformers and for tertiary windings used for, among other things, third-harmonic suppression. Figure 2.14 shows a layer winding during assembly that will be used as a regulating winding in an LTC transformer.

2.5.2.3 Helical Windings

Helical windings are also referred to as screw or spiral windings, with each term accurately characterizing the coil's construction. A helical winding consists of 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 included to minimize circulating currents between parallel strands. The manner of construction is such that the coil resembles a corkscrew. Figure 2.15 shows a helical winding during the winding process. Helical windings are used for the higher-current applications frequently encountered in the lower-voltage classes.

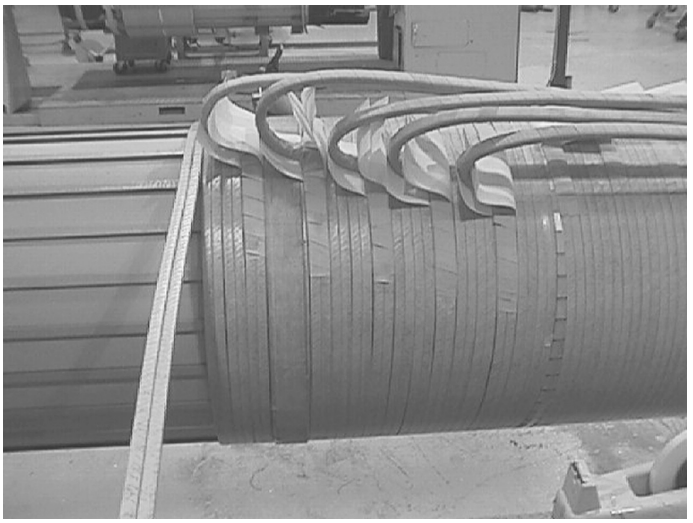


FIGURE 2.14 Layer windings (single layer with two strands wound in parallel).

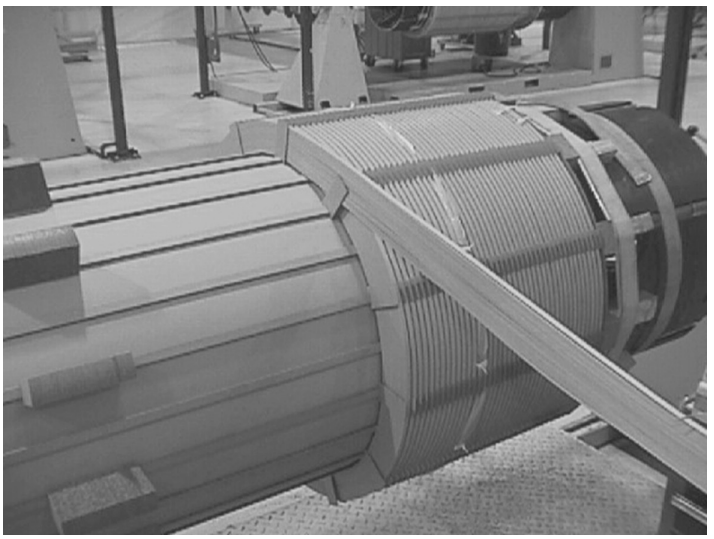


FIGURE 2.15 Helical winding during assembly.

2.5.2.4 Disc Windings

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 crossover point. Each disc comprises multiple turns wound over other turns, with the crossovers alternating between inside and outside. Figure 2.16 outlines the basic concept, and Figure 2.17 shows typical crossovers during the winding process. Most windings of 25 kV class and above used in core-form transformers are disc type. Given the high voltages involved in test and operation, particular attention is required 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.

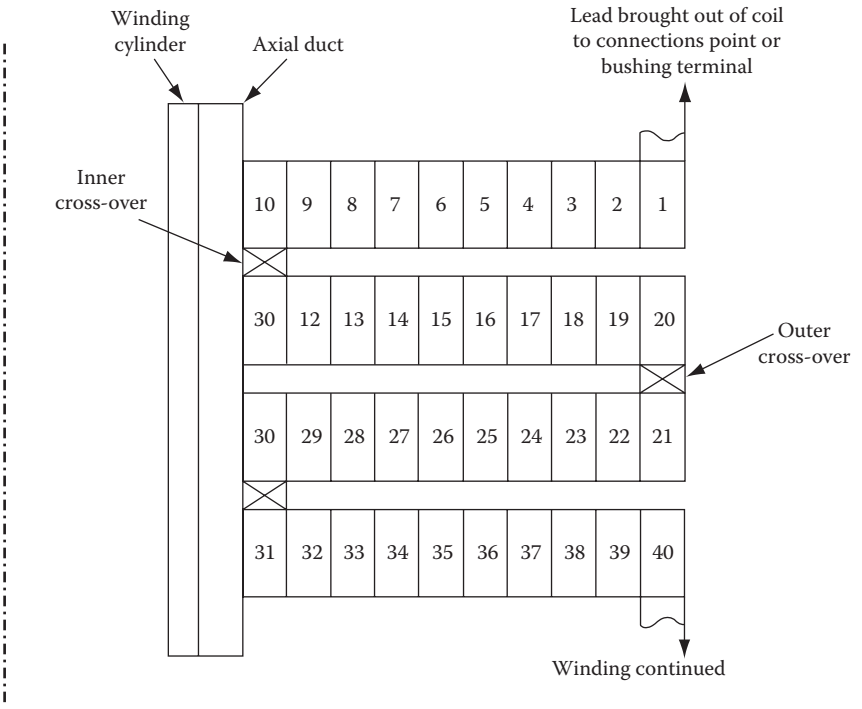


FIGURE 2.16 Basic disc winding layout.

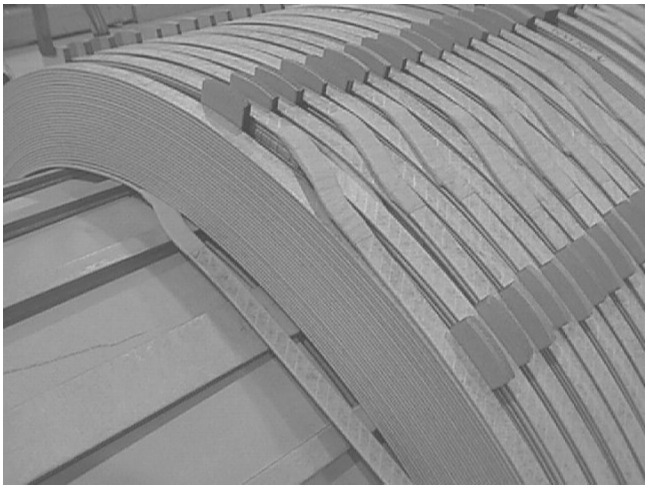
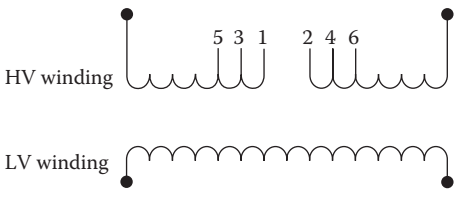


FIGURE 2.17 Disc winding inner and outer crossovers.

