Overview & Energy Optimization of Power Distribution Transformers

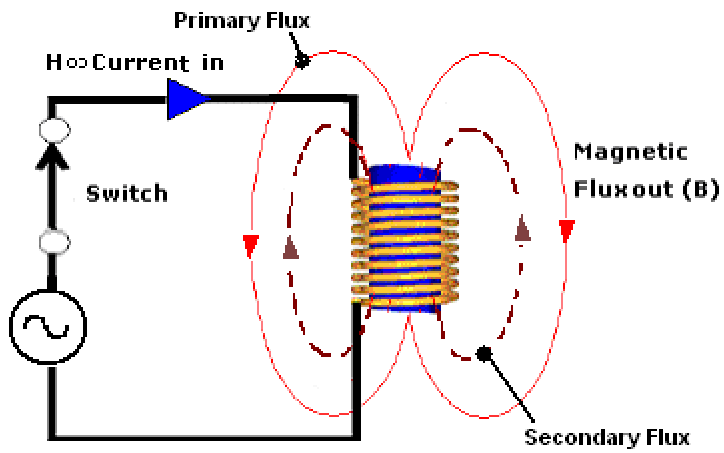
Course Content

A transformer is a static piece of apparatus used for transferring power from one AC circuit to another at a different voltage, but without change in frequency. It can step up or step down the voltage level with a corresponding decrease or increase of current. These are used extensively for AC power transmissions and for various control and indication circuits. Knowledge of the basic theory of how these components operate is necessary to understand the role transformers play in today's facilities.

Mutual Inductance

`A transformer operates on the principal of magnetic induction.`

When an AC voltage is applied to a coil, it produces a varying magnetic field around the coil. If a second coil is placed within this magnetic field then a voltage is induced in this second coil. This is called mutual induction. The magnetic field strength H, required to produce a magnetic flux density B, is proportional to the current flowing in the coil. The figure below shows the flux produced by the currents in the primary and secondary windings of a transformer when source current is flowing in the primary winding.



Relationship between current, magnetic field strength and flux

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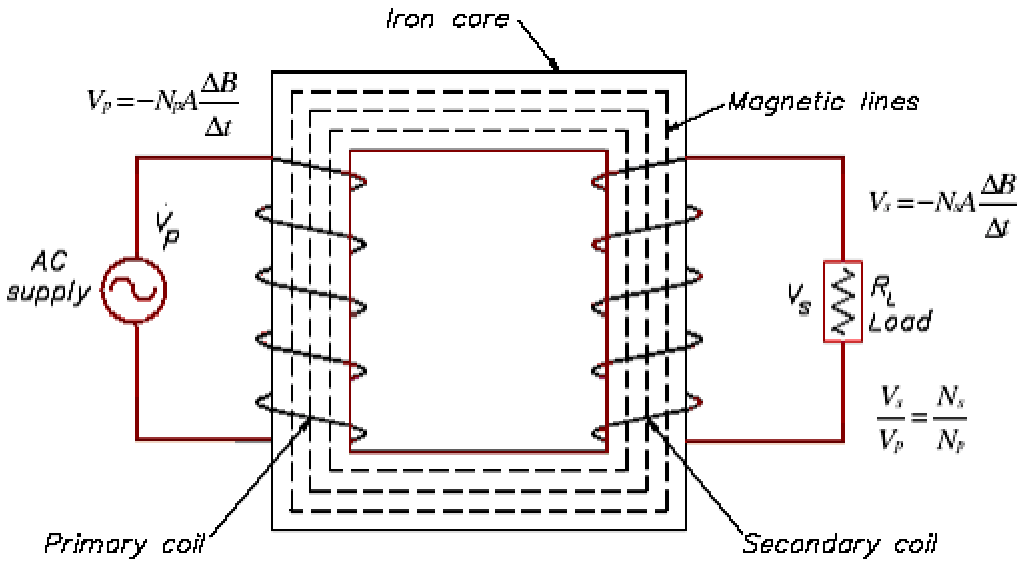
Basic Transformer Action

Each transformer consists of two or more coils which are not electrically connected, but are arranged in such a way that the magnetic field surrounding one coil cuts through the other coil. When an alternating voltage is applied to the one coil, the varying magnetic field set up around this coil creates an alternating voltage in the other coil.

The coil that receives power from the AC source is called "primary" winding and the coil where voltage is induced or load is delivered is called "secondary" coil. The voltage induced from the primary to the secondary coils is directly proportional to the turns ratio between the two coils and can be explained by Faraday's law.



TRANSFORMER SCHEMATIC

Faraday's induction law

First Law:

Whenever the magnetic flux linked with a circuit changes, an electromagnetic force (EMF) is induced in it or whenever a conductor cuts magnetic flux, an EMF is induced in that conductor.

Second Law:

The magnitude of the induced EMF is equal to the rate of change of flux linkages or in other words is proportional to the number of turns and the speed of the alternating flux (dB/dt). The amount of magnetic flux through an area equals the product of the area and the magnetic field strength at a point within that area.

If we neglect resistance and other losses in the transformer, the terminal voltage equals the EMF. The mathematical model of faraday's induction law is

$$EMF = Vp = -Np \; A \frac{\Delta B}{\Delta t} \quad \text{----(1)}$$

A current in the primary winding produces a magnetic field in the core. The magnetic field is almost totally confined in the iron core and couples around through the secondary coil. When a load resistance is connected to the secondary winding, the voltage induced into the secondary winding causes current to flow in the secondary winding. This current produces a flux field about the secondary (shown as broken lines in figure-1) which is in opposition to the flux field about the primary (Lenz's law). Thus, the flux about the secondary cancels some of the flux about the primary. With less flux surrounding the primary, the counter EMF is reduced and more current is drawn from the source. The additional current in the primary generates more lines of flux, nearly reestablishing the original number of total flux lines. Thus, some of the electrical power fed into the primary is delivered to the secondary. The induced voltage in the secondary winding is also given by Faraday’s law

$$Vs = -N_s \; A \frac{\Delta B}{\Delta t} \quad \text{---- (2)}$$

The rate of change of flux is the same as that in primary winding. Dividing equation (2) by (1) gives

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} = a$$

Where "a" is the turns ratio; the voltage induced from the primary to the secondary coils is directly proportional to the turns ratio between the two coils. The voltage developed by transformer action is given by

$E = 4.44 \times f \times N \times B_{max} \times A_{core}$

Where

E = rated coil voltage (volts),

f = operating frequency (hertz),

N = number of turns in the winding,

B_{max} = maximum flux density in the core (tesla), and

A_{core} = cross sectional area of the core material in sq-m.

In addition to the voltage equation, a power equation expressing the volt-ampere rating in terms of the other input parameters is also used in transformer design. Specifically, the form of the equation is

$kVA = 444 \times f \times N \times B_{max} \times A_{core} \times J \times A_{coil}$

Where,

N, B_{max}, A_{core} and f are as defined above, J is the current density (A /mm^2), and A_{coil} is the coil cross-sectional area (mm^2) in the core window; of the conducting material for primary winding. J depends upon heat dissipation and cooling.

Note that a transformer can also be used with pulsating dc, but a pure dc voltage cannot be used, since only a varying voltage creates the varying magnetic field which is the basis of the mutual induction process.

The total flux in the core of the transformer is common to both the primary and secondary windings. It is also the means by which energy is transferred from the primary winding to the secondary winding. Since this flux links both windings, it is called "mutual flux". The primary and secondary inductances aren't *perfectly* linked due to "stray" or "*leakage*" inductance; this reduces the effectiveness of the transformer. Magnetic leakage is the part of the magnetic flux that passes through either one of the coils, but not through both. For optimum efficiency it is important to have better coupling between the primary and secondary coils. The larger the distance between the primary and secondary windings, the longer is the magnetic circuit and the greater the leakage. In practice, it is not practical to achieve 100% perfect coupling, but it easy to design coils with low inductance and have excellent efficiency even with poor magnetic coupling. To maximize flux linkage with the secondary circuit, an iron core is often used to provide a low-reluctance path for the magnetic flux.

TRANSFORMER COMPONENTS

The principle parts of a transformer are -

1) The primary winding that receives power from the AC power source.
2) The secondary winding that receives power from the primary winding and delivers it to the load.
3) The core, which provides a path for the magnetic lines of flux.
4) The enclosure, which protects the above components from dirt, moisture, and mechanical damage.

Windings

The primary and secondary windings consist of aluminum or copper conductors wound in coils around an iron core. The winding material depends on the application. Small power and signal transformers are wound with insulated solid copper wire. Larger power transformers may be wound with wire, copper or aluminum rectangular conductors, or strip conductors for very heavy currents.

Each turn of wire in the primary winding has an equal share of the primary voltage. The same is induced in each turn of the secondary. Therefore, any difference in the number of turns in the secondary as compared to the primary will produce a voltage change. *If there are fewer turns in the secondary winding than in the primary winding, the secondary voltage will be lower than the primary. If there are fewer turns in the primary winding than in the secondary winding, the secondary voltage will be higher than the secondary circuit. The primary winding is the winding which receives the energy; it is not always the high-voltage winding.*

Winding Physical Location:

In most transformers the high voltage winding is wound directly over the low voltage winding to create efficient coupling of the two windings. Other Designs may have the high voltage winding wound inside, side-by-side or sandwiched between layers of the low voltage winding to meet special requirements.

Windings on both primary and secondary of a power transformer may have taps to allow adjustment of the voltage ratio; taps may be connected to automatic on-load tapchanger switchgear for voltage regulation of distribution circuits.

Core types

A core supports and magnetically couples the primary and secondary windings. The composition of a transformer core depends on voltage, current, and frequency. Size limitations and construction costs are also factors to be considered. Commonly used core materials are air, soft iron, and steel. Each of these materials is suitable for particular applications and unsuitable for others.

1) For the transformers designed to operate at low frequencies, the windings are usually formed around an iron core. This helps to confine the magnetic field within the transformer and increase its efficiency, although the presence of the core causes energy losses. A soft-iron-core transformer is very useful where the transformer must be physically small, yet efficient.
2) High-frequency transformers (above 20 kHz) in low-power circuits may have air cores. These eliminate the loss due to hysteresis in the core material. Such transformers maintain high coupling efficiency (low stray field loss) by overlapping the primary and secondary windings.The iron-core transformer provides better power transfer than does the air-core transformer.

There are five main groups of magnetically soft alloys classified primarily by the chief constituents of the metal. These are 1) low-carbon steel, 2) silicon steel, 3) nickel-iron, 4) cobalt-nickel-iron and 5) cobalt iron.

Cores manufactured from the highest quality non-aging, cold rolled, grain oriented silicon steel laminations are efficient. Cores are carefully assembled and rigidly clamped and then either bolted or welded to minimize gaps and assure low losses and quiet operation.

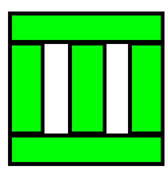
Cores are precision cut to close tolerances to eliminate burrs and improve performance. Most feature fully interleaved, stepped core construction for optimum energy efficiency.

Steel cores

Transformers often have silicon steel *cores* to channel the magnetic field. This keeps the field more concentrated around the wires, so that the transformer is more compact. The core of a power transformer must be designed so that it does not reach magnetic saturation. Carefully designed gaps are sometimes placed in the magnetic path to help prevent saturation. Practical transformer cores are always made of many stamped pieces of thin steel. The high resistance between layers reduces eddy currents in the cores that waste power by heating the core. These are common in power and audio circuits. A typical laminated core is made from E-shaped and I-shaped pieces, leading to the name "EI transformer". One problem with a steel core is that it may retain a static magnetic field when power is removed. When power is then reapplied, the residual field may cause the core to temporarily saturate. This can be a significant problem in transformers of more than a few hundred watts output, since the higher inrush current can cause mains fuses to blow unless current-limiting circuitry is added. More seriously, inrush currents can physically deform and damage the primary windings of large power transformers.

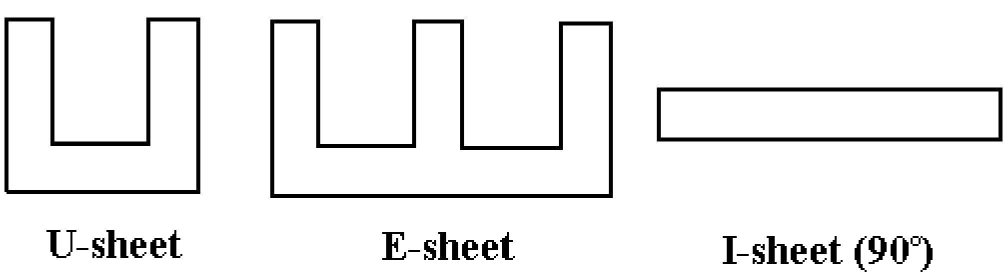
Laminated Steel Cores

A transformer whose core is constructed of laminated sheets of steel dissipates heat readily; thus it provides for the efficient transfer of power. The majority of transformers you will encounter contain laminated-steel cores. These steel laminations are insulated with a non-conducting material, such as varnish, and then formed into a core. It takes about 50 such laminations to make a core an inch thick. The purpose of the laminations is to reduce certain losses which will be discussed later in this course. An important point to remember is that the most efficient transformer core is one that offers the best path for the most lines of flux with the least loss in magnetic and electrical energy. There are two main shapes of cores used in laminated-steel-core transformers. One is the “Hollow Core”, so named because the core is shaped with a hollow square through the center. Figure below illustrates this shape of core. Notice that the core is made up of many laminations of steel.



Hollow-core construction

The most popular and efficient transformer core is the “Shell Core”, as shown in figure below. Each layer of the core consists of U, E- and I-shaped sections of metal. These sections are butted together to form the laminations. The laminations are insulated from each other and then pressed together to form the core.



Solid cores

In higher frequency circuits such as switch-mode power supplies, powdered iron cores are sometimes used. These materials combine a high magnetic permeability with a high material resistivity. At even higher frequencies (radio frequencies typically) other types of core made of nonconductive magnetic materials, such as various ceramic materials called ferrites are common.

Some transformers in radio-frequency circuits have adjustable cores which allow tuning of the coupling circuit.

Insulation

The conductor material must have insulation to ensure the current travels around the core and not through a turn-to-turn short-circuit. In power transformers, the voltage difference between parts of the primary and secondary windings can be quite large.

