

**Practical Power Transformers:
Operation, Maintenance and Testing**

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Practical
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Revision 7

Website: www.idc-online.com

E-mail: idc@idc-online.com

IDC Technologies Pty Ltd
PO Box 1093, West Perth, Western Australia 6872
Offices in Australia, New Zealand, Singapore, United Kingdom, India, Ireland, Malaysia, Poland, United States of America, Canada, South Africa and Vietnam.

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Introduction

1.1 Why transformers?

In today's world, the bulk of electrical power is generated in the form of AC using generators whether thermal, hydro, and nuclear or gas. However due to equipment sizing, insulation requirements, etc., the generating voltage in the present day power stations is limited in the order of 15 to 25 kV though the power generated is in hundreds of mega watts. It is impractical to distribute this much power at the generated voltage due to the magnitudes of currents, which are in the order of about 1000 amps for every 25 MVA at 15 kV.

If such high currents are to be transmitted over long distances, it will be necessary to overcome the following:

- The total power loss in a transmission/distribution system is proportional to I^2Z where I is the magnitude of current and Z is the impedance of the transmission/distribution system. The larger the current transferred, the larger will be the power loss and lower the transmission efficiency.
- The cross section of conductors required would increase as the value of current increases and it is impractical to install heavy conductors across a country to carry and transmit higher currents to remote parts.
- The voltage drop in a distribution system is proportional to $I \times Z$ and it is necessary to keep the value of I as low as possible to limit the voltage drops (since the value of Z cannot be reduced very much).

All the above factors necessitate that the transmission current is reduced as much as possible, which is achievable only by increasing the transmission voltage. A transformer is the answer to the above issues and today's AC distribution cannot be what it is without the use of transformers.

A transformer is an essential device in any Electrical AC power distribution system, which is used to convert (transform) AC voltage magnitudes of any value obtained from a power source to any desired value. The development of power transformers dates back to the 19th Century. The main feature of a transformer is its constant VA rating whether referred to its primary or secondary side. With VA being constant (V refers to the voltage magnitude and A refers to the current magnitude in a transformer winding), it is just possible to get a higher V with lower A OR a lower V with a higher A , by choosing suitable turns ratio for the transformer windings.

It is to be noted that the transformers can be used only for changing the magnitudes of AC voltages. They cannot be used for varying DC voltages, without converting them to AC voltages.

1.2 About this manual

To make the full use of transformers it is necessary that a basic knowledge on the following is a must:

- Theory of transformers.
- Terminal markings and connection methods.
- Construction of a transformer and its parts
- Types of transformers based on application
- Test requirements
- Installation practices to be followed.
- Proper operation and maintenance to ensure continuous service.
- Protecting the transformers while in service to keep outages to a minimum.

1.2.1 Theory of transformers

Though the operation of a transformer may look simple, it is necessary to understand the basic functioning of a transformer and its components. The basic theory of transformers is mainly related to elementary electricity, magnetism and the magnetic properties of materials, behavior with different types of loads, and factors defining a transformer (such as its impedance, regulation, losses, efficiency, etc.).

1.2.2 Terminal markings and connections

Depending upon the method of connections inside a transformer, there are appreciable differences in the output phase voltages and currents with respect to the main source. It is necessary to know the method of connections employed inside transformer windings, so that there is a clear understanding on transformer output and protections to be employed. It is internationally common practice to identify transformer connections by simple letters and also to show them in the nameplate. A section covering the connection methods and their identification is covered in this manual.

1.2.3 Construction of Transformers

A transformer basically comprises of a primary and a secondary winding with a magnetic core and is normally represented as per Figure 1.1. The study of transformer construction basically covers its windings, insulation, core materials, duty/application/type, standard/special accessories, etc. For example, it is necessary to keep the losses in a transformer to a minimum to ensure that the major portion of the power transferred is not dissipated in the transformer itself. Hence knowledge of the core and its construction is required and is covered in this manual.