2.5.3 Taps-Turns Ratio Adjustment

The ability to adjust the turns ratio of a transformer is often desirable to compensate for variations in voltage that occur due to the regulation of the transformer and loading cycles. This task can be accomplished by several means. There is a significant difference between a transformer that is capable of changing the ratio while the unit is on-line (an LTC transformer) and one that must be taken off-line, or de-energized, to perform a tap change.

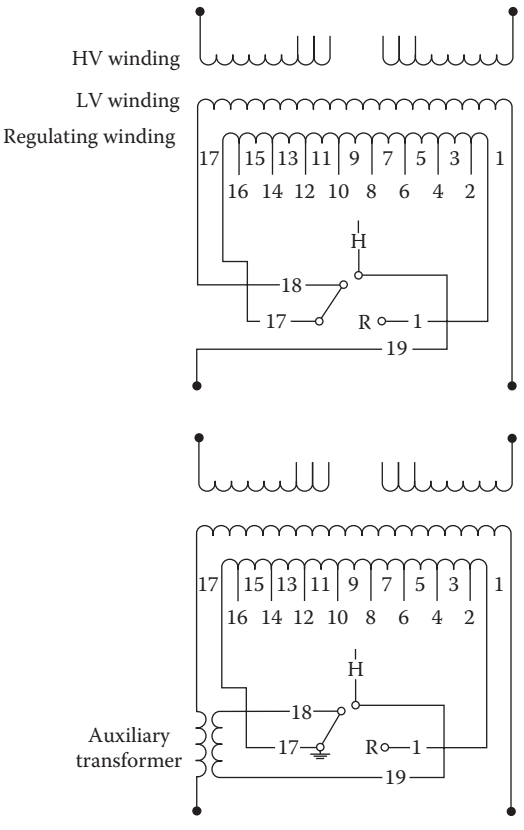


Volts L–L	DETC Positions	Leads Connected
144900	A	1–2
141450	B	2–3
138000	C	3–4
134550	D	4–5
131100	E	5–6

FIGURE 2.18 High-voltage winding schematic and connection diagram for 138 kV example.

Most transformers are provided with a means of changing the number of turns in the high-voltage circuit, whereby a part of the winding is tapped out of the circuit. In many transformers, this is done using one of the main windings and tapping out a section or sections, as illustrated by the schematic in Figure 2.18.

With larger units, a dedicated tap winding may be necessary to avoid the ampere-turn voids that occur along the length of the winding. 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 for convenient access external to the transformer to change the tap position. When LTC capabilities are desired, additional windings and equipment are required, which significantly increase the size and cost of the transformer. This option is specified on about 60% of new medium and large power transformers. Figure 2.19 illustrates the basic operation by providing



Volts L–L	LTC Positions	R Connects at Direction		H Connects
		Raise	Lower	
14520	16R	18–1	18–1	17–19
14438	15R	18–1	18–1	16–19
14355	14R	18–1	18–1	15–19
14272	13R	18–1	18–1	14–19
14190	12R	18–1	18–1	13–19
14108	11R	18–1	18–1	12–19
14025	10R	18–1	18–1	11–19
13943	9R	18–1	18–1	10–19
13860	8R	18–1	18–1	9–19
13778	7R	18–1	18–1	8–19
13695	6R	18–1	18–1	7–19
13613	5R	18–1	18–1	6–19
13530	4R	18–1	18–1	5–19
13447	3R	18–1	18–1	4–19
13365	2R	18–1	18–1	3–19
13283	1R	18–1	18–1	2–19
13200	RN	18–1	18–1	1–19
13200	N	18–17	18–17	18–19
13200	LN	18–17	18–17	17–19
13118	1L	18–17	18–17	16–19
13035	2L	18–17	18–17	15–19
12953	3L	18–17	18–17	14–19
12870	4L	18–17	18–17	13–19
12788	5L	18–17	18–17	12–19
12705	6L	18–17	18–17	11–19
12623	7L	18–17	18–17	10–19
12540	8L	18–17	18–17	9–19
12458	9L	18–17	18–17	8–19
12375	10L	18–17	18–17	7–19
12293	11L	18–17	18–17	6–19
12210	12L	18–17	18–17	5–19
12128	13L	18–17	18–17	4–19
12045	14L	18–17	18–17	3–19
11963	15L	18–17	18–17	2–19
11880	16L	18–17	18–17	1–19

FIGURE 2.19 Schematic and connection chart for transformer with an LTC supplied on a 13.2 kV low voltage.

a sample schematic and connection chart for a transformer supplied with an LTC on the low-voltage (secondary) side. It should be recognized that there would be slight differences in this schematic based on the specific LTC being used. Figure 2.19 also shows a sample schematic where an auxiliary transformer is used between the main windings and the LTC to limit the current through the LTC mechanism.

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 (e.g., 24.94 × 12.47 kV or 138 × 69 kV) are easier for manufacturers to accommodate.

2.6 Accessory Equipment

2.6.1 Accessories

There are many different accessories used to monitor and protect power transformers, some of which are considered standard features and others of which are used based on miscellaneous requirements. A few of the basic accessories are briefly discussed here.

2.6.1.1 Liquid-Level Indicator

A liquid-level indicator is a standard feature on liquid-filled transformer tanks since 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.

2.6.1.2 Pressure-Relief Devices

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

2.6.1.3 Liquid-Temperature Indicator

Liquid-temperature indicators measure the temperature of the internal liquid at a point near the top of the liquid using a probe inserted in a well and mounted through the side of the transformer tank.

2.6.1.4 Winding-Temperature Indicator

A winding-temperature simulation method is used to approximate the hottest spot in the winding. An approximation is needed because of the difficulties involved in directly measuring winding temperature. The method applied to power transformers involves a current transformer, which is 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, which approximates a reading that models 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.

2.6.1.5 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. These relays can be mounted on the top or side of the transformer, or they can operate in liquid or gas space.

2.6.1.6 Desiccant (Dehydrating) Breathers

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

2.6.2 Liquid-Preservation Systems

There are several methods 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 interaction, or "breathing," is required to accommodate variations in pressure that occur under operational conditions, such as expansion and contraction of liquid with temperature. Free-breathing systems, where the liquid is exposed to the atmosphere, are no longer used. The most commonly used methods are outlined as follows and illustrated in Figure 2.20:

- Sealed-tank systems have the tank interior sealed from the atmosphere and maintain a layer of gas—a gas space or cushion—that sits above the liquid. The gas-plus-liquid volume remains constant. Negative internal pressures can exist in sealed-tank systems at lower loads or temperatures with positive pressures as load and temperatures increase.
- Positive-pressure systems involve the use of inert gases to maintain a positive pressure in the gas space. An inert gas, typically from a bottle of compressed nitrogen, is incrementally injected into the gas space when the internal pressure falls out of range.
- Conservator (expansion tank) systems are used both with and without air bags, also called bladders or diaphragms, and involve the use of a separate auxiliary tank. The main transformer tank is completely filled with liquid, the auxiliary tank is partially filled, and the liquid expands and contracts within the auxiliary tank. The auxiliary tank is allowed to "breathe," usually through a dehydrating breather. The use of an air bag in the auxiliary tank can provide further separation from the atmosphere.