Layers of insulation are inserted between layers of windings to prevent arcing.The insulation rating is the maximum allowable winding (hot spot) temperature of a transformer operating at an ambient temperature of 40°C. Insulation systems are classified by the temperature rating. The following table summarizes the different insulation systems available.

Insulation Rating	Insulation Class	Average Winding Temperature Rise	Hot Spot Temperature Rise	Maximum Winding Temperature
Class 105	A	55°C	65°C	105°C
Class 150	B	80°C	110°C	150°C
Class 180	F	115°C	145°C	180°C
Class 220	H	150°C	180°C	220°C

Note: The maximum acceptable temperature rise based on an average ambient of 30°C during any 24 hour period and a maximum ambient of 40°C at any time.

Shielding

Although an ideal transformer is purely magnetic in operation, the close proximity of the primary and secondary windings can create a mutual capacitance between the windings. Where transformers are intended for high electrical isolation between primary and secondary circuits, an electrostatic shield can be placed between windings to minimize this effect.

Transformers may also be enclosed by magnetic shields, electrostatic shields, or both to prevent outside interference from affecting the operation of the transformer or to prevent the transformer from affecting the operation of other devices (such as CRTs in close proximity to the transformer). Transformers may also be enclosed for reasons of safety, both to prevent contact with the transfomer during normal operation and to contain possible fires that occur as a result of abnormal operation. The enclosure may also be part of the transformer's cooling system.

Coolant

Small transformers up to a few thousand watts in size usually are adequately cooled by air circulation. Larger "dry" type transformers may have cooling fans.

High-power or high-voltage transformers are bathed in highly-refined mineral oil that is stable at high temperatures. Large transformers to be used indoors must use a non-flammable liquid. Formerly, polychlorinated biphenyl, "PCB" was used as it was not a fire hazard in indoor power transformers. Due to the stability of PCB and its environmental accumulation, it is no longer permitted in new equipment. Today, nontoxic, stable silicone-based or fluorinated hydrocarbons may be used, where the expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Other less-flammable fluids such as canola oil may be used but all fire resistant fluids have some drawbacks in performance, cost, or toxicity compared with mineral oil.

The oil cools the transformer, and provides part of the electrical insulation between internal live parts. It has to be stable at high temperatures so that a small short or arc will not cause a breakdown or fire. To improve cooling of large power transformers, the oil-filled tank may have radiators through which the oil circulates by natural convection. Very large or high-power transformers (with capacities of millions of watts) may have cooling fans, oil pumps and even oil to water heat exchanger. Large and high-voltage transformers undergo prolonged drying processes, using electrical self-heating, the application of a vacuum, or both to ensure that the transformer is completely free of water vapor before the cooling oil is introduced. *The moisture will reduce the dielectric strength of the oil and hence insulation is weekend.*

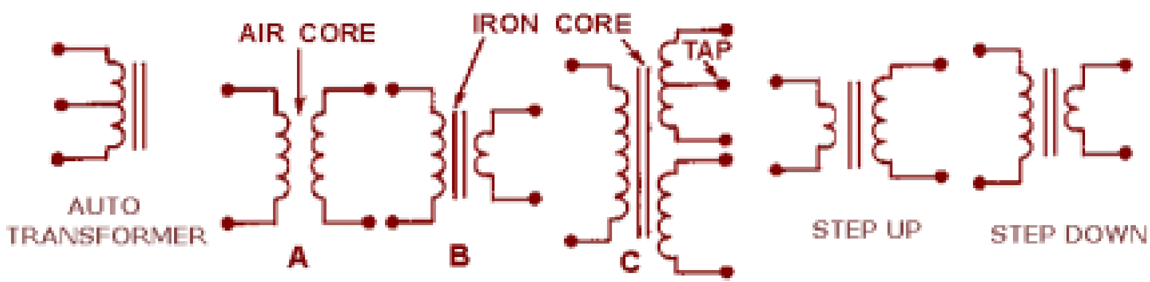
Experimental power transformers in the 2000 kVA range have been built with superconducting windings which eliminates the copper losses, but not the core steel loss. These are cooled by liquid nitrogen or helium.

Terminals

Very small transformers will have wire leads connected directly to the ends of the coils, and brought out to the base of the unit for circuit connections. Larger transformers may have heavy bolted terminals, bus bars or high-voltage insulated bushings made of polymers or porcelain. A large bushing can be a complex structure since it must both provide electrical insulation, and contain oil within the transformer tank.

Schematic symbols for transformers

Figure below shows typical schematic symbols for transformers. The symbol for an air-core transformer is shown in (A). Parts (B) and (C) show iron-core transformers. The bars between the coils are used to indicate an iron core. Frequently, additional connections are made to the transformer windings at points other than the ends of the windings. These additional connections are called TAPS. When a tap is connected to the center of the winding, it is called a center tap.



Schematic symbols for various types of transformers

Turns and voltage ratios

Each winding of a transformer contains a certain number of turns of wire. The turn's ratio is defined as the ratio of turns of wire in the primary winding to the number of turns of wire in the secondary winding. Turns ratio can be expressed using equation

$$\text{Turns Ratio} = \frac{N_p}{N_s}$$

Np = number of turns on the primary coil

Ns = number of turns on the secondary coil

When the turns ratio is stated, the number representing turns on the primary is always stated first. For example, if a turn ratio is given as 6:1, you can assume a number of turns for the primary and compute the secondary number of turns (60:10, 36:6, 30:5, etc.).

The total voltage induced into the secondary winding of a transformer is determined mainly by the ratio of the number of turns in the primary to the number of turns in the secondary and by the amount of voltage applied to the primary.

Consider for example a transformer whose primary consists of 10 turns of wire and secondary consists of a single turn of wire i.e. the transformer has the turns ratio of 10:1. As lines of flux generated by the primary expand and collapse, they cut both the ten turns of the primary and the single turn of the secondary. Since the length of the wire in the secondary is approximately the same as the length of the wire in each turn in the primary, EMF induced into the secondary will be the same as the EMF induced into each turn in the primary. This means that if the voltage applied to the primary winding is 10 volts, the counter EMF in the primary is almost 10 volts and each turn will have an EMF of one volt (one-tenth of the total applied voltage) induced into it. Thus, the EMF across the secondary is one volt. Similarly for a 10:2 turns ratio, when 10 V is applied to the primary, the total voltage across the secondary will be two volts.

Note that the volts per turn are the same for both primary and secondary windings. The electromotive force (EMF) developed in the secondary is proportional to the ratio of the number of turns in the secondary coil to the number of turns in the primary coil. Neglecting all leakage flux, an ideal transformer follows the equation

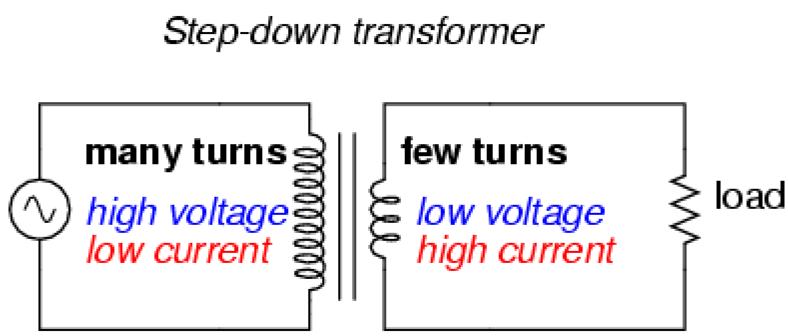
$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

Where Vp is the voltage in the primary coil, Vs is the voltage in the secondary coil, Np is the number of turns of wire on the primary coil, and Ns is the number of turns of wire on the secondary coil. This leads to the commonest use of the transformer: to convert power at one voltage to power at a different voltage.

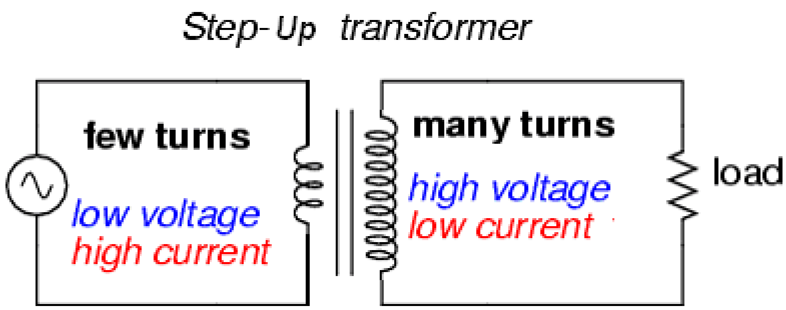
The ratio of primary voltage to secondary voltage is known as the voltage ratio (VR). As mentioned previously, the ratio of primary turns of wire to secondary turns of wire is known as the turns ratio (TR). Therefore VR = TR.

Note the following:

1) A transformer that has more turns on the primary than on the secondary side of the transformer will decrease the input voltage. A transformer in which the voltage across the secondary is less than the voltage across the primary is called a “step-down” transformer. The ratio of a four-to-one step-down transformer is written as 4:1.



2) A transformer that has more turns on the secondary than on the primary side of the transformer will increase the input voltage. A transformer in which the voltage across the secondary is greater than the voltage applied to the primary is called a “step-up” transformer. The ratio of a one-to-four step-up transformer should be written as 1:4. Notice in the two ratios that the value of the primary winding is always stated first.

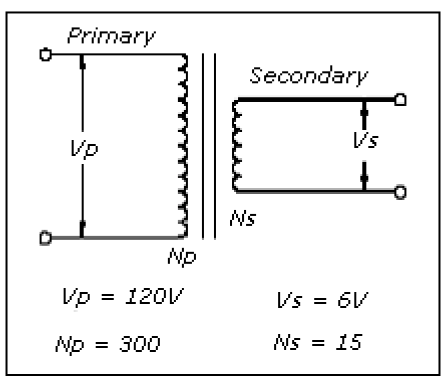


3) A transformer can also be used neither step-up nor step-down device. In this case, the transformer is being used as an isolation device to electrically isolate the circuit on the primary side of the transformer from the circuit on the secondary side of the circuit. Electrical isolation can be used to improve the safety of electrical appliances that have non-polarized power cords. Since the transformer only works for AC voltages, any DC voltages on the primary side of a transformer will not be passed to the secondary side of the transformer. In this application, the transformer is being used as a DC isolation device.

4) Refer the table below for examples of Turn Ratio:

Primary Windings	Secondary Voltage	Turns Ratio	Primary Voltage	Secondary Voltage	Terns Ratio
480	480	2/1	600	120	5/1
480	120	4/1	600	208	2.88/1
480	24	20/1	208	120	1.73/1

Example # 1: A transformer (refer schematic below) reduces voltage from 120 volts in the primary to 6 volts in the secondary. If the primary winding has 300 turns and the secondary has 15 turns, find the voltage and turns ratio.

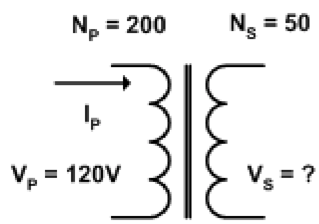


Solution:

$$VR = \frac{Vp}{Vs} = \frac{120}{60} = \frac{20}{1} = 20:1$$

$$TR = \frac{Np}{Ns} = \frac{300}{15} = \frac{20}{1} = 20:1$$

Example # 2: Determine the output voltage for the transformer shown below.



Solution:

$$\frac{Vs}{Vp} = \frac{Ns}{Np}$$

Solve for Vs

$$Vs = \frac{Ns}{Np} Vp$$

$$Vs = \frac{50}{200} 120$$

$$Vs = 30 \text{ V}$$

Example # 3: A power transformer has a turns ratio of 1:4. If the secondary coil has 5000 turns and secondary voltage is 60 volts, find the voltage ratio, Vp, and number of primary turns, Np.

Solution:

VR = TR

VR = 1: 4

$$\frac{Vp}{Vs} = VR = 1:4 = \frac{1}{4}$$

$$Vp = \frac{1}{4} Vs = \frac{60}{4} = 15 \text{ volts}$$

$$TR = \frac{Np}{Ns} = \frac{1}{4}$$

$$Np = \frac{1}{4} Ns = \frac{5000}{4} = 1250 \text{ turns}$$

Example # 4: If turn ratio is given as 6:1, what is the voltage across the secondary?

Answer: The voltage in secondary is one-sixth the voltage applied to the primary.

Example # 5: A transformer has 200 turns in the primary, 50 turns in the secondary, and 120 volts applied to the primary (E_p). What is the voltage across the secondary (E_s)?

Solution:

Np = 200 turns

Ns = 50 turns

Ep = 120 volts

Es =? Volts

$$Es = \frac{Ep * Ns}{Np}$$

$$Es = \frac{120 \text{ volts} \times 50 \text{ turns}}{200 \text{ turns}}$$

Es = 30 volts

Example # 6: There are 400 turns of wire in an iron-core coil. If this coil is to be used as the primary of a transformer, how many turns must be wound on the coil to form the secondary winding of the transformer to have a secondary voltage of one volt if the primary voltage is five volts?

Given :

Np = 400 turns

Vp = 5 volts

Vs = 1 volt

Ns = ? turns

Solution : $Vp\ Ns = Vs\ Np$

Transposing for Ns :

$$Ns = \frac{Vs\ Np}{Vp}$$

Substitution :

$$Ns = \frac{1 \text{ volt} \times 400 \text{ turns}}{5 \text{ volts}}$$

Ns = 80 turns

Note: The ratio of the voltage (5:1) is equal to the turns ratio (400:80). Sometimes, instead of specific values, you are given a turns or voltage ratio. In this case, you may assume any value for one of the voltages (or turns) and compute the other value from the ratio.

TURNS AND CURRENT RATIOS

The number of flux lines developed in a core is proportional to the magnetizing force (in Ampere-Turns) of the primary and secondary windings. The ampere-turn (I X N) is defined as the magnetomotive force developed by one ampere of current flowing in a coil of one turn. The flux which exists in the core of a transformer surrounds both the primary and secondary windings. Since the flux is the same for both windings, the ampere-turns in both the primary and secondary windings must be the same. Therefore:

$$N_P\ I_P = I_S\ N_S$$

Where Ip Np is ampere-turns in primary winding and Is Ns is ampere-turns in secondary winding.