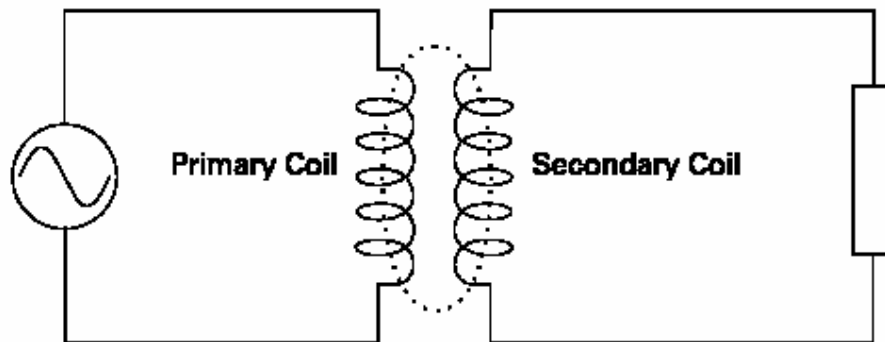


Figure 1.1
Typical connection of a transformer

1.2.4 Types of Transformers

Though the basic principle of transformers is one, the applications which employ these transformers have different requirements based on the load requirements such as furnace loads, step up transformers, autotransformers, etc. The actual application could demand either a simple two winding single-phase transformer stepping up or stepping down the available voltage or it could also cover multiple winding three-phase transformers with some specific requirements to overcome harmonics, etc. The insulation could also be different. A small chapter is devoted to the types of transformers.

1.2.5 Testing Requirements

Before a transformer is accepted for installation or put in service after receipt at a site, it is necessary to ensure that it meets the basic functions/requirements expected of it. International standards are available which give the standard tests that are to be conducted on a transformer at various stages. The standards also differ region wise depending upon the developments in that region and local regulations. A section of this manual will cover the tests normally conducted on transformers and also briefly cover the comparison between IEC and NEMA standards. These are mostly referenced transformer standards.

1.2.6 Installation Practices

A transformer needs to be installed at the right place to meet its objectives and it is vital that the best installation practices are followed while locating and erecting them. This could be related to safe clearances to be provided between transformers and other equipment, safety clearances to be maintained from live parts to the ground/operating personnel, cabling practices, provisions to drain out the oil to safe places during critical situations, etc. A part of this manual briefly covers the various guidelines to be followed for installing a transformer.

1.2.7 Operation and maintenance

The proper operation of a transformer is achieved by following good maintenance practices to keep the transformer and its components healthy and functional throughout its life. For example, it is very necessary to keep the insulation properties of a transformer almost constant to avoid internal and external flashovers, which are the major causes of transformer breakdowns. This manual will also briefly cover the best maintenance practices to be followed to keep the transformer healthy throughout its life.

1.2.8 Protection

The transformers shall be protected against possible failures due to external and internal faults. This is possible by having an understanding on the types of faults likely to occur and providing monitoring devices which continuously oversee the functioning of the transformers (like its voltage/current parameters through relays), the condition of its internal parts like oil (pressure, level, temperatures), windings (temperature), etc. These devices warn before any major failure of transformer occurs. A section of this manual covers a brief study and practices related to the protection of transformers.

Transformer Theory

2.1 Alternating Current System

The most common power generators in power stations generate AC voltages, which follow sinusoidal waveforms alternating between positive and negative value around a zero axis. In simple terms, if V_p is the maximum voltage attained at a generator terminal then normally $-V_p$ is the minimum voltage attained at the same point, both with respect to zero in one complete cycle. The magnitude of voltage V at a point/terminal at any time t alternating at a frequency ' f ' cycles/second, can be mathematically expressed as

$$V = V_p \sin(2\pi \times f \times t) \quad \dots\dots\dots (2.1)$$

This follows the curve as shown in Figure 2.1. Vectorially the position of V at any time ' t ' can be indicated as per Figure 2.1, changing from 0 to 360° around a reference point. The magnitude V at 0° is Zero, rises to $+V_p$ at 90°, goes down in magnitude to reach Zero at 180°, reaching a negative peak at 270° position and again becoming zero to go over the cycle repeatedly. On a time scale 0° corresponds to $t=0$, 90° corresponds to $t = 1/4f$, 180° corresponds to $t = 1/2f$, 360° corresponds to $t = 1/f$, 720° corresponds to $t = 2/f$ and so on where f is the frequency in cycles/second. The magnitude of V will be arrived at by using the formula above.