2.6.2.1 "Buchholz" Relay

On power transformers using a conservator liquid-preservation system, a "Buchholz" relay can be installed in the piping between the main transformer tank and the conservator. The purpose of the Buchholz relay is to detect faults that may occur in the transformer. One mode of operation is based on the generation of gases in the transformer during certain minor internal faults. Gases accumulate in the relay, displacing the liquid in the relay, until a specified volume is collected, at which time a float actuates a contact or switch. Another mode of operation involves sudden increases in pressure in the main transformer tank, a sign of a major fault in the transformer. Such an increase in pressure forces the

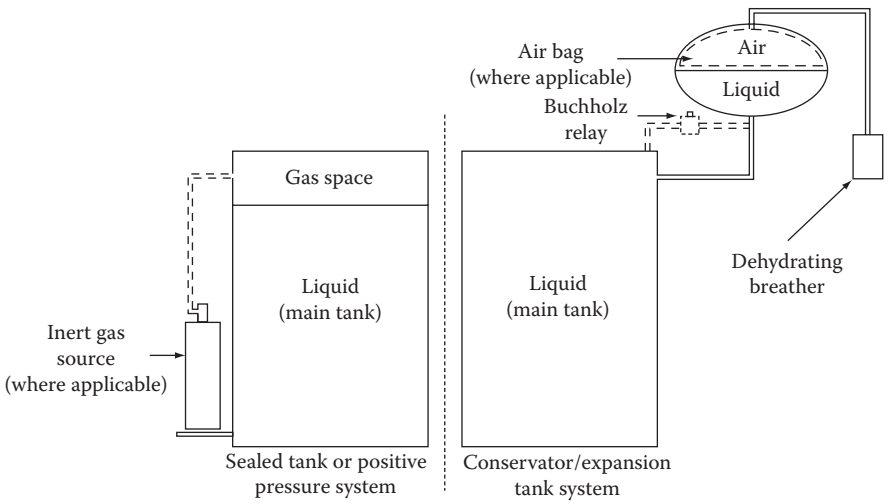


FIGURE 2.20 General arrangements of liquid preservation systems.

liquid to surge through the piping between the main tank and the conservator, through the "Buchholz" relay, which actuates another contact or switch.

2.6.2.2 Gas-Accumulator Relay

Another gas-detection device uses a system of piping from the top of the transformer to a gas-accumulator relay. Gases generated in the transformer are routed to the gas-accumulator relay, where they accumulate until a specified volume is collected, actuating a contact or switch.

2.7 Inrush Current

When a transformer is taken off-line, a certain amount of residual flux remains in the core due to the properties of the magnetic core material. The residual flux can be as much as 50%–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 builds upon that already existing 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 is similar to a sine wave, but largely skewed to the positive or negative direction. This inrush current experiences a decay, partially due to losses that 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 application engineer. Actual values for inrush current depend on where in the source-voltage wave the switching operations occur, the moment of opening affecting the residual flux magnitude, and the moment of closing affecting the new flux.

2.8 Transformers Connected Directly to Generators

Power transformers connected directly to generators can experience excitation and short-circuit conditions beyond the requirements defined by ANSI/IEEE standards. Special design considerations may be necessary to ensure that a power transformer is capable of withstanding the abnormal thermal and mechanical aspects that such conditions can create.

Typical generating plants are normally designed such that two independent sources are required to supply the auxiliary load of each generator. Figure 2.21 shows a typical one-line diagram of a generating station. The power transformers involved can be divided into three basic subgroups based on their specific application:

1. Unit transformers (UT) that are connected directly to the system
2. Station service transformers (SST) that connect the system directly to the generator auxiliary load
3. Unit auxiliary transformers (UAT) that connect the generator directly to the generator auxiliary load

In such a station, the UAT will typically be subjected to the most severe operational stresses. Abnormal conditions have been found to result from several occurrences in the operation of the station. Instances of faults occurring at point F in Figure 2.21—between the UAT and the breaker connecting it to the auxiliary load—are fed by two sources, both through the UT from the system and from the generator itself. Once the fault is detected, it initiates a trip to disconnect the UT from the system and to remove the generator excitation. This loss of load on the generator can result in a higher voltage on the generator, resulting in an increased current contribution to the fault from the generator. This will continue to feed the fault for a time period dependent upon the generator's fault-current decrement characteristics.

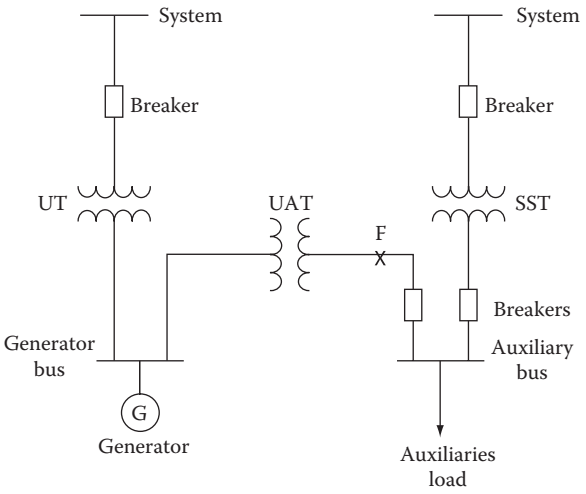


FIGURE 2.21 Typical simplified one-line diagram for the supply of a generating station's auxiliary power.

Alternatively, high generator-bus voltages can result from events such as generator-load rejection, resulting in overexcitation of a UAT connected to the generator bus. If a fault were to occur between the UAT and the breaker connecting it to the auxiliary load during this period of overexcitation, it could exceed the thermal and mechanical capabilities of the UAT. Additionally, nonsynchronous paralleling of the UAT and the SST, both connected to the generator auxiliary load, can create high circulating currents that can exceed the mechanical capability of these transformers.

Considerations can be made in the design of UAT transformers to account for these possible abnormal operating conditions. Such design considerations include lowering the core flux density at rated voltage to allow for operation at higher volts per hertz without saturation of the core, as well as increasing the design margin on the mechanical-withstand capability of the windings to account for the possibility of a fault occurring during a period of overexcitation. The thermal capacity of the transformer can also be increased to prevent overheating due to increased currents.

2.9 Modern and Future Developments

Superconducting technologies and their applications in power systems have the potential to have significant impact on future power transformer design, manufacture, and application, with numerous ongoing development efforts around the world. High-temperature superconducting (HTS) transformers, in which the copper and aluminum conductors are replaced by superconductors, are expected to be utilized in next-generation electric power grids. In the field of superconductors, "high" temperatures are considered to be in the range of 116–144 K (–157°C to –129°C), which is a major departure from the operating temperatures of conventional transformers. Application of superconductors in power transformers requires advances in cooling methodology (refrigeration) and in dielectric design, using media such as liquid nitrogen as a dielectric and heat transfer fluid. This requires cooling equipment such as cryogenic coolers as well as establishing dielectric properties of solid insulation impregnated with liquid nitrogen. Power transformers built using HTS technology are reportedly smaller and lighter, and would be capable of overloads without experiencing "loss of life" due to insulation degradation, instead using increased amounts 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 component of the load losses.

All of these developments will require appropriate electromagnetic modeling and analysis tools to represent superconductor windings, their small but definite ac losses, and effect of carrier metals on short-circuit currents. It is envisioned that these transformers can be made fault-current-limiting devices. This opens up many new technology development opportunities such as low-leakage-impedance transformer with reduction in voltage regulation issues and reactive power requirements.