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

Since

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

Then

$$\frac{V_P}{V_S} = \frac{I_S}{I_P}$$

Where

Vp: voltage applied to primary in volts

Vs: voltage across secondary in volts

Ip: current in primary in amperes

Is: current in secondary in amperes

Notice the equations show the current ratio to be the inverse of the turns ratio and the voltage ratio. This means, a transformer having less turns in the secondary than in the primary would step down the voltage, but would step up the current.

Example # 7: When operated at 120 V in the primary of an iron core transformer, the current in the primary is 4 amps. Find the current in the secondary if the voltage is stepped up to 500 V.

Solution:

$$\frac{V_P}{V_S} = \frac{I_S}{I_P}$$

Next, we solve for I_S.

$$I_S = \frac{V_P}{V_S} I_P$$

$$I_S = \frac{120}{500} \text{ 4 amps}$$

$$I_S = 0.96 \text{ amps}$$

Example # 8: A transformer with 480 turns on the primary and 60 turns on the secondary draws 0.6 amps from a 120 V line. Find secondary current.

Solution:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

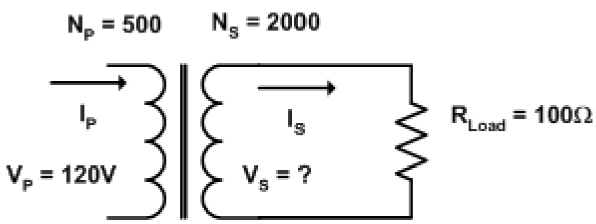
Next, we solve for I_S.

$$I_S = \frac{N_P}{N_S} I_P$$

$$I_S = \frac{480}{60} 0.6 \text{ amps}$$

$$I_S = 4.8 \text{ amps}$$

Example # 9: Calculate V_s, I_s and I_p for the transformer shown below.



Solution:

Calculation of V_s and I_S:

$V_S/V_P = N_S/N_P$

$V_S = (N_S/N_P) * V_P = 2000/500 * 120V = 480V$

$I_S = V_S/R_{Load} = 480 V/100 = 4.8A$

Calculation of I_p:

Using the power formula for an ideal transformer:

$P_p = P_s$

$V_P * I_P = V_S * I_S$

$I_P = (V_S * I_S)/V_P$

$I_P = (480V * 4.8A)/120V = 19.2A$

Example # 10: A transformer with a turns ratio of 1:12 has 3 amperes of current in the secondary. What is the value of current in the primary?

Solution:

Np = 1 turn (assumed)

Ns = 12 turns

Is = 3 A

Lp = ?

$$\frac{Np}{Ns} = \frac{Is}{Ip}$$

Transposing for Ip:

$$Ip = \frac{Is \times Ns}{Np}$$

$$Ip = \frac{12 \text{ turns} \times 3 \text{ A}}{1 \text{ turn}}$$

Ip = 36 A

POWER RELATIONSHIP BETWEEN PRIMARY & SECONDARY WINDINGS

The power and current ratios of a transformer are dependent on the fact that power delivered to the secondary is always equal to the power delivered to the primary minus the losses of the transformer. If voltage is doubled in the secondary, current is halved in the secondary. Conversely, if voltage is halved in the secondary, current is doubled in the secondary.

For an ideal transformer, the primary power; Pp is equal to the secondary power Ps, or the power input is equal to the power output.

For instance consider a transformer with the turns ratio of 20:1. If the input to the primary is 0.1 ampere at 300 volts, the power in the primary is P = V X I = 30 watts. If the transformer has no losses, 30 watts is delivered to the secondary. The secondary steps down the voltage to 15 volts (300/20) and steps up the current to 2 amperes (Is = 0.1 * 300/15). Thus, the power delivered to the load by the secondary is P = V X I = 15 volts X 2 amps = 30 watts.

The reason for this is that when the number of turns in the secondary is decreased, the opposition to the flow of the current is also decreased. Hence, more current will flow in the secondary. If the turns ratio of the transformer is increased to 1:2, the number of turns on the secondary is twice the number of turns on the primary. This means the opposition to current is doubled. Thus, voltage is doubled, but current is halved due to the increased opposition to current in the secondary. The important thing to remember is that *with the exception of the power consumed within the transformer, all power delivered to the primary by the source will be delivered to the load.* The form of the power may change, but the power in the secondary almost equals the power in the primary.

In practical transformers however, all power delivered by the source is delivered to the load by the secondary (minus whatever power is consumed by the transformer in the form of losses).

As a formula:

$Ps = Pp – P_L$

Where

Ps = power delivered to the load by the secondary

Pp = power delivered to the primary by the source

P_L = power losses in the transformer

Calculation of Primary Current (I_p) for a non-ideal transformer

A non-ideal transformer will have an efficiency rating of less than 100%. In this case,

$P_{Secondary} = P_{Primary}$ * (Efficiency Rating) or

$P_{out} = P_{in}$ * (Efficiency Rating)

Example # 11: Repeat the example 9 above for a transformer with an efficiency rating of 80%. What happens to the voltage?

$P_s = P_p$ * (Efficiency Rating)

$V_S * I_S = V_P * I_P * (.80)$

$V_S * I_S / (V_P * .80) = Ip$

I_P = (480V * 4.8A)/ (120V * .80) = 24 A

Additional current is drawn on the primary side of the transformer to make up for the power loss in the transformer.

Power losses in a non-ideal transformer:

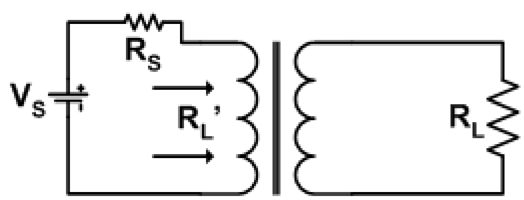
Winding resistance: The natural resistance of the windings of the transformer result in a loss in load voltage compared to the values predicted by the turns ratio formula for an ideal transformer. These are normally very small losses and do not significantly affect the transformer output.

Hysteresis losses are power losses due to the heating of ferrite and iron cores. Air cores are not affected by hysteresis losses.

Flux leakage: For an ideal transformer, the assumption is that all lines of flux are linked between the primary and secondary. In a real transformer, some of the magnetic lines of flux escape the core and pass through the surrounding air back to the other end of the winding. This causes reduced secondary voltage.

TRANSFORMERS USED FOR IMPEDANCE MATCHING

For maximum or optimum transfer of power between two circuits, it is necessary for the impedance (resistance and reactance) of one circuit to be matched to that of the other circuit. Transformers can be used for impedance matching. For instance, when the source resistance does not match the load resistance, a transformer can be used to convert the amount of load resistance that the source sees.



To obtain proper matching, you must use a transformer having the correct turns ratio. As a load is seen through a transformer, the value of the load resistance is changed by the value of the turns ratio of the transformer. The resistance that is seen from the primary can be calculated by using the power formula.

$P_{in} = P_{out}$

$V_P * I_P = V_S * I_S$

Substituting I = V/R, we obtain:

$V_P * (V_P/R_L') = V_S * (V_S/R_L)$

Where R_L' is the resistance seen on the primary side of the transformer.
Then,

$V_P^2/R_L' = V_S^2/R_L$

And, solving for R_L':

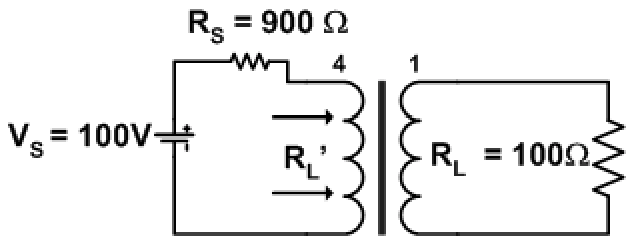
$R_L' = (V_P/V_S)^2 * R_L$

Replacing V_P/V_S by N_P/N_S results in:

$R_L' = (N_P/N_S)^2 * R_L$

An easy way to remember this formula is to note that the transferred resistance is proportional to the inverse of the turns ratio squared. Because of this ability to match impedances, the impedance-matching transformer is widely used in electronic equipment.

Example # 12: Determine the load resistance seen on the primary side of the transformer for the diagram below. Also, determine the ideal turns ratio needed to obtain maximum power delivered from the source to the load.



Solution

$R_L' = (N_P/N_S)^2 * R_L = (4/1)^2 * 100 = 1600$ ohms

For maximum power transfer $R_L' = R_{source} = 900$ ohms

$900 = (N_P/N_S)^2 * 100$

$(N_P/N_S)^2 = 900/100 = 9$

$N_P/N_S = 3$

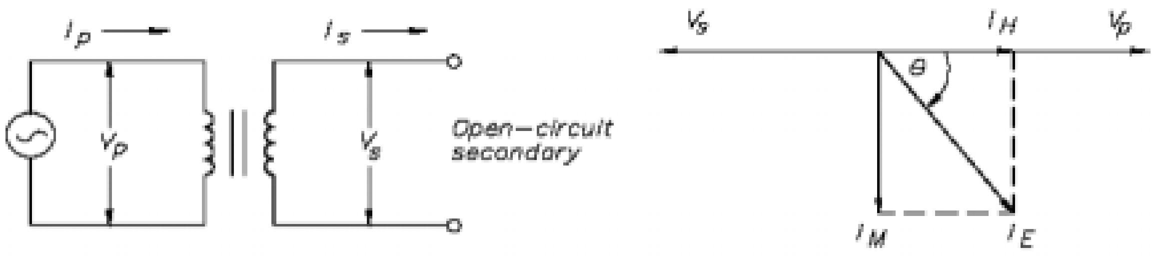
Therefore, a *turns ratio of 1:3* would produce a load resistance as seen from the primary side of the transformer of 900 ohms, which would equal the source resistance.

TRANSFORMER OPERATION UNDER NO-LOAD

A no-load condition is said to exist when a voltage is applied to the primary, but no load is connected to the secondary. When the secondary of a transformer is left open-circuited, no current flows through the secondary and a very small amount of current called "no load current" or "exciting current" flows in the primary. This very small amount of exciting current serves two functions:

1) Produce magnetic flux and maintain the magnetic field of the primary
2) Supplies the hysteresis and eddy current losses in the core i.e. overcome the resistance of the wire and core losses which are dissipated in the form of heat (power loss).

The no-load current (I_E) consists of two components: the magnetizing current (I_M) and the core loss (I_H). The core-loss current is a real-power component and is due to the core losses. The magnetizing current is in effect, the component of current that furnishes the mmf to overcome the magnetic reluctance of the core. Magnetizing current lags applied voltage by 90°, while core loss is in phase with the applied voltage. Fig (b) illustrates Vp and Vs as 180° out of phase. I_H is very small in comparison with I_M and I_M is nearly equal to I_E.



(a) No—load condition (b) Phasor diagram

The waveform of the exciting current is not sinusoidal. However, it is symmetrical; the exciting current can therefore be represented by a series of odd harmonics. Exciting current flows in the primary winding at all times to maintain this magnetic field, but no transfer of energy takes place as long as the secondary circuit is open.

Effect of a Load

When a load device is connected across the secondary winding, the current will start flowing through the secondary and the load. The magnetic field produced by the current in the secondary interacts with the magnetic field produced by the current in the primary. This interaction results from the mutual inductance between the primary and secondary windings.

PRIMARY & SECONDARY PHASE RELATIONSHIP

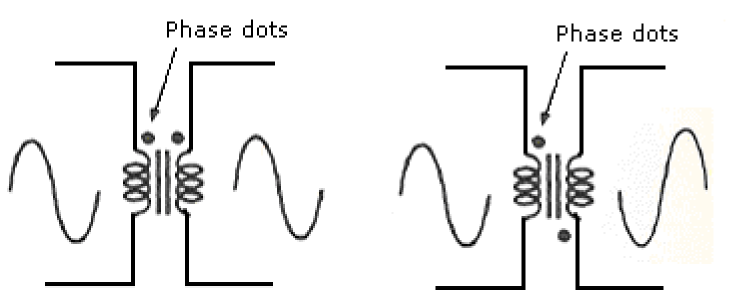
The secondary voltage of a simple transformer may be either in phase or out of phase with the primary voltage. This depends on the direction in which the windings are wound and the arrangement of the connections to the external circuit (load). Simply, this means that the two voltages may rise and fall together or one may rise while the other is falling.

Transformers in which the secondary voltage is in phase with the primary are referred to as “like-wound” transformers, while those in which the voltages are 180 degrees out of phase are called “unlike-wound” transformers.

Dots are used in diagrams of transformers to indicate the current polarities for the windings. Dotted terminals have the same polarity (points that are in phase).

The use of phase-indicating dots is illustrated in figure below. Figure (a) illustrates that both the primary and secondary windings are wound from top to bottom in a clockwise direction, as viewed from above the windings. When constructed in this manner, the top lead of the primary and the top lead of the secondary have the *same* polarity. This is indicated by the dots on the transformer symbol. A lack of phasing dots indicates a reversal of polarity.

Figure - Instantaneous polarity depends on direction of winding



Voltage are in Phase **(a)** Volatages are out of phase **(b)**

Figure (b) illustrates a transformer in which the primary and secondary are wound in opposite directions. The primary is wound in a clockwise direction from top to bottom, while the secondary is wound in a counterclockwise direction. Notice that the top leads of the primary and secondary have *opposite* polarities. This is indicated by the dots being placed on opposite ends of the transformer symbol. Thus, the polarity of the voltage at the terminals of the secondary of a transformer depends on the direction in which the secondary is wound with respect to the primary.

Note: transformer coils can be in phase, which means that the output voltage will follow the input voltage, or 180 degrees out of phase, which means that the output voltage from the secondary will move in the opposite direction from the input voltage of the primary.

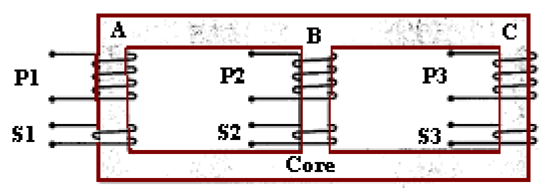
COEFFICIENT OF COUPLING

The Coefficient of Coupling of a transformer is dependent on the portion of the total flux lines that cuts both primary and secondary windings. The coefficient of coupling (K) of a transformer is dependent upon the size and shape of the coils, their relative positions, and the characteristic of the core between the two coils. An ideal transformer is one where all the magnetic lines of flux produced by the primary cut the entire secondary. The coefficient of coupling (K) would then be one (unity); the higher the K of the transformer, the higher is the transfer of the energy from the primary to the secondary. Practical power transformers use high-permeability silicon steel cores and close spacing between the windings to provide a high coefficient of coupling.