Developments in insulating materials that are expected to influence the future design, manufacture, and application approaches of conventional transformers include nanotechnology-based synthetic insulation materials with superior performance that are becoming available, open cell polyester epoxy insulation materials that have shown good impregnation characteristics, and PPLP- and PPS-type conductor wrap insulation materials that are now available.

The feasibility of transformer core steels with higher saturation flux density is also being investigated by the U.S. Department of Energy and may represent one of the major breakthroughs in power transformer technology.

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3

Distribution Transformers

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3.1 Historical Background

3.1.1 Long-Distance Power

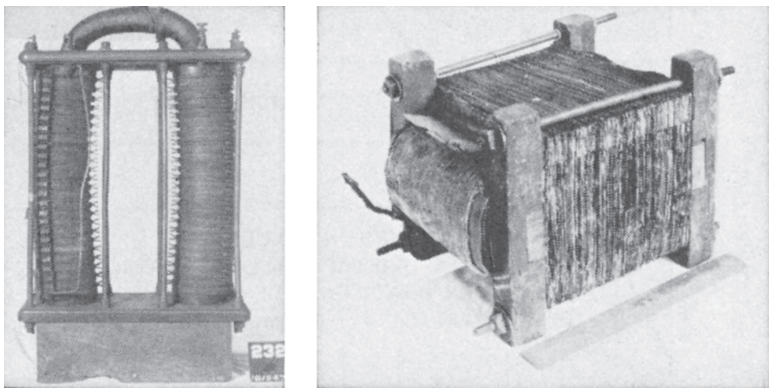
In 1886, George Westinghouse built the first long-distance ac (alternating current) electric lighting system in Great Barrington, Massachusetts. The power source was a 25 hp steam engine driving an alternator with an output of 500 V and 12 A. In the middle of town, 4000 ft away, transformers were used to reduce the voltage to serve light bulbs located in nearby stores and offices (Powel, 1997).

3.1.2 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 developed by Gaulard and Gibbs, shown in Figure 3.1a. 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. The Stanley transformer is shown in Figure 3.1b.

3.1.3 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. Many industry standards tend to limit this definition by kVA rating (e.g., 500 kVA and smaller for single-phase and 5000 kVA and smaller for three-phase), distribution transformers can have lower ratings and can have ratings of 5000 kVA or even higher.



(a) (b)

FIGURE 3.1 (a) Gaulard and Gibbs transformer and (b) William Stanley's early transformer. (By permission of ABB Inc., Raleigh, NC.)

3.2 Construction

3.2.1 Early Transformer Materials

From the pictures in Figure 3.1, 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 still used for some applications today. Paper-tape wrapping of conductors has been used extensively, but this has now been almost completely replaced by other methods.

3.2.2 Oil Immersion

In 1887, the year after Stanley designed and built the first transformers in the United States, 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.

3.2.3 Core Improvements

The major improvement in core materials was the introduction of silicon steel in 1932. Over the years, the performance of electrical steels has been improved by grain orientation (1933) and continued improvement in the steel chemistry and insulating properties of surface coatings. The thinner and more effective the insulating coatings are, the more efficient a particular core material will be. The thinner the laminations of electrical steel, the lower the losses in the core due to circulating currents. Mass production of distribution transformers has made it feasible to replace stacked cores with wound cores. C-cores were first used in distribution transformers around 1940. A C-core is made from a continuous strip of steel, wrapped and formed into a rectangular shape, and then annealed and bonded together. The core is then sawn in half to form two C-shaped sections that are machine faced and reassembled around the coil. In the mid-1950s, various manufacturers developed wound cores that were die formed into a rectangular shape and then annealed to relieve their mechanical stresses. The cores of most distribution transformers made today are made with wound cores (originally patented in 1933). Typically, the individual layers are cut, with each turn slightly lapping over itself. This allows the core to be disassembled and put back together around the coil structures while allowing a minimum of energy loss in the completed core. Electrical steel manufacturers now produce stock for wound cores that is from 0.35 to 0.18 mm thick in various grades. In the early 1980s, rapid increases in the cost of energy prompted the introduction of amorphous core steel. Amorphous metal is cooled down from the liquid state so rapidly that there is no time to organize into a crystalline structure. Thus it forms the metal equivalent of glass and is often referred to as metal glass or "met-glass." Amorphous core steel is usually 0.025 mm thick and offers another choice in the marketplace for transformer users that have very high energy costs.

3.2.4 Winding Materials

Conductors for low-voltage windings were originally made from small rectangular copper bars, referred to as "strap." Higher ratings could require as many as 16 of these strap conductors in parallel to make one winding having the needed cross section. A substantial improvement was gained by using copper strip, which could be much thinner than strap but with the same width as the coil itself. In the early 1960s, instability in the copper market encouraged the use of aluminum strip conductor. The use of aluminum round wire in the primary windings followed in the early 1970s (Palmer, 1983) as a direct result of advanced methods in terminating aluminum wire. Today, both aluminum and copper

conductors are used in distribution transformers, and the choice is largely dictated by economics. Round wire separated by paper insulation between layers has several disadvantages. The wire tends to "gutter," that is, to fall into the troughs in the layer below. Also, the contact between the wire and paper occurs only along two lines on either side of the conductor. This is a significant disadvantage when an adhesive is used to bind the wire and paper together. To prevent these problems, manufacturers often flatten the wire into an oval or rectangular shape in the process of winding the coil. This allows more conductor to be wound into a given size of coil and improves the mechanical and electrical integrity of the coil (Figure 3.4).

3.2.5 Conductor Insulation

The most common insulation today for high-voltage windings is an enamel coating on the wire, with thermally upgraded kraft paper used between layers. Low-voltage strip can be bare with paper insulation between layers. The use of paper wrapping on strap conductor is slowly being replaced by synthetic polymer coatings or wrapping with synthetic cloth. For special applications, synthetic paper such as DuPont's Nomex* can be used in place of kraft paper to permit higher continuous operating temperatures within the transformer coils.

3.2.5.1 Thermally Upgraded Paper

In 1958, manufacturers introduced insulating paper that was chemically treated to resist breakdown due to thermal aging. At the same time, testing programs throughout the industry were showing that the estimates of transformer life being used at the time were extremely conservative. By the early 1960s, citing the functional-life testing results, the industry began to change the standard average winding-temperature rise for distribution transformers, first to a dual rating of 55°C/65°C and then to a single 65°C rating as is currently used in IEEE C57.91. In some parts of the world, the distribution transformer standard remains at 55°C rise for devices using non-upgraded paper.

3.2.6 Conductor Joining

The introduction of aluminum wire, strap, and strip conductors and enamel coatings presented a number of challenges to distribution transformer manufacturers. Aluminum spontaneously forms an insulating oxide coating when exposed to air. This oxide coating must be removed or avoided whenever an electrical connection is desired. Also, electrical-conductor grades of aluminum are quite soft and are subject to cold flow and differential expansion problems when mechanical clamping is attempted. Some methods of splicing aluminum wires include soldering or crimping with special crimps that penetrate enamel and oxide coatings and seal out oxygen at the contact areas. Aluminum strap or strip conductors can be TIG (tungsten inert gas) welded. Aluminum strip can also be cold welded or crimped to other copper or aluminum connectors. Bolted connections can be made to soft aluminum if the joint area is properly cleaned. "Belleville" spring washers and proper torquing are used to control the clamping forces and contain the metal that wants to flow out of the joint. Aluminum joining problems are sometimes mitigated by using hard alloy tabs with tin plating to make bolted joints using standard hardware.