Lines of flux which do not link with the other winding are called 'leakage flux'. The leakage flux does not induce a voltage into the secondary and therefore the voltage induced into the secondary is less than it would be if the leakage flux did not exist. Since the effect of leakage flux is to lower the voltage induced into the secondary, the effect can be duplicated by assuming an inductor to be connected in series with the primary. This series "leakage inductance" is assumed to drop part of the applied voltage, leaving less voltage across the primary.

SINGLE & THREE PHASE TRANSFORMER

Up to this point, we have focused primarily upon single-phase transformers. Single-phase meaning (2) power lines as an input source; therefore, only (1) primary and (1) secondary winding is required to accomplish the voltage transformation. However, most power is distributed in the form of three-phase A.C. Therefore, before proceeding any further let's understand what is meant by three-phase power. In a three-phase transformer, there is a three-legged iron core as shown below. Each leg has a respective primary and secondary winding.



A basic 3-phase transformer consists of three sets of primary windings (P1, P2, P3), one for each phase, and three sets of secondary windings (S1, S2, S3) wound on the same iron core. Separate single-phase transformers can be used and externally interconnected to yield the same results as a 3-phase unit.

The primary windings are connected in one of several ways. The two most common configurations are the "Delta", in which the polarity end of one winding is connected to the non-polarity end of the next, and the "Wye", in which all three non-polarity (or polarity) ends are connected together. The secondary windings are connected similarly. This means that a 3-phase transformer can have its primary and secondary windings connected the same (delta-delta or wye-wye), or differently (delta-wye or wye-delta). It's important to remember that the secondary voltage waveforms are in phase with the primary waveforms when the primary and secondary windings are connected the same way. This condition is called “no phase shift.” But when the primary and secondary windings are connected differently, the secondary voltage waveforms will differ from the corresponding primary voltage waveforms by 30 electrical degrees. This is called a 30° phase shift. When two transformers are connected in parallel, their phase shifts must be identical; if not, a short circuit will occur when the transformers are energized.

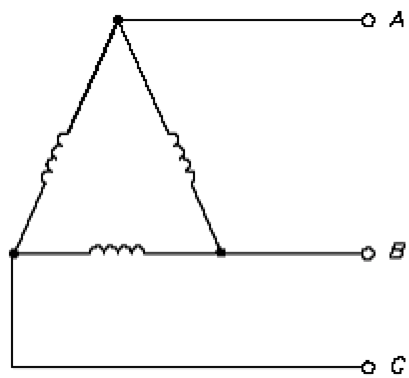
Three phase electricity powers large industrial loads more efficiently than single-phase electricity. When single-phase electricity is need, it is available between any two phases of a three-phase system, or in some systems, between one of the phases and ground. By the use of three conductors a three-phase system can provide 173% more power than the two conductors of a single-phase system. Three-phase power allows heavy duty industrial equipment to operate more smoothly and efficiently. Three-phase power can be transmitted over long distances with smaller conductor size.

THREE-PHASE TRANSFORMER CONNECTIONS

So far, our discussion has dealt with the operation of single-phase transformers. Three-phase transformer operation is identical except that three single-phase windings are used. These windings may be connected in wye, delta, or any combination of the two.

Delta (Δ) Connection

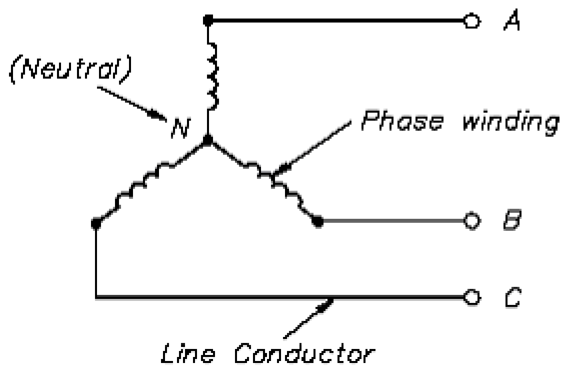
The delta connection is a standard three phase connection with the ends of each phase winding connected in series to form a closed loop with each phase 120 degrees from the other.



Delta Connection

Wye Connection

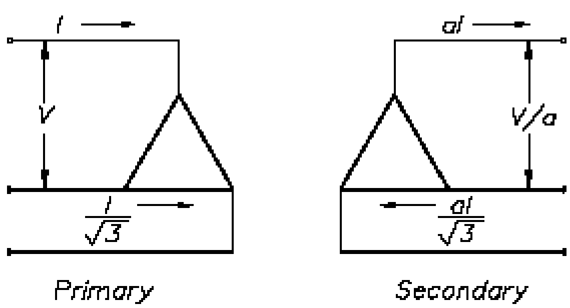
In the wye connection, three common ends of each phase are connected together at a common terminal (marked "N" for neutral), and the other three ends are connected to a three-phase line.



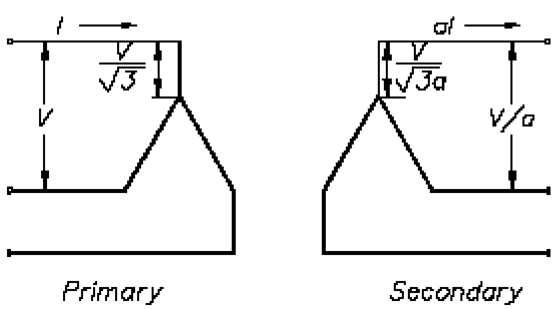
Wye Connection

Combinations of Delta and Wye (Δ-Y) Transformer Connections

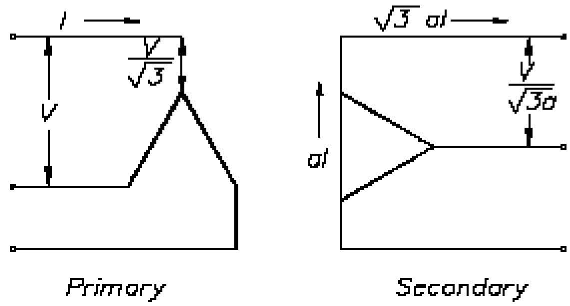
Delta Wye is a term indicating the primary connected in delta and the secondary in Wye when pertaining to a three phase transformer bank or three phase transformer. A three-phase transformer may have three separate but identical single-phase (1Ø) transformers or a single 3Ø unit containing three-phase windings. The transformer windings may be connected to form a 3Ø bank in any of four different ways.



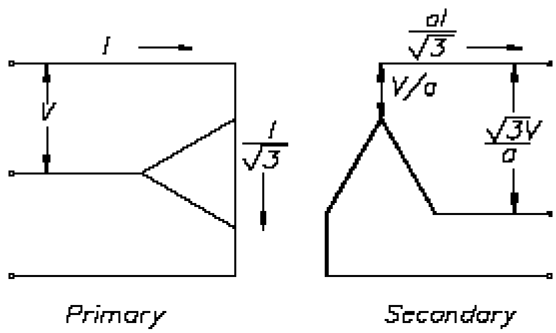
(a) Delta–to–delta (Δ-Δ)



(b) Wye–to–wye (Y–Y)



(c) Wye–to–delta (Y–Δ)



(d) Delta–to–wye (Δ –Y)

Figure above shows the voltages and currents in terms of applied line voltage (V) and line current (I), where the turn's ratio (a) is equal to one. Voltage and current ratings of the individual transformers depend on the connections and are indicated by Table below for convenience of calculations.

Voltage and Current Ratings of Transformers								
Transformer Connection (Primary to Secondary)	Primary				Secondary			
	Line		Phase		Line		Phase	
	Volt.	Current	Volt.	Current	Volt. *	Current	Volt.	Current
Δ-Δ	V	I	V	$\frac{I}{\sqrt{3}}$	$\frac{V}{a}$	aI	$\frac{V}{a}$	$\frac{aI}{\sqrt{3}}$
Y-Y	V	I	$\frac{V}{\sqrt{3}}$	I	$\frac{V}{a}$	aI	$\frac{V}{\sqrt{3}\,a}$	aI
Y-Δ	V	I	$\frac{V}{\sqrt{3}}$	I	$\frac{V}{\sqrt{3}\,a}$	$\sqrt{3}\,aI$	$\frac{V}{\sqrt{3}\,a}$	aI
Δ-Y	V	I	V	$\frac{I}{\sqrt{3}}$	$\frac{\sqrt{3}\,V}{a}$	$\frac{aI}{\sqrt{3}}$	$\frac{V}{a}$	$\frac{aI}{\sqrt{3}}$

*a = N_1/N_2; $\sqrt{3}$ = 1.73

Example 1:

If line voltage is 440 V to a 3Ø transformer bank, find the voltage across each primary winding for all four types of transformer connections.

Solution:

Δ-Δ:

V = 440 volts

Y-Y:

$$\frac{V}{\sqrt{3}} = \frac{440}{1.73} = 254.3 \text{ volts}$$

Y-Δ:

$$\frac{V}{\sqrt{3}} = \frac{440}{1.73} = 254.3 \text{ volts}$$

Δ-Y:

V = 440 volts

Example 2:

If line current is 10.4 A in a 3Ø transformer connection, find the primary phase current.

Solution:

Primary Phase Current

Δ-Δ:

$$\frac{I}{\sqrt{3}} = \frac{10.4}{1.73} = 6 \text{ amps}$$

Y-Y:

I = 10.4 amps

Y-Δ:

I = 10.4 amps

Δ-Y:

$$\frac{I}{\sqrt{3}} = \frac{10.4}{1.73} = 6 \text{ amps}$$

Example 3:

Find the secondary line current and phase current for each type of transformer connection, if primary line current is 20 amps, and the turns ratio is 4:1.

Solution

Δ-Δ:

Secondary line current = 4 * 20 = 80 amps

Secondary phase current:

$$\frac{aI}{\sqrt{3}} = \frac{4\ (20)}{1.73} = 46.2 \text{ amps}$$

Y-Y:

Secondary line current = 4 * 20 = 80 amps

Secondary phase current= 4 * 20 = 80 amps

Y-Δ:

Secondary line current:

$$\sqrt{3}\ aI = (1.73)(4)(20) = 138.4 \text{ amps}$$

Secondary phase current = 4 * 20 = 80 amps

Δ-Y:

Secondary line current:

$$\frac{aI}{\sqrt{3}} = \frac{4\ (20)}{1.73} = 46.2 \text{ amps}$$

Secondary phase current:

$$\frac{aI}{\sqrt{3}} = \frac{4\ (20)}{1.73} = 46.2 \text{ amps}$$

TRANSFORMER TYPES

Transformers are constructed so that their characteristics match the application for which they are intended. The differences in construction may involve the size of the windings or the relationship between the primary and secondary windings. Transformer types are also designated by the function the transformer serves in a circuit, such as an isolation transformer.

Distribution Transformer

Distribution transformers are generally used in electrical power distribution and transmission systems. This class of transformer has the highest power, or volt-ampere ratings and the highest continuous voltage rating. The power rating is normally determined by the type of cooling methods the transformer may use. Some commonly-used methods of cooling are by using oil or some other heat-conducting material. Ampere rating is increased in a distribution transformer by increasing the size of the primary and secondary windings; voltage ratings are increased by increasing the voltage rating of the insulation used in making the transformer.

General purpose distribution transformers are rated for 600 volts and below. They are either ventilated or totally enclosed, and are available in standard ratings from 250 VA up to 750 kVA.

Shielded Distribution Transformer

Often the distribution transformers provide a copper electrostatic shield between the primary and secondary windings. The shield is grounded and thus shunts most noise and transients to the ground path rather than passing them through to the secondary. Applications for shielded transformers are similar to electrical distribution (supplying appliance, lighting, motorized machine and power loads etc) and they are ideal for commercial or electrical installations where electronic circuitry operating at low voltage DC is present and is very sensitive to ‘noise’.

Power Transformer

Power transformers are used to supply voltages to the various circuits in electrical equipment. These transformers have two or more windings wound on a laminated iron core. The number of windings and the turns per winding depend upon the voltages that the transformer is to supply. Their coefficient of coupling is 0.95 or more.

You can usually distinguish between the high-voltage and low-voltage windings in a power transformer by measuring the resistance. The low-voltage winding usually carries the higher current and therefore has the larger diameter wire. This means that its resistance is less than the resistance of the high-voltage winding, which normally carries less current and therefore may be constructed of smaller diameter wire.

There are many types of power transformers. They range in size from the huge transformers weighing several tons-used in power substations of commercial power companies-to very small ones weighing as little as a few ounces-used in electronic equipment.

K-Factor Transformers

K-factor transformers are used as a general purpose transformer but are designed to withstand the variety of harmonics created in today's office and industrial environments. The expanding use of devices with switch mode power supplies and rectifier circuits with the subsequent wave distortion requires transformers to withstand the higher harmonics in the neutral conductor in the distribution system.

K-Factor is designed as a ratio between the additional losses created by the harmonics and the eddy losses at the rated 60 Hz. This factor is used to specify the size of the transformer to meet the magnitude of the harmonic load in the circuit.

A standard general purpose transformer does not have the shielding, conductor sizes, core cross-section, or the capacity in the neutral to provide the same service.

Control Transformer

A control transformer is an isolation transformer designed to provide a high degree of secondary voltage stability (regulation) during a brief period of overload condition (also referred to as "Inrush Current"). Control transformers are usually rated for 600 volts or less.

Control transformers are generally used in electronic circuits that require constant voltage or constant current with a low power or volt-amp rating. Various filtering devices, such as capacitors, are used to minimize the variations in the output. This results in a more constant voltage or current. Electronics or power transformers are sometimes considered to be those with ratings of 300 volt-amperes and below. These transformers normally provide power to the power supply of an electronic device, such as in power amplifiers in audio receivers.

Buck-Boost Transformers

Buck-Boost transformers are control transformers with low voltage secondary windings. By field connecting the primary and secondary windings in an autotransformer configuration, they offer an economical solution to the adjustment of line voltages that are slightly above or below normal.