3.2.7 Coolants

3.2.7.1 Mineral Oil

Mineral oil surrounding a transformer core–coil assembly enhances the dielectric strength of the winding and prevents oxidation of the core. Dielectric improvement occurs because oil has a greater electrical

* Nomex is a registered trademark of E.I. du Pont de Nemours & Co., Wilmington, DE.

withstand than air and because the dielectric constant of oil, 2.2, is closer to that of the insulation. As a result, the stress on the insulation is lessened when oil replaces air in a dielectric system. Oil also picks up heat while it is in contact with the conductors and carries the heat out to the tank surface by self-convection. Thus a transformer immersed in oil can have smaller electrical clearances and smaller conductors for the same voltage and kVA ratings.

3.2.7.2 Askarels

Beginning about 1932, a class of liquids called askarels or polychlorinated biphenyls (PCBs) was used as a substitute for mineral oil where flammability was a major concern. Askarel-filled transformers could be placed inside or next to a building where only dry types were used previously. Although these coolants were considered nonflammable, when used in electrical equipment they could decompose when exposed to electric arcs or fires to form hydrochloric acid and toxic furans and dioxins. The compounds were further undesirable because of their persistence in the environment and their ability to accumulate in higher animals, including humans. Testing by the U.S. Environmental Protection Agency has shown that PCBs can cause cancer in animals and cause other noncancerous health effects. Studies in humans provide supportive evidence for potential carcinogenic and noncarcinogenic effects of PCBs (http://www.epa.gov). The use of askarels in new transformers was outlawed in 1977 (Claiborne, 1999). Work still continues to retire and properly dispose of transformers containing askarels or askarel-contaminated mineral oil. IEEE C57.12.00 requires transformer manufacturers to state on the nameplate that new equipment left the factory with less than 2 ppm PCBs in the oil.

3.2.7.3 High-Temperature Hydrocarbons

Among the coolants used to take the place of askarels in distribution transformers are high-temperature hydrocarbons (HTHCs), also called high-molecular-weight hydrocarbons. These coolants are classified by the National Electric Code as "less flammable" if they have a fire point above 300°C. The disadvantages of HTHCs include increased cost and a diminished cooling capacity from the higher viscosity that accompanies the higher molecular weight.

3.2.7.4 Silicones

Another coolant that meets the National Electric Code requirements for a less-flammable liquid is a silicone, chemically known as polydimethylsiloxane. Silicones are only occasionally used because they exhibit biological persistence if spilled and are more expensive than mineral oil or HTHCs.

3.2.7.5 Halogenated Fluids

Mixtures of tetrachloroethane and mineral oil were tried as an oil substitute for a few years. This and other chlorine-based compounds are no longer used because of a lack of biodegradability, the tendency to produce toxic by-products, and possible effects on the Earth's ozone layer.

3.2.7.6 Natural Esters

Natural ester insulating fluids, particularly Cooper Power System's Envirotemp™ FR3™ and ABB's BIOTEMP®, have become mainstream. Originating from vegetable seed, these fluids are renewable and biodegradable. In comparison to mineral oil, natural ester insulating fluids provide many improved characteristics. They are rated as a "less flammable fluid" per the NEC, providing increased fire safety from superior flash and fire resistance. They also provide high-temperature operating capability, and they are biodegradable. A few utilities and manufacturers are starting to design and operate natural ester insulated transformers at 75°C rise, marking the first major innovation since the adoption of upgraded kraft paper and the resulting shift from 55°C to 65°C operating temperature.

FIGURE 3.2 Typical three-phase pad-mounted distribution transformer. (By permission of ABB Inc., Jefferson City, MO.)

3.2.8 Tank and Cabinet Materials

A distribution transformer is expected to operate satisfactorily for 30 years in an outdoor environment while extremes of loading work to weaken the insulation systems inside the transformer. This high expectation demands the best in state-of-the-art design, metal processing, and coating technologies. A typical three-phase pad-mounted transformer is illustrated in Figure 3.2.

A suite of "enclosure integrity" standards has been developed to foster the ability of these transformers to withstand the environments in which they operate:

- IEEE C57.12.28, *Standard for Pad-Mounted Equipment—Enclosure Integrity*
- IEEE C57.12.29, *Standard for Pad-Mounted Equipment—Enclosure Integrity for Coastal Environments*
- IEEE C57.12.30, *Standard for Pole-Mounted Equipment—Enclosure Integrity for Coastal Environments*
- IEEE C57.12.31, *Standard for Pole-Mounted Equipment—Enclosure Integrity*
- IEEE C57.12.32, *Standard for Submersible Equipment—Enclosure Integrity*

3.2.8.1 Mild Steel

Most overhead and pad-mounted transformers have their tank and cabinet parts made from mild carbon steel. In recent years, major manufacturers have started using coatings applied by electrophoretic methods (aqueous deposition) and by powder coating. These new methods have largely replaced the traditional flow-coating and solvent-spray application methods.

3.2.8.2 Stainless Steel

Since the mid-1960s and continuing through the 1990s, single-phase submersibles were almost exclusively made using AISI 400-series stainless steel. These grades of stainless steel were selected for their good welding properties and their tendency to resist pit corrosion. Lately, both 400-series and 304L (low-carbon chromium–nickel) stainless steel have been used for transformer tanks and cabinets. While 304L is more expensive than 400, it is available in larger sheets. This made it feasible to build three-phase submersibles and pad mounts in stainless steel.

Utilities specify stainless steel tanks and cabinets for pad mounts and pole types where severe environments justify the added cost. Transformer users with severe coastal environments have observed

FIGURE 3.3 Single-phase transformer with composite hood. (By permission of ABB Inc., Jefferson City, MO.)

that pad mounts show the worst corrosion damage where the cabinet sill and lower areas of the tank contact the pad. This is easily explained by the tendency for moisture, leaves, grass clippings, lawn chemicals, etc., to collect on the pad surface. Higher areas of a tank and cabinet are warmed and dried by the operating transformer, but the lowest areas in contact with the pad remain cool. Also, the sill and tank surfaces in contact with the pad are most likely to have the paint scratched. To address this, manufacturers sometimes offer hybrid transformers, where the cabinet sill, hood, or the tank base may be selectively made from stainless steel.

3.2.8.3 Composites

There have been many attempts to conquer the corrosion tendencies of transformers by replacing metal structures with reinforced plastics. One of the more successful was a one-piece composite hood for single-phase pad-mounted transformers (Figure 3.3). However the major disadvantage of composites is the high cost of the mold and the extremely limited ability to make structural modifications. Metal cabinets, on the other hand, are infinitely and easily variable over large ranges.

3.2.9 Modern Processing

3.2.9.1 Adhesive Bonding

Today's distribution transformers almost universally use thermally upgraded kraft insulating paper that has a diamond pattern of epoxy adhesive on each side. Each finished coil is heated before assembly. The heating drives out any moisture that might have been absorbed in the insulation. Bringing the entire coil to the elevated temperature also causes the epoxy adhesive to bond and cure, making the coil into a solid mass. Thus it is more capable of sustaining the high thermal and mechanical stresses that the transformer encounters under short-circuit current conditions. Sometimes the application of heat is combined with clamping of the coil sides to ensure intimate contact of the epoxy-coated paper with the conductors as the epoxy cures. Another way to improve adhesive bonding in the high-voltage winding is to flatten round wire as the coil is wound. This produces two flat sides, hence more surface area, to contact adhesive on the layer paper above and below the conductor. It also improves the space factor of the conductor cross section, permitting more actual conductor to fit within the same core window. Flattened conductor is less likely to "gutter" or fall into the spaces in the previous layer, damaging the layer insulation. Figure 3.4 shows a cross section of enameled round wire after flattening.

FIGURE 3.4 Cross section of enameled round wire after flattening. (By permission of ABB Inc., Jefferson City, MO.)

3.2.9.2 Vacuum Processing

With the coil still warm from the bonding process, transformers are held at a high vacuum while oil flows into the tank. The combination of heat and vacuum assures that all moisture and all air bubbles have been removed from the coil, providing electrical integrity and a long service life. Factory processing with heat and vacuum is impossible to duplicate in the field or in most service facilities. Transformers, if opened, should be exposed to the atmosphere for minimal amounts of time, and oil levels should never be taken down below the tops of the coils. All efforts must be taken to keep air bubbles out of the insulation structure.

3.3 General Transformer Design

3.3.1 Liquid-Filled vs. Dry Type

The vast majority of distribution transformers on utility systems today are liquid filled. Liquid-filled transformers offer the advantages of smaller size, lower cost, and greater overload capabilities compared with dry types of the same rating.

3.3.2 Stacked vs. Wound Cores

Stacked-core construction favors the manufacturer who makes a small quantity of widely varying special designs in its facility. A manufacturer who builds large quantities of identical designs will benefit from the automated fabrication and processing of wound cores. Figure 3.5 shows three-phase stacked and wound cores.

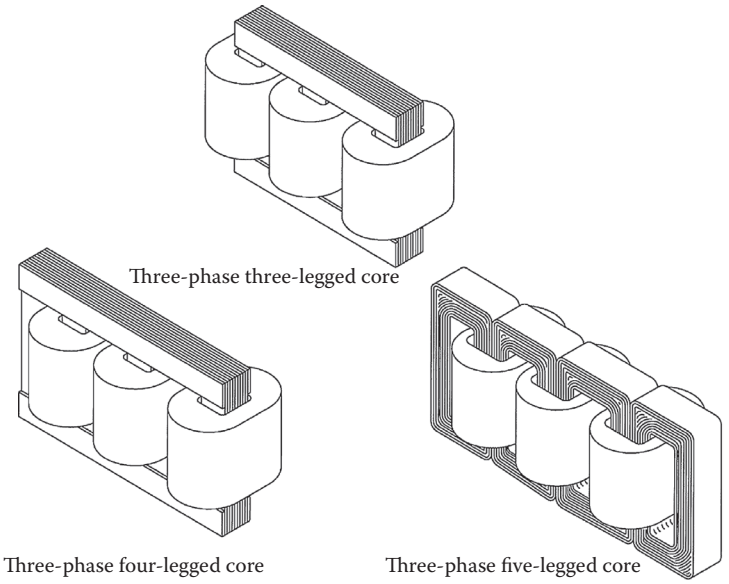
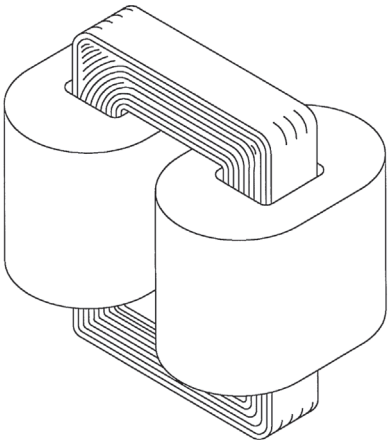


FIGURE 3.5 Three- and four-legged stacked cores and five-legged wound core. (From IEEE C57.105-1978, *IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems*, Copyright 1978, Institute of Electrical and Electronics Engineers, Inc., Piscataway, NJ. Reprinted with the permission of the IEEE. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner.)



Single-phase core-type transformer

FIGURE 3.6 Core-form construction. (From IEEE C57.105-1978, *IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems*, Copyright 1978, Institute of Electrical and Electronics Engineers, Inc., Piscataway, NJ. Reprinted with the permission of the IEEE. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner.)

3.3.3 Single-Phase

The vast majority of distribution transformers used in North America are single-phase transformers serving single-phase, 120/240 V, residential load. Single-phase transformers can also be connected into banks comprised of two or three separate units. Each unit in a bank has the same voltage ratings but need not have the same kVA rating. These banks can then serve three-phase load.

3.3.3.1 Core-Form Construction

A single core loop linking two identical winding coils is referred to as core-form construction. This is illustrated in Figure 3.6.

3.3.3.2 Shell-Form Construction

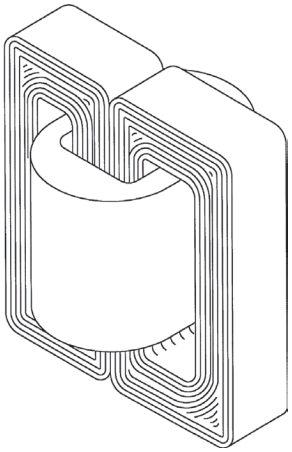
A single winding structure linking two core loops is referred to as shell-form construction. This is illustrated in Figure 3.7.

3.3.3.3 Winding Configuration

Most distribution transformers for residential service are built as a shell form, where the secondary winding is split into two sections with the primary winding in between. This so-called LO-HI-LO configuration results in lower impedance than if the secondary winding is contiguous. The LO-HI configuration is used where higher impedance is desired and especially on higher-kVA ratings where higher impedances are mandated by standards to limit short-circuit current. Core-form transformers are always built LO-HI because the two coils must always carry the same currents. A 120/240 V service using core-form in the LO-HI-LO configuration would need eight interconnected coil sections. This is considered too complicated to be commercially practical. LO-HI-LO and LO-HI configurations are illustrated in Figure 3.8.

3.3.4 Three-Phase

Most distribution transformers built and used outside North America are three-phase, even for residential service. In North America, three-phase transformers serve agricultural, commercial, and industrial loads.



Single-phase shell-type transformer

FIGURE 3.7 Shell-form construction. (From IEEE C57.105-1978, *IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems*, Copyright 1978, Institute of Electrical and Electronics Engineers, Inc., Piscataway, NJ. Reprinted with the permission of the IEEE. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner.)