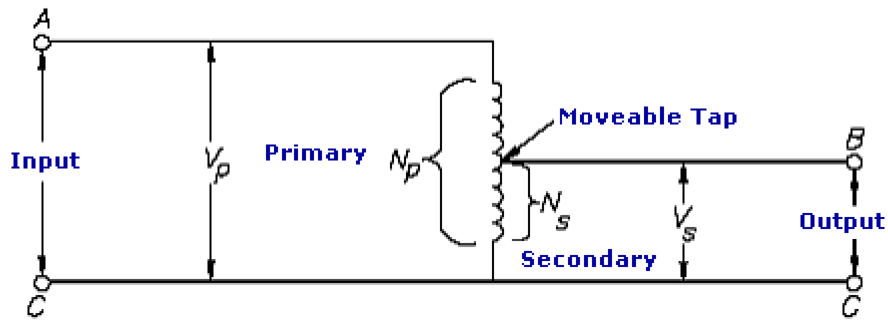
Buck-Boost transformers can be used to adjust stable voltages only.

Auto Transformer

It is not necessary in a transformer for the primary and secondary to be separate and distinct windings. An autotransformer has only a single winding, which by tapping or connecting at certain points along the winding, different voltages can be obtained. The movable tap in the secondary is used to select a value of output voltage, either higher or lower than V_p, within the range of the transformer. Autotransformers are used to compensate for voltage drop in a distribution system or for matching two transmission voltages, for example 115,000 V and 138,000 V. Autotransformers have considerably more MVA capacity per pound of core iron and winding conductor than standard power transformers, but are limited to small turns rations — ideally 2:1.

For voltage ratios, not exceeding about 3:1, an autotransformer is less costly,lighter, smaller and more efficient than a two-winding transformer of a similar rating.

The auto transformer is generally used in low power applications where a variable voltage is required. The auto transformer is a special type of power transformer. It consists of only one winding. *Variac* is a trademark of General Radio for a variable autotransformer intended to conveniently vary the output voltage for a steady AC input voltage. The term is often used to describe similar variable autotransformers made by other makers. A variable autotransformer is an efficient and quiet method for adjusting the voltage to incandescent lamps. While lightweight and compact semiconductor light dimmers have replaced variacs in many applications such as theatrical lighting, variable autotransformers are still used when an undistorted variable voltage sine wave is required.



AUTO TRANSFORMER SCHEMATIC

Primary Voltage Taps

In some cases, the actual supply voltage to the primary of the transformer is either slightly higher or lower than the nameplate rating. Taps are provided on most transformers on the primary winding to correct this condition and maintain full rated output voltage and capacity. Standard taps are usually in 2½% or 5% increments. Example: The transformer has a 480V primary rating and the incoming voltage is at 504V. The primary connection should be made at the +5% tap in order to maintain the nominal secondary voltage.

Motor Starting Transformers

Motors have a large inrush current component that requires a special design. Motor starting transformers are designed to withstand an inrush of upwards of 25 times normal current. They typically are tapped on larger sizes to soft-start the motor until it is up to full RPM.

Isolation Transformer

Isolation transformers are normally low power transformers used to isolate noise from or to ground electronic circuits. Since a transformer cannot pass DC voltage from primary to secondary, any DC voltage (such as noise) cannot be passed, and the transformer acts to isolate this noise.

Drive isolation transformers are designed to supply power to AC and DC variable speed drives. The harmonics created by SCR type drives requires careful designing to match the rated hp of each drive system. The duty cycle included is approximately one start every 2 hours. The windings are designed for an over current of 150% for 60 seconds, or 200% for 30 seconds.

Instrument Potential Transformer

The instrument potential transformer (PT) steps down voltage of a circuit to a low value that can be effectively and safely used for operation of instruments such as ammeters, voltmeters, watt meters, and relays used for various protective purposes.

Instrument Current Transformer

The instrument current transformer (CT) steps down the current of a circuit to a lower value and is used in the same types of equipment as a potential transformer. This is done by constructing the secondary coil consisting of many turns of wire, around the primary coil, which contains only a few turns of wire. In this manner, measurements of high values of current can be obtained.

A current transformer should always be short-circuited when not connected to an external load. Because the magnetic circuit of a current transformer is designed for low magnetizing current when under load, this large increase in magnetizing current will build up a large flux in the magnetic circuit and cause the transformer to act as a step-up transformer, inducing an excessively high voltage in the secondary when under no load.

Special transformers

Transformers can have more than two windings per phase. These designs help reduce fault current levels. Other transformers have been built to operate at relatively low voltages but extremely high currents. Arc furnace transformers fall into this category, and can have secondary current ratings in excess of 150,000A. Regulating transformers are designed to maintain their secondary voltage within specific limits as the primary voltage fluctuates. Transformers can also be built to shift phase a specified amount to control the flow of real power in a networked system.

Encapsulated Transformers for Harsh Locations

These units are encapsulated and completely enclosed. The encapsulated design is especially suited for installations in harsh environments where dust, lint, moisture and corrosive contaminants are present. Typical applications include: pulp and paper plants; steel mills; food processing plants; breweries; mines; marine and shipboard installations.

Audio Frequency Transformers

Audio-frequency (AF) transformers are used in AF circuits as coupling devices. Audio-frequency transformers are designed to operate at frequencies in the audio frequency spectrum (generally considered to be 15 Hz to 20 kHz).

They consist of a primary and a secondary winding wound on a laminated iron or steel core. Because these transformers are subjected to higher frequencies than are power transformers, special grades of steel such as silicon steel or special alloys of iron that have a very low hysteresis loss must be used for core material. These transformers usually have a greater number of turns in the secondary than in the primary; common step-up ratios being 1 to 2 or 1 to 4. With audio transformers the impedance of the primary and secondary windings is as important as the ratio of turns, since the transformer selected should have its impedance match the circuits to which it is connected.

Radio Frequency Transformers

Radio-frequency (RF) transformers are used to couple circuits to which frequencies above 20,000 Hz are applied. The windings are wound on a tube of nonmagnetic material, have a special powdered-iron core, or contain only air as the core material. In standard broadcast radio receivers, they operate in a frequency range of from 530 kHz to 1550 kHz. In a short-wave receiver, RF transformers are subjected to frequencies up to about 20 MHz - in radar, up to and even above 200 MHz.

Resonant transformers

A resonant transformer is one that operates at the resonant frequency of one or more of its coils. The resonant coil, usually the secondary, acts as an inductor and is connected in series with a capacitor. If the primary coil is driven by a periodic source of alternating current, such as a square or sawtooth wave, each pulse of current helps to build up an oscillation in the secondary coil. Due to resonance, a very high voltage can develop across the secondary, until it is limited by some process such as electrostatic breakdown. These devices are therefore used to generate high alternating voltages.

Energy Efficient Transformers

There is a growing movement in the electrical industry towards energy efficient products in all sectors including dry type transformers. In addition to the benefits to the environment, energy efficient transformers also can realize substantial savings in operating costs thereby having a direct impact on the initial investment evaluated over a period of time.

The specifications covering energy efficiency in transformers is the NEMA Standards Publication,

TP-1-1996, *"Guide for Determining Energy Efficiency for Distribution Transformers".* This specification has carefully considered the total owning cost unique for industrial or commercial installations where the load factor is an integral part of the efficiency rating.

The NEMA TP-1 guide lists minimum efficiencies based on transformer size, but has limitations. The most serious limitation of TP-1 is that it assumes a low load factor (35-50%), which critics say is not representative for industrial environments and is not recommended by manufacturers because of the waste of load capacity. The larger core results in higher losses. The TP-1 minimum standard may be properly applied to utilities and applications where the transformer loading is unknown or highly variable. For many industrial or large commercial applications, where loading is better defined, operating hours are long, or electricity costs are higher than the national average, selecting a transformer of higher efficiency and lower coil loss may be a better economic choice than the minimum standard.

Low Temperature Rise Transformers

All transformers have operating losses, and heat is the product of these losses. Low temperature rise transformers are designed with reduced 115°C or 80°C full load operating temperature rises. These units decrease total operating losses by 20% and 35% respectively, compared with the standard 150°C rise operating system. Hammond low temperature rise transformers provide greater efficiency under normal operating conditions, and overload capability without harm to their service life or reliability.

TRANSFORMER EFFICIENCY

Efficiency of a transformer is the ratio of the power output to the power input, as illustrated by equation.

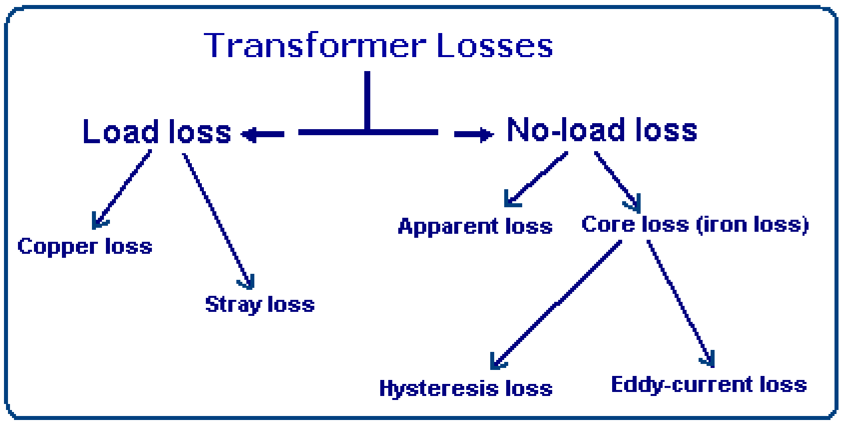
$$\text{Efficiency (\%)} = \frac{\text{Power Output}}{\text{Power Input}} \times 100$$

To compute the efficiency of a transformer, the input power to and the output power from the transformer must be known. The input power is equal to the product of the voltage applied to the primary and the current in the primary. The output power is equal to the product of the voltage across the secondary and the current in the secondary. In practice, real transformers are less than 100% efficient. The difference between the input power and the output power represents a power loss. The efficiency could also be expressed as

$$\text{Efficiency} = 1 - \frac{\text{Losses}}{\text{Input}}$$

TRANSFORMER LOSSES

Practical power transformers, although highly efficient, are not perfect devices. Small power transformers used in electrical equipment have an 80 to 90 percent efficiency range, while large, commercial transformers may have efficiencies exceeding 98 percent.



The total power loss in a transformer is a combination of three types of losses. One loss is due to winding resistance of the primary and secondary. This loss is called "copper loss" or I^2R loss. The two other losses are due to "eddy currents" and to "hysteresis" in the core of the transformer. Copper loss, eddy-current loss, and hysteresis loss result in undesirable conversion of electrical energy into heat energy.

The efficiency of a transformer can also be calculated using equations below:

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Output} + \text{Copper Loss} + \text{Core Loss}} \times 100$$

$$\text{Efficiency} = \frac{V_S\, I_S \times PF}{(V_S\, I_S \times PF) + \text{Copper Loss} + \text{Core Loss}} \times 100$$

Where

PF = power factor of the load

LOAD LOSS

The sum of copper losses and the stray losses is called the load losses, which for a given voltage and frequency is practically independent of the load.

Copper Loss

The copper losses are due to the resistance of the windings. Unless superconducting wires are used, there will always be power dissipated in the form of heat through the resistance of current-carrying conductors. Because transformers require such long lengths of wire, this loss can be a significant factor. Increasing the gauge of the winding wire is one way to minimize this loss, but only with substantial increases in cost, size, and weight.

Whenever current flows in a conductor, power is dissipated in the resistance of the conductor in the form of heat. The amount of power dissipated by the conductor is directly proportional to the resistance of the wire, and to the square of the current through it. Copper loss, in watts, can be found using equation:

$$\text{Copper Loss} = I_P^2 R_P + I_S^2 R_S$$

Where

Ip = primary current

Is = secondary current

Rp = primary winding resistance

Rs = secondary winding resistance

The resistance in turn varies with the resistivity, the conductor dimensions; and the temperature.

$$R = \frac{\rho \times l}{A}$$

Where

R = Winding resistance,

ρ = Resistivity in Ohms - mm^2/m

l = Length of conductor in meters

A = Area of cross section of the conductor, mm^2

In addition, these losses vary with winding temperature and thus will vary with the extent of loading and method of cooling. The winding resistance at a temperature T_L is given by the following equation.

$$R_L = R_0 \times \left(\frac{T_L + 235}{T_0 + 235} \right)$$

The constant 235 is for Copper; for Aluminum, use 225 and for Alloyed Aluminum use 227

Where

R_0 = Winding resistance at temperature T_0,

R_L = Winding resistance at temperature, T_L,

The greater the value of resistance or current, the greater is the power dissipated. The primary and secondary windings of a transformer are usually made of low-resistance copper wire. Copper loss can be minimized by using the proper diameter wire. Large diameter wire is required for high-current windings, whereas small diameter wire can be used for low-current windings.

Note that the term copper loss is used to indicate resistance losses of winding materials whether copper or aluminum is used.

Stray loss

The stray losses are largely due to eddy currents induced by the leakage fluxes in the tank and other parts of the structure. Two factors that contribute to losses (and other undesirable phenomena) are stray capacitance and leakage inductance. Stray capacitance inevitably exists between turns, between one winding and another, and between windings and the core. Usually this capacitance is of no concern in a power application, but small signal applications (especially those of high frequency) may not tolerate this quirk well. Also, the effect of having capacitance along with the windings' designed inductance gives transformers the ability to resonate at a particular frequency, definitely a design concern in signal applications where the applied frequency may reach this point (usually the resonant frequency of a power transformer is well beyond the frequency of the AC power it was designed to operate on).

Flux containment (making sure a transformer's magnetic flux doesn't escape so as to interfere with another device, and making sure other devices' magnetic flux is shielded from the transformer core) is another concern shared both by inductors and transformers. Closely related to the issue of flux containment is leakage inductance. Because leakage inductance is equivalent to an inductance connected in series with the transformer's winding, it manifests itself as series impedance with the load. Thus, the more current drawn by the load, the less voltage will be available at the secondary winding terminals.

NO- LOAD LOSS

No-load losses are mainly iron losses. The iron loss become important in cases where a lighting load is being supplied and in which the transformer itself remains excited, even though not actually supplying any load. It is also important in cases where a transformer is working on a low load factor.

Apparent loss

The loss that is due to the magnetizing current in the primary winding is called the apparent loss. The flow of the magnetizing current through the resistance of the winding does create a real I^2R loss and voltage drop, although both are generally quite small.

Core loss (Iron loss)

Resistive losses aside, the bulk of transformer power loss is due to magnetic effects in the core. Core losses are caused by two factors: hysteresis and eddy current losses. Hysteresis loss is that energy lost by reversing the magnetic field in the core as the magnetizing AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core.

Eddy Current Loss

Perhaps the most significant of these "core losses" is eddy-current loss, which is resistive power dissipation due to the passage of induced currents through the iron of the core. Because iron is a conductor of electricity as well as being an excellent "conductor" of magnetic flux, there will be currents induced in the iron just as there are currents induced in the secondary windings from the alternating magnetic field. These induced currents -- as described by the perpendicularity clause of Faraday's Law -- tend to circulate through the cross-section of the core perpendicularly to the primary winding turns. Their circular motion gives them their unusual name: like eddies in a stream of water that circulates rather than move in straight lines.

Iron is a fair conductor of electricity, but not as good as the copper or aluminum from which wire windings are typically made. Consequently, these "eddy currents" must overcome significant electrical resistance as they circulate through the core. In overcoming the resistance offered by the iron, they dissipate power in the form of heat. Hence, we have a source of inefficiency in the transformer that is difficult to eliminate.

Core loss occurs whenever the transformer is energized; core loss does not vary with load. The resulting circulating currents depend inversely upon the resistivity of the material and directly upon the thickness of the core. The losses per unit mass of core material thus vary with square of the flux density, frequency and thickness of the core laminations.

$$\text{Eddy Losses, } W_e = K_e \times B_m^2 \times f^2 \times t^2 \quad \text{Watts/Kg.}$$

Where

Ke = Eddy current constant

f = Frequency in Hertz.

Bm = Maximum flux density in Tesla

t = Thickness of lamination strips.

Hysteresis Loss

Another "core loss" is that of magnetic hysteresis. All ferromagnetic materials tend to retain some degree of magnetization after exposure to an external magnetic field. This tendency to stay magnetized is called "hysteresis," and it takes a certain investment in energy to overcome this opposition to change every time the magnetic field produced by the primary winding changes polarity (twice per AC cycle*). This type of loss can be mitigated through good core material selection (choosing a core alloy with low hysteresis), and designing the core for minimum flux density (large cross-sectional area).*

Transformer energy losses tend to worsen with increasing frequency. The skin effect within winding conductors reduces the available cross-sectional area for electron flow, thereby increasing effective resistance as the frequency goes up and creating more power lost through resistive dissipation. Magnetic core losses are also exaggerated with higher frequencies, eddy currents and hysteresis effects becoming more severe. For this reason, transformers of significant size are designed to operate efficiently in a limited range of frequencies. In most power distribution systems where the line frequency is very stable, one would think excessive frequency would never pose a problem. Unfortunately it does, in the form of harmonics created by nonlinear loads. In significant measure, they can cause severe transformer overheating. Power transformers can be engineered to handle certain levels of power system harmonics, and this capability is sometimes denoted with a "K factor" rating.

Hysteresis losses are proportional to the area of the hysteresis loop, volume of the iron core and the frequency of the flux in hertz.

ENERGY CONSERVATION MEASURES AT DESIGN STAGE

Reducing losses can increase transformer efficiency. As discussed above, there are two components that make up transformer losses. The first is "core" loss (also called no-load loss), which is the result of the magnetizing and de-magnetizing of the core during normal operation. The second component of loss is called “coil or load loss”, which is a function of the resistance of the winding materials and varies with the load on the transformer.

There are many ways to design more efficient transformers, some of them are:

1) Design to lower operating temperatures
2) Use lower loss magnetic materials
3) Use copper instead of aluminum
4) Improve core window fill factors
5) Minimize stray losses
6) Minimize coil temperature gradients (Hot-Spot)
7) Improved distribution of materials
8) Improvement in cooling medium and methods

Specifically the iron loss, copper loss and eddy loss can be reduced by:

1) **Minimizing Iron Losses**

   There are two important core materials used in transformer manufacturing 1) Amorphous metal and 2) CRGO. The evolution of materials used in transformer core is summarized below.

YEAR (approx.)	CORE MATERIAL	THICKNESS (mm)	Loss (W/kg at 50Hz)
1910	Warm rolled FeSi	0.35	2 (1.5T)
1950	Cold rolled CRGO	0.35	1 (1.5T)
1960	Cold rolled CRGO	0.3	0.9 (1.5T)
1965	Cold rolled CRGO	0.27	0.84 (1.5T)
1975	Amorphous metal	0.03	0.2 (1.3T)
1980	Cold rolled CRGO	0.23	0.75 (1.5T)
1985	Cold rolled CRGO	0.18	0.67 (1.5T)

It can be seen that losses in amorphous metal core is less than 25% of that in CRGO. This material gives high permeability and is available in very thin formations (like ribbons) resulting in much less core losses than CRGO. The trade off between these types is interesting. The use of higher flux densities in CRGO (up to 1.5 T) results in higher core losses; however, less amount of copper winding is required, as the volume of core is less. This reduces the copper losses. Amorphous iron is expensive but reduces core loss to less than 30% those of conventional steel cores. An alternative, less expensive core material is silicone steel, which has losses higher than amorphous iron, but less than standard carbon steel.

2) **Minimizing Copper losses**

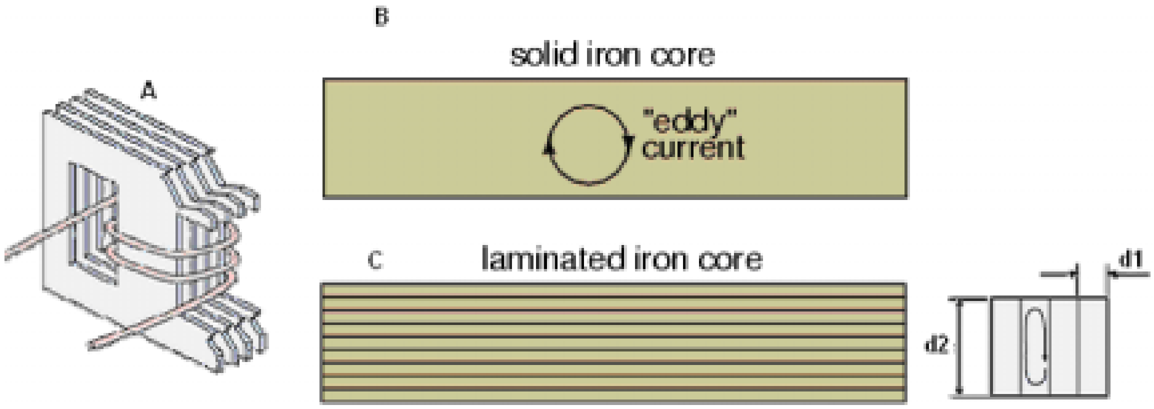
Copper losses (I^2R) can be reduced by using larger diameter wires of the conductor and using better resistive materials for winding.

However note that an arbitrary increase in thickness can increase eddy current losses. In general, decreasing radial thickness by sectionalization leads to reduction in eddy current losses. A properly configured coil winding is useful in this context. The designer has to take care of the proper buildup of turns with transposition and also take care of the mechanical strength to sustain short circuit in addition to needed insulation and surge voltage distribution.

The resistivity can also be made low by using copper instead of aluminum. Copper is a better electrical conductor than any other metal except silver. Electricity flowing through copper wires meets far less resistance than it does in aluminum or steel wires of the same diameter. Copper wires result in lower electrical losses, which appear as unwanted heat. Use of copper windings minimizes transformer full-load losses and may permit smaller cores, minimizing core (no-load) losses.

3) **Minimizing Eddy Current Losses**

Eddy current losses in the core can be reduced by laminating the core. Laminations reduce the area of circuits in the core, and so reduce the Faraday EMF, and so the current flowing in the core, and so the energy thus lost. The main strategy in mitigating these wasteful eddy currents in transformer cores is to form the iron core in sheets (laminations) covered with an insulating varnish so that the core is divided up into thin slices. The result is very little width in the core for eddy currents to circulate in. By using a laminated core, (thin sheets of silicon steel instead of a solid core) the path of the eddy current is broken up without increasing the reluctance of the magnetic circuit. Refer figure below for a comparison of solid iron core and a laminated iron core. Figure below shows a solid core, which is split up by laminations of thickness ‘d1’ and depth ‘d2’.



Core Lamination to reduce Eddy Current Losses

Laminated cores like the one shown here are standard in almost all low-frequency transformers. Eddy current losses increase with frequency, so transformers designed to run on higher-frequency power (such as 400 Hz, used in many military and aircraft applications) must use thinner laminations to keep the losses down to a respectable minimum. This has the undesirable effect of increasing the manufacturing cost of the transformer.

Another, similar technique for minimizing eddy current losses which works better for high-frequency applications is to make the core out of iron powder instead of thin iron sheets. Like the lamination sheets, these granules of iron are individually coated in an electrically insulating material, which makes the core nonconductive except for within the width of each granule. Powdered iron cores are often found in transformers handling radio-frequency currents.

All of the above approaches will not only raise the efficiency of transformers but also benefit in

- ✓ Reduced physical size (unit dimensions);
- ✓ Reduced transformer heating, hence lower need for additional cooling or insulation (hence reduced variable costs such as coolants, ageing insulation materials);
- ✓ Reduced noise levels;
- ✓ Longer insulation life;
- ✓ Low-loss transformers also better withstand electronic (harmonic) loads

Though it is true that the energy efficiency measures in design will raise the basic selling price of the transformer; note that it's not the first cost but the total cost of owning and operating a transformer that must be evaluated, since the unit will be in service for decades. The only proper method to evaluate alternatives is to request the manufacturer or bidder to supply the load and no-load losses, in watts. Then, simple multiplication can reveal anticipated losses at planned loading levels. Frequently, a small increase in purchase price will secure a unit with lower operating costs. For many applications, very short paybacks are possible.

TRANSFORMER LOSS MINIMIZATION IN APPLICATION & OPERATION

Transformers have a long life and do not generally suffer from technical obsolescence. The energy conservation measures do not end at the design stage; the energy conservation opportunities also exist in the field. The following key points are useful to the facility managers and the energy auditors.

1) **Energy saving by under-utilization of transformers**

The application details are not clearly known during selection as the load and the type of load change with time. Hence transformer rating is likely to be over-specified. However, this is generally not a disadvantage from the view point of energy consumption. The usual best efficiency point is near 50% load.

Table below summarizes the variation in losses and efficiency for a 1000 kVA transformer and also shows the difference in losses by using a 1600 kVA transformer for the same. The 1000 kVA transformer has a no load loss of 1700 watts and load loss of 10500 Watts at 100% load. The corresponding figures for 1600 kVA transformer are 2600 Watts and 17000 Watts respectively. Loading is by linear loads. Temperatures assumed equal.

Comparison of Transformer Losses

	1000 kVA, No load losses = 1700 W				1600 kVA. No load losses = 2600 W		Difference in losses, W
Per unit load	Load losses, W	Total losses, W	Output, kW	Efficiency, %	Load losses, W	Total losses, W	
0.1	105	1805	100	98.23	60	2660	861
0.2	420	2120	200	98.95	265	2865	745
0.3	945	2645	300	99.13	597	3197	552
0.4	1680	3380	400	99.16	1062	3662	282
0.5	2625	4325	500	99.14	1660	4267	-58
0.6	3780	5480	600	99.09	2390	4990	-490
0.7	5145	6845	700	99.03	3258	5853	-992
0.8	6720	8420	800	98.96	4250	6850	-1570
0.9	8505	10205	900	98.88	5379	7979	-2226
1.0	10500	12200	1000	98.78	6640	9240	-2960

The efficiency of 1000 kVA transformer is maximum at about 40% load. Using a 1600 kVA transformer cause under loading for 1000 kW loads. The last column shows the extra power loss due to oversized transformer. As expected, at light loads, there is extra loss due to dominance of no load losses. Beyond 50% load, there is saving which is 2.96 kW at 1000 kW load.

The saving by using a 1600 kVA transformer in place of a 1000 kVA transformer at 1000 kW load for 8760 hours/annum is 25960 kWh/year. This @ $ 0.1/kWh is worth $ 2596 per annum. The extra first cost would be around $ 50000; therefore deliberate over sizing may not be economically viable.

2) **Reduction of losses due to improvement of power factor**

Transformer load losses vary as square of current. Industrial power factor vary from 0.6 to 0.8. Thus the loads tend to draw 60% to 25% excess current due to poor power factor (PF). For the same kW load, current drawn is proportional to KW/PF. If PF is improved to unity at load end or transformer secondary, the saving in load losses is as under.

Saving in load losses = $(\text{Per unit loading as per kW})^2$ x Load losses at full load x $\{(1/PF)^2 - 1\}$

Thus, if PF is 0.8 and it is improved to unity, the saving will be 56.25% over existing level of load losses. This is a relatively simple opportunity to make the most of the existing transformer and it should not be missed. It should also be kept in mind that correction of PF downstream saves on cable losses, which may be almost twice in value compared to transformer losses.

3) **Balance Loading on Single and Three Phase Transformers**

A single phase transformer with 120/240V secondary has two separate 120V secondary windings and is usually connected into a 3 wire system. Care must be exercised in distributing the load on the two 120V windings evenly, so each winding is carrying about half of the total load.

Similarly for a three phase transformer, each phase should be considered as a single phase transformer. When distributing single phase loads between the three phases, each of the three windings should be evenly loaded.

4) **Segregation of nonlinear loads**

In new installations, non-linear loads should be segregated from linear loads. Apart from ease of separation and monitoring of harmonics, it can be supplied from a transformer which is specially designed for handling harmonics. The propagation of harmonics can be controlled much more easily and problems can be confined to known network. Perhaps a smaller than usual transformer will help in coordinating short circuit protection for network as well as active devices. The only disadvantage apart from additional cost is the increased interdependence of sensitive loads.

5) **Effect of operating temperature**

The losses have to be dissipated through the surface area. When the transformer volume increases, the ratio of surface area to volume reduces. Thus, larger transformers are difficult to cool. Oil cooling uses a liquid insulating medium for heat transfer. In cold countries the ambient temperature is lower, giving a lower operating temperature. In tropical countries, ambient temperature is higher giving a higher operating temperature.

Oil cooled transformers operate at lower temperatures compared to dry type transformers.