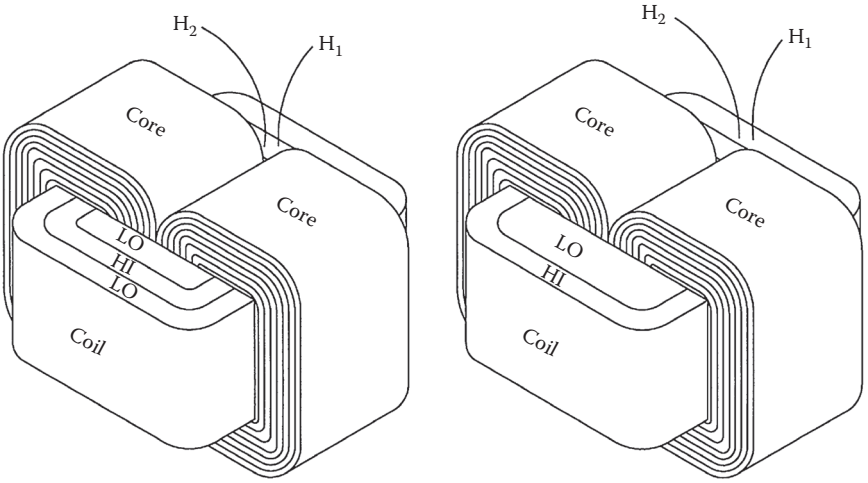


FIGURE 3.8 LO-HI-LO and LO-HI configurations. (By permission of ABB Inc., Jefferson City, MO.)

They are also used to supply large residential complexes, such as condominiums and high-rise buildings. A relatively new application for three-phase transformers is in "wind farms" where transformers are used to step up the voltage from wind turbines (around 600 V) to a distribution voltage (typically 19,920 V). All three-phase distribution transformers are said to be of core-form construction, although the definitions outlined earlier do not hold. Three-phase transformers have one coaxial coil for each phase encircling a vertical leg of the core structure. Stacked cores have three or possibly four vertical legs, while wound cores have a total of four loops creating five legs or vertical paths: three down through the center of the three coils and one on the end of each outside coil. The use of three vs. four or five legs in the core structure has a bearing on which electrical connections and loads can be used by a particular transformer. The advantage of three-phase electrical systems in general is the economy gained by having the phases share common conductors and other components. This is especially true of three-phase transformers using common core structures. See Figure 3.5.

3.3.5 Duplex and Triplex Construction

Occasionally, utilities will require a single tank that contains two completely separate core–coil assemblies. Such a design is sometimes called a duplex and can have any size combination of single-phase core–coil assemblies inside. The effect is the same as constructing a two-unit bank with the advantage of having only one tank to place. Duplexes are particularly useful in serving a small three-phase load in combination with single-phase load, such as a sewer lift pump and multiple residential houses. Similarly, a utility may request a triplex transformer with three completely separate and distinct core structures (of the same kVA rating) mounted inside one tank.

3.3.6 Serving Single- and Three-Phase Loads

The utility engineer has a number of transformer configurations to choose from, and it is important to match the transformer to the load being served. Small single-phase loads are easily served by a single-phase transformer. A large single-phase load may be best served by a three-phase transformer with the single-phase load balanced among the three phases. Add a little three-phase load, and the best bet is a bank of two transformers or a duplex. Increase the three-phase load and retain the single-phase load, and the best bank is a bank of three transformers. A balanced three-phase load is best served by a three-phase transformer, with each phase's coil identically loaded (ABB, 1995).

Another driver is the service voltage. Single-phase transformers commonly serve 120/240 V load, and banks of two or three single-phase transformers serve a mixture of 120/240 V single-phase and 240 V three-phase loads. These transformers are commonly available through 500 kVA. Three-phase 120/208 V can be served by a bank of three single-phase transformers or a three-phase transformer. Dense clusters of single-phase residential load can be served at 120/208 V using a three-phase transformer. The 120/208 V secondary is available through 1000 kVA. For larger loads, 277/480 V is commonly used, and while usually served from a three-phase transformer can also be supplied by a bank of appropriately rated single-phase transformers. Even larger loads are served using 2400, 4160, or 2400/4160 V from a three-phase transformer, utilizing what in older areas is a primary voltage as a service voltage.

3.4 Transformer Connections

3.4.1 Single-Phase Primary Connections

Single-phase transformers have a single primary winding and have either two insulated terminations or one insulated and one grounded termination.

3.4.1.1 Grounded Wye Connection

Single-phase transformers that must have one side of the primary grounded are only provided with one primary connection bushing. The primary circuit is completed by grounding the transformer tank to the grounded system neutral. Thus, it is imperative that proper grounding procedure be followed when the transformer is installed so that the tank never becomes "hot." Since one end of the primary winding is always grounded, the manufacturer can economize the design and grade the high-voltage insulation. Grading provides less insulation at the end of the winding closest to ground. A transformer with graded insulation usually cannot be converted to operate phase-to-phase. The primary-voltage designation on the nameplate of a graded insulation transformer will include the letters, "GRDY," as in "12470 GRDY/7200," indicating that it must be connected phase-to-ground on a grounded wye system.

3.4.1.2 Fully Insulated Connection

Single-phase transformers supplied with fully insulated (not graded) coils and two separate primary connection bushings may be connected phase-to-phase on a three-phase system or phase-to-ground on

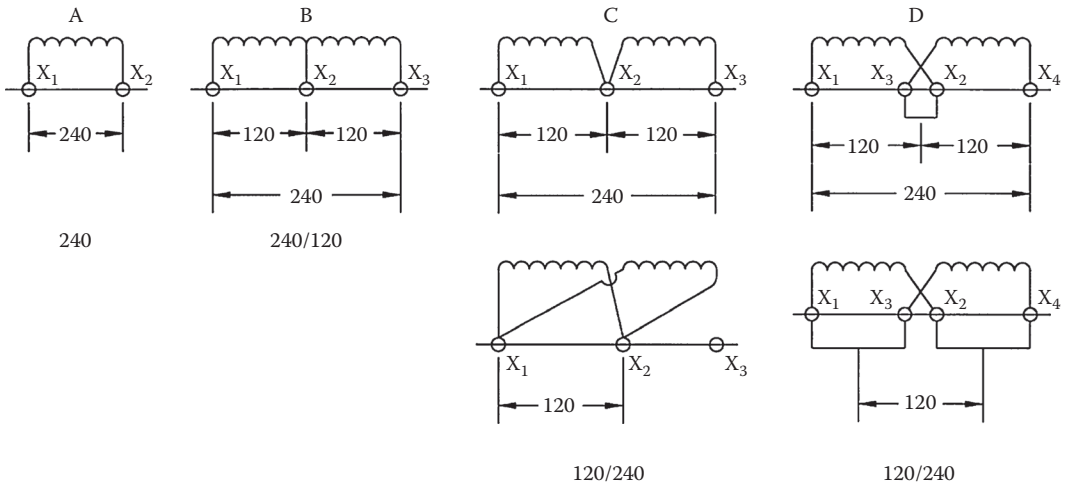


FIGURE 3.9 Single-phase secondary connections. (By permission of ABB Inc., Jefferson City, MO.)

a grounded wye system. The primary voltage designation on the nameplate of a fully insulated transformer will look like 7200/12470Y, where 7200 is the coil voltage. If the primary voltage shows only the coil voltage, as in 2400, then the bushings can sustain only a limited voltage from the system ground, and the transformer must be connected phase-to-phase.