Every 1°C rise in operating temperature gives about 0.4% rise in load losses. A reference temperature of 75° C is selected for expressing the losses referred to a standard temperature. The operating temperature limit is decided by the type of insulation used and the difficulties of cooling. This gives an additional factor for comparing losses during design.

Higher temperature permits reduction in material content and first cost. Operating temperature beyond the limits prescribed for the insulation, reduces life expectancy materially.

6) **Core saturation or Avoid Overloading**

Transformers are constrained in their performance by the magnetic flux limitations of the core. For ferromagnetic core transformers, we must be mindful of the saturation limits of the core. Remember that ferromagnetic materials cannot support infinite magnetic flux densities: they tend to "saturate" at a certain level (dictated by the material and core dimensions), meaning that further increases in magnetic field force (mmf) do not result in proportional increases in magnetic field flux (Φ).

When a transformer's primary winding is overloaded from excessive applied voltage, the core flux may reach saturation levels during peak moments of the AC sine-wave cycle. If this happens, the voltage induced in the secondary winding will no longer match the wave-shape as the voltage powering the primary coil. In other words, the overloaded transformer will distort the wave shape from primary to secondary windings, creating harmonics in the secondary winding's output. The harmonic content in AC power systems typically causes problems.

TRANSFORMER RATINGS

Sizing distribution transformers to meet their expected loading greatly influences transformer efficiency. Greatly oversized transformers can contribute to inefficiency, but when transformers are appropriately matched to their loads, efficiency increases. Core losses continue whenever the transformer is energized; therefore, when the expected loading is variable or unknown, the size selection is a compromise between core loss and coil loss. The higher efficiency is associated with lower temperature rise (80°C vs. 150°C above ambient), but the temperature rise alone does not always guarantee a more efficient unit.

More than just the turns ratio, the voltage, current, and power-handling capabilities of the primary and secondary windings must also be considered in selection of transformers.

1) The maximum voltage that can safely be applied to any winding is determined by the type and thickness of the insulation used. When a better (and thicker) insulation is used between the windings, a higher maximum voltage can be applied to the windings.

2) The maximum current that can be carried by a transformer winding is determined by the diameter of the wire used for the winding. If current is excessive in a winding, a higher than ordinary amount of power will be dissipated by the winding in the form of heat. This heat may be sufficiently high to cause the insulation around the wire to break down. If this happens, the transformer may be permanently damaged.

3) The power-handling capacity of a transformer is dependent upon its ability to dissipate heat. If the heat can safely be removed, the power-handling capacity of the transformer can be increased. This is sometimes accomplished by immersing the transformer in oil, or by the use of cooling fins. The power-handling capacity of a transformer is measured in either the volt-ampere unit or the watt unit.

4) If the frequency applied to a transformer is increased, the inductive reactance of the windings is increased, causing a greater ac voltage drop across the windings and a lesser voltage drop across the load. However, an increase in the frequency applied to a transformer should not damage it. But, if the frequency applied to the transformer is decreased, the reactance of the windings is decreased and the current through the transformer winding is increased. If the decrease in frequency is enough, the resulting increase in current will damage the transformer. *For this reason a transformer may be used at frequencies above its normal operating frequency, but not below that frequency.*

SELECTION FEATURES

In general, selection of only one transformer of large rating gives maximum efficiency and simpler installation. For large plants with long in plant distances, two or more transformers of equal rating may be selected. Moreover for critical continuous operation plants, power may be had from two independent feeders at similar or different voltage levels. In all such cases, each transformer may be sufficient to run the plant. Thus normal operation may be at 50% load. Such a situation can lead to lower than 25% load at times. For non-continuous operation of plants with holidays or seasonal industries, switching off one transformer to save part load losses is generally considered.

1) Planning for growth of loads and addition of non linear loads is equally important. The factors to be considered are:
    - ✓ Expected growth of load over around five to ten years
    - ✓ Margin for minimum 15 to 20% growth
    - ✓ 10 to 15% margin for non-linear loads
    - ✓ Availability of standard rating

2) Generally, 30 to 50% excess capacity reduces load losses, but the extra first cost is rarely justified by energy saving alone. On the contrary, a close realistic estimate permits extra first cost on a smaller transformer designed on the basis of Least total ownership cost (TOC) basis.

3) For nonlinear loads, a transformer with minimum eddy losses in total load loss is preferred. Transformer losses may be specified at a standard reference temperature of 75° C. They

have to be corrected to expected site operating temperature. Basic I^2R losses increase with temperature, while eddy losses decrease with increase in temperature.

4) For nonlinear loads, the derating factor may be worked out taking a K-factor of 20. This will need derating of 12% for 10% nonlinear load to about 27% for 40% nonlinear load.

5) Transformers with relatively low no load losses (Amorphous Core Type) will maintain good efficiency at very low loads and will help in cases where high growth is expected, but risk of slow growth is to be minimized.

6) Transformers rated at 60Hz should not be used on a 50Hz supply due to higher losses and core saturation, and the resultant higher temperature rise. Transformers rated for 50Hz, however, can be operated on a 60Hz supply.

7) Sound needs to be considered when transformers are located in close proximity to occupied areas. All energized transformers emanate sound due to the alternating flux in the core. This normal sound emitted by the transformer can be a source of annoyance unless it is kept below acceptable levels.

ECONOMIC ANALYSIS

For any investment decision, the cost of capital has to be weighed against the cost/benefits accrued. Benefits may be in cash or kind, tangible or intangible and immediate or deferred. The benefits will have to be converted into their equivalent money value and deferred benefits have to be converted into their present worth in money value for a proper evaluation. Similarly, future expenses have to be accounted for.

The cost of capital is reckoned as the rate of interest; where as the purchasing power of the currency measured against commodities determines the relative value of money in a given economic domain. Thus interest rates increases value of capital where as inflation degrades the value of capital.

The deferred monetary gains/expenses are expressed in terms of their present worth (PW). If $

90.91 is invested at an annual interest of 10%, it will yield 90.91x (1+ 10/100) = $100/- at the end of one year. Hence the present worth of $100 after one year is $90.91/- , if the annual rate of interest is 10%.

$$PW = \frac{1-\left[\frac{1+a}{1+i}\right]^n}{i-a} \quad \text{where PW is present worth.}$$

a = per unit inflation index, annual

i = per unit interest rate

n = number of years

Purchase of a transformer involves first cost and subsequent payment of energy charges during a given period. The effective first cost or the total ownership cost can be had by adding the present worth of future energy charges. The Total Ownership Cost (TOC) adds an appropriate amount to account for energy expenses and shows a better measure of comparing equipment with higher first cost, but having a higher efficiency and thus lower running charges.

The concept of evaluation can be applied to transformers with the assumptions that the annual losses and the load level remain steady at an equivalent annual value, the tariff is constant and the rates of inflation and interest are constant. These assumptions have obvious limitations, but the TOC concept is widely used method for evaluation. The period of ‘n’ years may be 10 to 15 years. The longer the period, greater is the uncertainty. Generally, ‘n’ will be roughly equal to the economic life of the equipment governed by the technical obsolescence, physical life and perceptions of return of capital of the agency making the investment decision.

Total Ownership cost of transformers

TOC = Capital Cost + Cost of Core loss + Cost of Load loss

Cost of core loss = A X Core loss in Watts

Cost of Load loss = B X Load loss in Watts

Where

1) A = equivalent first cost of "no load losses", $/Watt

$$= \frac{PW \times EL \times HPY}{1000}$$

PW = Present worth, explained in previous Para

EL = Cost of electricity, $/kWh, to the owner of the transformer

HPY = Hours of operation per year

2) B = Equivalent first cost of load losses

$= A \times p^2 \times T$

p = Per Unit load on transformer

T = Temperature correction factor

Decisions for changeover to new equipment

In this case there is an added cost of the existing working equipment. The value left in a working equipment can be evaluated either by its technical worth, taking its left over life into consideration or by the economic evaluation by its depreciated value as per convenience. For transformers, the prediction of life is very difficult due to varying operating parameters. Moreover, for any equipment, there is a salvage value, which can be taken as equivalent immediate returns.

Thus TOC = (Present depreciated effective cost of old equipment – Salvage value) + A x Core loss + B x Load loss

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TRANSFORMER SAFETY

If transformers are being worked on or inspected, the following rules apply:

1) Remove the transformer from all power sources in the primary and secondary circuitry.
2) Remove all the fuses from the power source.
3) Trip circuit breakers and take action to prevent their accidental resetting.
4) Short out transformer secondary before connecting and disconnecting equipment.
5) To prevent potentially high voltage and current levels, always connect a load to the secondary side of the transformer before energizing the primary. The voltmeter is an excellent high-resistance load when connected with alligator clips.

SALIENT FEATURES- REVIEW

1) A transformer is a device made of two or more inductors, one of which is powered by AC, inducing an AC voltage across the second inductor. If the second inductor is connected to a

load, power will be electromagnetically coupled from the first inductor's power source to that load.

2) Direct current (DC) is not transformed, as DC does not vary its magnetic fields

3) The powered inductor in a transformer is called the primary winding. The un-powered inductor in a transformer is called the secondary winding.

4) The induction of an EMF in a coil by magnetic flux lines generated in another coil is called mutual induction. Mutual inductance is where the magnetic flux of two or more inductors is "linked" so that voltage is induced in one coil proportional to the rate-of-change of current in another.

5) Core flux induces a voltage in any coil wrapped around the core. The induced voltage is ideally in phase with the primary winding source voltage and share the same wave shape.

6) Any current drawn through the secondary winding by a load will be "reflected" to the primary winding and drawn from the voltage source, as if the source were directly powering a similar load.

7) Magnetic flux in the core (Φ) lags 90° behind the source voltage waveform. The current drawn by the primary coil from the source to produce this flux is called the magnetizing current, and it also lags the supply voltage by 90°.

8) Total primary current in an unloaded transformer is called the exciting current, and is comprised of magnetizing current plus any additional current necessary to overcome core losses. It is never perfectly sinusoidal in a real transformer, but may be made more so if the transformer is designed and operated so that magnetic flux density is kept to a minimum.

9) The ratio of turns of wire in the primary winding to the number of turns of wire in the secondary winding is termed turns ratio. If a turn ratio is given as 6:1, you can assume a number of turns for the primary and compute the secondary number of turns (60:10, 36:6, 30:5, etc.).

10) The total voltage induced into the secondary winding of a transformer is determined mainly by the ratio of the number of turns in the primary to the number of turns in the secondary and by the amount of voltage applied to the primary.

11) Transformers "step up" or "step down" voltage according to the ratios of primary to secondary wire turns. A transformer designed to increase voltage from primary to secondary is called a step-up transformer. A transformer designed to reduce voltage from primary to secondary is called a step-down transformer.

12) Transformers designed to provide electrical isolation without stepping voltage and current either up or down is called isolation transformers.

13) The dot convention is a type of polarity marking for transformer windings showing which end of the winding is which, relative to the other windings.

14) Transformers can be equipped with more than just a single primary and single secondary winding pair. This allows for multiple step-up and/or step-down ratios in the same device.

15) Transformer windings can also be "tapped:" that is, intersected at many points to segment a single winding into sections.

16) Variable transformers can be made by providing a movable arm that sweeps across the length of a winding, making contact with the winding at any point along its length. The winding, of course, has to be bare (no insulation) in the area where the arm sweeps.

17) An autotransformer is a single, tapped inductor coil used to step up or step down voltage like a transformer, except without providing electrical isolation.

18) Voltage regulation is the measure of how well a power transformer can maintain constant secondary voltage given a constant primary voltage and wide variance in load current. The

lower the percentage (closer to zero), the more stable the secondary voltage and the better the regulation it will provide.

19) A ferroresonant transformer is a special transformer designed to regulate voltage at a stable level despite wide variation in input voltage.

20) Transformers can be used to transform impedance as well as voltage and current. When this is done to improve power transfer to a load, it is called impedance matching.

21) The ratio between the primary and secondary impedances is referred to as the impedance ratio. The transformation ratio of a transformer will be equal to the square root of its primary to secondary inductance (L) ratio.

$$\text{Voltage transformation ratio} = \sqrt{\frac{L_{secondary}}{L_{primary}}}$$

22) A Potential Transformer (PT) is a special instrument transformer designed to provide a precise voltage step-down ratio for voltmeters measuring high power system voltages.

23) A Current Transformer (CT) is another special instrument transformer designed to step down the current through a power line to a safe level for an ammeter to measure.

24) An air-core transformer is one lacking a ferromagnetic core.

25) A Tesla Coil is a resonant, air-core, step-up transformer designed to produce very high AC voltages at high frequency.

26) In a delta connection, all three phases are connected in series to form a closed loop.

27) In a wye connection, three common ends of each phase are connected together at a common terminal, and the other three ends are connected to a three-phase line.

28) In a Δ connected transformer:

$$V_L = V\phi$$

$$I_L = \sqrt{3}\ I\phi$$

29) In a Y connected transformer:

$$I_L = \sqrt{3}\ V\phi$$

$$I_L = I\phi$$

30) Distribution transformers are generally used in power distribution and transmission systems.

31) Power transformers are used in electronic circuits and come in many different types and applications.

32) Control transformers are generally used in circuits that require constant voltage or constant current with a low power or volt-amp rating.

33) Auto transformers are generally used in low power applications where a variable voltage is required.

34) Isolation transformers are normally low power transformers used to isolate noise from or to ground electronic circuits.

35) Instrument potential and instrument current transformers are used for operation of instruments such as ammeters, voltmeters, watt meters, and relays used for various protective purposes.

36) The total power loss in a transformer is a combination of Copper loss and the Core loss (Hysteresis & the Eddy Current loss). Copper loss is due to the resistance of primary and secondary windings and is ~ I^2R loss. Hysteresis loss is energy lost by reversing the magnetic field in the core as the magnetizing AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core.

37) Copper losses (I^2R) can be reduced by using larger diameter wires of the conductor and using better resistive materials for winding.

38) Core loss occurs whenever the transformer is energized; core loss does not vary with load. To minimize the loss resulting from eddy currents; transformer cores are 'Laminated".

39) Hysteresis losses are proportional to the area of the hysteresis loop, volume of the iron core and the frequency of the flux in hertz. *Air cores are not affected by hysteresis losses.*

40) Every 1°C rise in operating temperature gives about 0.4% rise in load losses. A reference temperature of 75° C is selected for expressing the losses referred to a standard temperature.

41) Power transformers can be engineered to handle certain levels of power system harmonics, and this capability is sometimes denoted with a "K factor" rating.

42) The high voltage handling capacity of transformer is dependent on type and thickness of insulation, the current carrying capacity by diameter of winding wire and the power handling capacity by ability to dissipate heat.

43) If the frequency applied to a transformer is increased, the inductive reactance of the windings is increased, causing a greater ac voltage drop across the windings and a lesser voltage drop across the load. However, an increase in the frequency applied to a transformer should not damage it. But, if the frequency applied to the transformer is decreased, the reactance of the windings is decreased and the current through the transformer winding is increased. If the decrease in frequency is enough, the resulting increase in current will damage the transformer. For this reason transformers rated at 60Hz should not be used on a 50Hz supply; transformers rated for 50Hz, however, can be operated on a 60Hz supply.

Appendix - A

Transformer Terminology

1) **Air Cooled:** A transformer which uses "air" as the cooling medium. This term is abbreviated with the ANSI designation AA, indicating open, natural draft ventilated construction.

2) **Ambient Noise Level:** The noise level of the surrounding area, measured in decibels (dB).

3) **Ambient Temperature:** The inherent or existing temperature of the atmosphere surrounding a transformer into which its heat is dissipated.

4) **Ampere:** Is the unit of measurement for electric current flow.

5) **ANSI:** American National Standards Institute Inc. - one of the recognized organizations which specify the standards for transformers.

6) **Autotransformer:** A transformer which has only one winding per phase, part of which is common to both the primary and secondary circuits.

7) **Banked:** Two or more single phase transformers connected together to supply a three phase load.

8) **BIL:** Basic impulse level is a means to express the ability of the insulation system to withstand high voltage surges.

9) **Buck Boost Transformer:** Two-winding, single phase transformer with low voltage secondary windings which can be connected as an autotransformer. Used to raise or lower single and three phase line voltages by 10 - 20%.

10) **Cast Coil Transformer:** Transformer with coils solidly cast in epoxy resin under vacuum in a mold. Also called cast resin or epoxy cast coil transformers.

11) **Center Tap:** A reduced capacity tap at the midpoint in a winding

12) **Coil:** Turns of electrical grade wire or strip conductor material wound on a form, referred to as a winding.

13) **Coil Hot-Spot Temperature:** The absolute maximum temperature present in the transformer. This number is equal to the sum of the ambient temperature, temperature rise and a variable.

$T_{\text{Hot Spot}} = T_{\text{ambient}} + T_{\text{rise}} + (10\text{-}20)\ °C.$

14) **Common Mode:** Electrical noise or voltage disturbance that occurs between all of the line leads and the common ground, or between the ground plane and either line or the neutral.

15) **Compensated Transformer:** A transformer with a turns ratio, which provides a higher than rated voltage at no load and rated voltage at rated load. These transformers CANNOT be used for reverse feed.

16) **Continuous Rating:** The constant load which a transformer can carry its rated primary voltage and frequency, without exceeding its specified temperature rise.

17) **Control Transformer:** A transformer which is designed to supply good voltage regulation characteristics when low power factor or high inrush current is drawn.

18) **Core:** Electrical grade steel laminations which carry the Magnetic flux.

19) **Core Loss:** Losses in watts caused by magnetization of the core and its resistance to magnetic flux when excited or energized at rated voltage and frequency ;(also referred to as excitation loss or no-load loss).

20) **Current Transformer:** Transformer generally used in control or instrumentation circuits for measuring current.

21) **Delta (Δ):** The delta connection is a standard three phase connection with the ends of each phase winding connected in series to form a closed loop with each phase 120 degrees from the other.

22) **Delta Wye (Δ-Y):** Delta Wye is a term indicating the primary connected in delta and the secondary in wye when pertaining to a three phase transformer bank or three phase transformer.

23) **Dielectric Tests:** These tests consist of the application of a voltage higher than the rated voltage for a specified time, for the purpose of determining the adequacy against breakdowns of insulating materials and spacing under normal conditions.

24) **Dry Type Transformer:** A dry type transformer is one in which the transformer core and coils are not immersed in liquid.

25) **Dual Winding:** A winding consisting of two separate parts which can be connected in series or parallel. It is also referred to as dual voltage or series-multiple winding.

26) **Efficiency:** The percentage of power transferred from the input of equipment to the output of equipment in Watts. (Power out/power in x 100)

27) **Electrostatic Shield:** Copper or other conducting material placed between the primary and secondary winding and grounded to reduce electrical interference and to provide additional protection.

28) **Exciting Current (No-Load Current):** Current which flows in any winding used to excite the transformer when all other windings are open-circuited. It is usually expressed in percent of the rated current of a winding in which it is measured.

29) **Encapsulated:** Transformer with its coils either encased or cast in an epoxy resin or other encapsulating materials.

30) **FCAN:** Full Capacity above Normal. This designates that a transformer will deliver its rated kVA when connected to a voltage source which is higher than the rated voltage.

31) **FCBN:** Full Capacity below Normal. Same as FCAN except that the taps are below rated voltage.

32) **Fan Cooled:** A transformer cooled mechanically to maintain its rated temperature rise, typically using auxiliary fans to accelerate heat dissipation.

33) **Flexible Connection:** A non rigid connection used to reduce transmission of noise and vibration.

34) **Flux Density:** The magnetic field strength in the core, typically measured in Tesla or Gauss.

35) **Frequency:** On AC circuits, designates the number of times the polarity alternates from positive to negative and back again . . . such as 60 cycles per second; measured in Hertz.

36) **Full Capacity Tap:** A full capacity tap is one through which the transformer can deliver its rated kVA output without exceeding the specified temperature rise.

37) **Grounding Transformer:** A special three phase auto transformer for establishing a neutral on a 3-wire delta secondary; (It is also referred to as a Zig-Zag transformer).

38) **Grounds or Grounding:** Connecting one side of a circuit to the earth through low resistance or low impedance paths.

39) **Harmonic:** A Harmonic is a sinusoidal component of a periodic wave having a frequency that is a multiple of the fundamental frequency. For example, a component whose frequency is twice the fundamental frequency is referred to as the second harmonic, (120 Hz is the 2^{nd} harmonic of 60 Hz).

40) **Hertz (Hz):** A term for AC frequency in cycles per second.

41) **High Voltage and Low Voltage Windings:** These terms are used to distinguish the winding having the greater voltage rating from that having the lesser in two winding transformers.

42) **Hi Pot:** High potential dielectric test impressed on the windings to check insulation materials and clearances.

43) **Impedance:** The apparent resistance in a circuit to the flow of an alternating current analogous to the actual resistance to a direct current.

44) **Impulse Test:** Dielectric test which determines BIL capability by applying high frequency, steep wave-front voltage between windings and ground.

45) **Induced Potential Test:** A standard dielectric test which verifies the integrity of insulating materials and electrical clearances between turns and layers of a transformer winding.

46) **Inductance:** A property which opposes a change in current flow.

47) **Inrush Current:** Abnormally high transient current, caused by residual flux in the core, which maybe drawn when a transformer is energized.

48) **Insulating Materials:** Those materials used to electrically insulate the transformer's windings; turn to turn or layer to layer, and other assemblies in the transformer such as the core and busswork.

49) **Isolation Transformer:** A transformer which insulates the primary circuit from the secondary circuit. Also referred to as a two-winding or insulating transformer.

50) **KVA:** Kilovolt ampere rating designates the output which a transformer can deliver for a specified time at rated secondary voltage and rated frequency without exceeding the specified temperature rise. (1 kVA = 1000 VA, or 1000 volt amperes)

51) **Knockouts:** Easily removable circle of metal in an enclosure which eliminates the need for punching holes for conduit.

52) **Lamination:** Thin sheets of special steel used to make the core of a transformer.

53) **Line Reactor:** A device whose primary purpose is to introduce a specific amount of inductive reactance into a circuit, usually to reduce or control current.

54) **Load:** The load of a transformer is the power in kVA or volt amperes supplied by the transformer.

55) **Load Losses:** Losses in a transformer which is incident to load carrying. Load loses include I^2R loss in the windings due to load current, stray loss due to stray fluxes in the windings, core clamps, etc., and to circulating currents (if any), in parallel windings.

56) **Mid-tap:** A reduced capacity taps midway in a winding. Also referred to as a 'Center tap' and are usually provided in the secondary winding.

57) **Moisture Resistance:** Materials or equipment constructed or treated so that it will not be harmed readily by exposure to a moist atmosphere.

58) **NEC:** National Electric Code

59) **NEMA:** National Electrical Manufacturers Association.

60) **No-Load Losses (Excitation Losses):** Loss in a transformer which is excited at rated voltage and frequency, but without a load connected to the secondary. No-load losses include core loss, dielectric loss, and copper loss in the winding due to exciting current.

61) **Overload:** When a transformer is overloaded, excessive heat develops and the insulation system begins to breakdown. Life expectancy of the transformer is decreased due to heat exceeding the rating of the insulation system.

62) **Parallel Operation:** Single and three phase transformers may be operated in parallel by connecting similarly marked terminals, provided their ratios, voltages, resistances, reactance's and ground connections are designed to permit parallel operation. Current and voltage angular displacements are also required to be the same in the case of three phase transformers.

63) **Phase:** Type of AC electrical circuit, usually single phase 2-wire or 3-wire, or three phases, 3 or 4 wires.

64) **Polarity:** Designates the instantaneous direction of voltages in the primary compared to the secondary.

65) **Potential (Voltage) Transformer:** A transformer generally used in instrumentation circuits for measuring or controlling voltage.

66) **Power Factor:** The relation of watts to volt amps in a circuit.

67) **Primary Taps:** Taps added to the primary winding.

68) **Primary Voltage Rating:** Designates the input circuit voltage for which the primary winding is designed.

69) **Primary Winding:** The primary winding is the winding on the energy input (supply) side.

70) **Rating:** The design characteristics, such as primary and secondary voltage, kVA capacity, temperature rise, frequency, etc.

71) **Ratio (Voltage):** A reference to either the primary to secondary winding turns ratio or to the voltage ratio of the transformer.

72) **Ratio Test:** A standard test of transformers to determine the ratio of the primary to secondary voltage.

73) **Reactance:** The impedance component due to inductance and/or capacitance.

74) **Reactor:** A single winding device with an air or iron core which produces a specific amount of inductive reactance into a circuit, usually to reduce or control current.

75) **Rectifier Transformer:** A transformer designed to supply AC input to a rectifier to obtain the desired DC output and have the ability to withstand the heating effects caused by rectifier commutation or ripple.

76) **RCBN - Reduced Capacity below Normal:** Taps which carry full-rated winding current only, thus reducing available power because of lower output voltage.

77) **Regulation:** Usually expressed as the percent change output voltage when the load goes from full load to no load at a given power factor.

78) **SCR:** A silicon-controlled rectifier.

79) **Saturation:** Saturation is a natural condition in which an increase in current results in a decrease in inductance.

80) **Scott Connection:** Connection for polyphase using two special single phase transformers. Usually used to change from two phase to three phase or three phase to two phase.

81) **Secondary Voltage Rating:** Designates the no-load circuit voltage for which the secondary winding (winding on the output side) is designed.

82) **Secondary Winding:** The transformer winding connected to the load or output side.

83) **Series/Multiple:** A winding consisting of two or more sections which can be connected for series operation or multiple (parallel) operations; (Also referred to as dual voltage or series parallel).

84) **Short Circuit:** A short circuit condition occurs when an abnormal connection or relatively low impedance, whether made accidentally or intentionally, occurs between to points of different potential in a circuit.

85) **Solid State Device:** One which contains components that do not depend on electronic conduction in a vacuum or gas. The electrical function is performed by semiconductors or the use of otherwise completely static components such as resistors or capacitors.

86) **Step-Down Transformer:** One in which the high voltage winding (primary) is connected to the input or power source and the low voltage winding (secondary) to the output or load.

87) **Step-Up Transformer:** A transformer in which the low voltage winding (secondary) is connected to the input or power source and the high voltage winding (primary) is connected to the output or load.

88) **Tap:** A tap is a connection brought out of a winding at some point between its extremities, usually to permit changing the voltage or current ratio.

89) **T-Connection:** A Scott connected three phase transformer utilizing two primary and two secondary coils called the main and the teaser.

90) **Temperature Class:** Is the maximum temperature that the insulation can continuously withstand. Class of insulation system in a transformer, i.e.

- Class 105°C
- Class 150°C
- Class 180°C
- Class 220°C

91) **Temperature Rise:** The increase over ambient temperature of the winding due to energizing and loading the transformer.

92) **Total Losses:** The transformer electrical losses which include no-load losses (core losses) and load losses (winding losses).

93) **Transformer:** A static electrical device which by electromagnetic induction transforms energy at one voltage and current to another voltage and current at the same frequency.

94) **Transient:** A temporary or brief change in a given parameter. This is typically associated with input voltage or output load parameters.

95) **Transformer Tests:** Normal, routine production tests include: (1) core loss; (2) load loss - winding or copper loss; (3) impedance; (4) hi-pot - high voltage between windings and ground; (5) induced - double induced two times voltage. Optional special tests include: (a) heat run - temperature testing; (b) noise tests - sound level measurement; (c) impulse tests - BIL tests: (d) partial discharge.

96) **Transverse Mode:** Electrical noise or voltage disturbance that occurs between phase and neutral (between lines), or from spurious signals across the metallic hot line and the neutral conductor.

97) **UL:** Underwriters Laboratories

98) **VPI Impregnation:** A vacuum and pressure impregnation process using a resin which is then oven cured to completely seal and protect the surface of a transformer and provides a strong mechanical bond.

99) **Voltage Regulation:** The change in secondary voltage which occurs when the load is reduced from rated value to zero, with the value of all other quantities remaining unchanged. Regulation may be expressed in percent (per unit) on the basis of rated secondary voltage at full load.

100) **Volt-Amperes (VA):** The current flowing in a circuit multiplied by the voltage of the circuit. An expression of the output rating of a transformer.

101) **Wye Connection:** A standard 3-wire transformer connection with similar ends of the single phase coils connected. This common point forms the electrical neutral point and may be grounded.

102) **Zig Zag Connection:** Special transformer connection commonly used in grounded transformers.