3.4.2 Single-Phase Secondary Connections

Single-phase distribution transformers usually have two, three, or four secondary bushings, and the most common voltage ratings are 240 and 480, with and without a mid-tap connection. Figure 3.9 shows various single-phase secondary connections.

3.4.2.1 Two Secondary Bushings

A transformer with two bushings can supply only a single voltage to the load.

3.4.2.2 Three Secondary Bushings

A transformer with three bushings supplies a single voltage with a tap at the midpoint of that voltage. This is the common three-wire residential service used in North America. For example, a 120/240 V secondary can supply load at either 120 or 240 V as long as neither 120 V coil section is overloaded. Transformers with handholes or removable covers can be internally reconnected from three to two bushings in order to serve full kVA from the parallel connection of coil sections. These are designated 120/240 or 240/480 V, with the smaller value first. Most pad-mounted distribution transformers are permanently and completely sealed and therefore cannot be reconnected from three to two bushings. The secondary voltage for permanently sealed transformers with three bushings is 240/120 or 480/240 V.

3.4.2.3 Four Secondary Bushings

Secondaries with four bushings can be connected together external to the transformer to create a mid-tap connection with one bushing in common, or a two-bushing connection where the internal coil sections are paralleled. The four-bushing secondary will be designated as 120/240 or 240/480 V, indicating that a full kVA load can be served at the lower voltage. The distinction between 120/240 and 240/120 V must be carefully followed when transformers are being specified.

3.4.3 Three-Phase Connections

When discussing three-phase distribution transformer connections, it is well to remember that this can refer to a single three-phase transformer or two or three single-phase transformers interconnected to create a three-phase bank. For either an integrated transformer or a bank, the primary or secondary can be wired in either delta or wye connection. The wye connections can be either grounded or ungrounded. However, not all combinations will operate satisfactorily, depending on the transformer construction, characteristics of the load, and the source system. Detailed information on three-phase connections can be found in IEEE C57.105 or in the ABB Distribution Transformer Guide (ABB, 1995). Some connections that are of special concern are listed as follows.

3.4.3.1 Ungrounded Wye–Grounded Wye

A wye–wye connection where the primary neutral is left floating produces an unstable neutral where high third-harmonic voltages are likely to appear. In some Asian systems, the primary neutral is stabilized by using a three-legged core and by limiting current unbalance on the feeder at the substation.

3.4.3.2 Grounded Wye–Delta

This connection is called a grounding transformer. Unbalanced primary voltages will create high currents in the delta circuit. Unless the transformer is specifically designed to handle these circulating currents, the secondary windings can be overloaded and burn out. Unless its use is intended to be as a grounding transformer, the use of the ungrounded wye–delta is suggested instead.

3.4.3.3 Grounded Wye–Grounded Wye

A grounded wye–wye connection will sustain unbalanced voltages, but it must use a four- or five-legged core to provide a return path for zero-sequence flux.

3.4.3.4 Three-Phase Secondary Connections–Delta

Three-phase transformers or banks with *delta* secondaries will have simple nameplate designations such as 240 or 480. If one winding has a mid-tap, say for lighting, then the nameplate will say 240/120 or 480/240, similar to a single-phase transformer with a center tap. Delta secondaries can be grounded at the mid-tap or any corner.

3.4.3.5 Three-Phase Secondary Connections–Wye

Popular voltages for wye secondaries are 208Y/120, 480Y/277, and 600Y/347.

3.4.4 Open-Delta Connections

Two single-phase transformers and duplex transformers can be connected into a bank having either an open-wye or open-delta primary along with an open-delta secondary. Such banks are usually used to serve loads that are predominantly single-phase in conjunction with some three-phase load. The secondary leg serving the single-phase load usually has a mid-tap, which is grounded.

3.4.5 Other Connections

For details on other connections such as T-T and zigzag, consult IEEE C57.12.80, IEEE C57.105, or the ABB Distribution Transformer Guide (ABB, 1995).

3.4.6 Preferred Connections

In the earliest days of electric utility systems, it was found that induction motors drew currents that exhibited a substantial third-harmonic component. In addition, transformers on the system that were

operating close to the saturation point of their cores had third harmonics in the exciting current. One way to keep these harmonic currents from spreading over an entire system was to use delta-connected windings in transformers. Third-harmonic currents add up in phase in a delta loop and flow around the loop, dissipating themselves as heat in the windings but minimizing the harmonic voltage distortion that might be seen elsewhere on the utility's system. With the advent of suburban underground systems in the 1960s, it was found that a transformer with a delta-connected primary was more prone to ferroresonance problems because of higher capacitance between buried primary cables and ground. An acceptable preventive was to go to grounded-wye–grounded-wye transformers on all but the heaviest industrial applications.

3.5 Operational Concerns

Even with the best engineering practices, abnormal situations can arise that may produce damage to equipment and compromise the continuity of the delivery of quality power from the utility.

3.5.1 Ferroresonance

Ferroresonance is an overvoltage phenomenon that occurs when charging current for a long underground cable or other capacitive reactance saturates the core of a transformer. Such a resonance can result in voltages as high as five times the rated system voltage, potentially damaging lightning arresters and other equipment and possibly even the transformer itself. When ferroresonance is occurring, the transformer is likely to produce loud squeals and groans, and the noise has been likened to the sound of steel roofing being dragged across a concrete surface. A typical ferroresonance situation is shown in Figure 3.10 and consists of long underground cables feeding a transformer with a delta-connected primary. The transformer is unloaded or very lightly loaded, and switching or fusing for the circuit operates one phase at a time. Ferroresonance can occur when energizing the transformer as the first or second switch is closed, or it can occur if one or two phases open and the load is very light. Ferroresonance will disappear as soon as all three phases are closed or opened. Ferroresonance is more likely to occur on systems

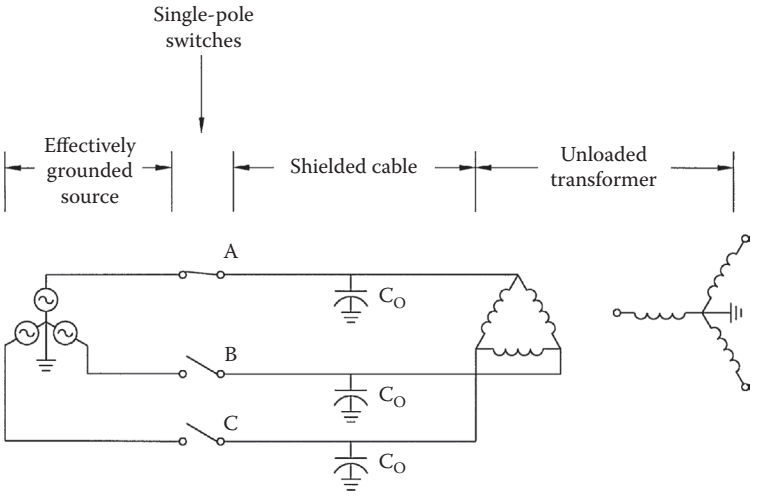


FIGURE 3.10 Typical ferroresonance situation. (From IEEE C57.105-1978, *IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems*, Copyright 1978, Institute of Electrical and Electronics Engineers, Inc., Piscataway, NJ. Reprinted with the permission of the IEEE. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner.)