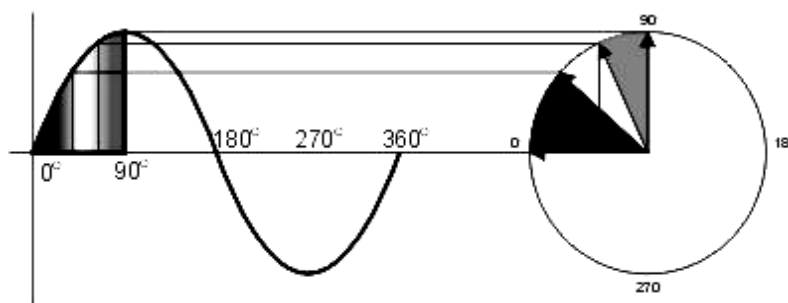


Figure 2.1
Typical AC sinusoidal wave form

The above waveform of voltage/current is normally referred to as AC voltage and AC current in Electrical Distribution.

The above-generated voltage is normally applied to a circuit, which can be represented as in Figure 2.2. Any standard inductive circuit can be normally represented with parameters called resistance R and inductance L , which are basically the measure of resistance offered by the circuit preventing/limiting the flow of current. The L is generally expressed as X when converted to the most common unit Ohm.

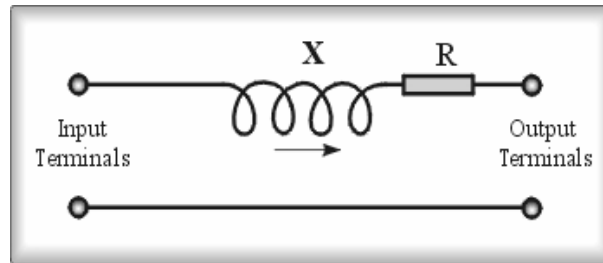


Figure 2.2
Typical Standard Electrical Circuit

As per Ohm's law, the magnitude of the resultant current also follows the same sinusoidal waveform except that its magnitude is based on the impedance Z of the circuit. Due to the inductive nature of the circuit the resultant current in the conductor will lag the applied voltage by an angle Φ . The instantaneous positions of voltage and current in relation to each other can be vectorially indicated as per Figure 2.3, with both V and I rotating 360° for each completed cycle.

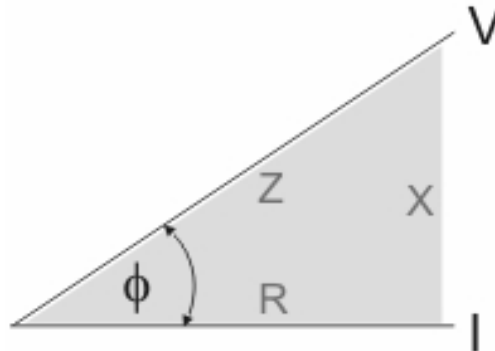


Figure 2.3
Typical Voltage and Current for an inductive circuit

Most of the time waveforms may not be purely sinusoidal, since they depend on system conditions and parameters but definitely follow alternating cycles at the generated frequency.

2.2 Electricity and magnetism

In the late 19th century, Orsted accidentally found that when a magnet is brought near a current carrying conductor, it gets deflected. The basic reason for this is that the electricity in the conductor produces a magnetic field in its vicinity and drops off when the electric source is removed.

It is known that the atoms of all basic elements have some charge in the form of electrons, which exhibit a magnetic field around each atom. However it had been found that not all matter in the universe creates magnetic fields around their atoms though all atoms consist of electrons.

It had been discovered that the atomic configuration of the materials is responsible for their magnetic characteristics. All matter can be either termed 'magnetic' or 'non-magnetic' depending upon its atomic configuration and its ability to retain/create magnetic fields. Magnetic materials have their magnetic fields aligned in a particular direction so that they have a cumulative magnetic property, which can be confirmed through experiments. However in non-magnetic materials, the arrangement of electrons is such that the magnetic fields get cancelled. The net effect is that they do not have the capacity to retain/produce magnetic fields when they are in the vicinity of electric currents.

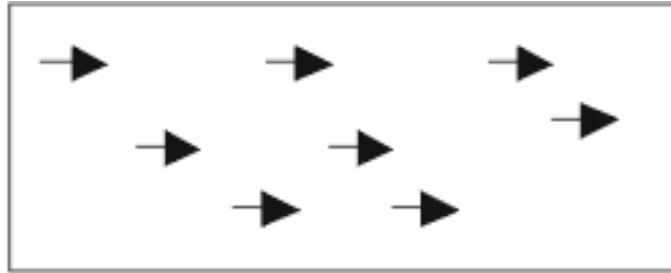


Figure 2.4
Typical magnetic fields in a permanent magnet

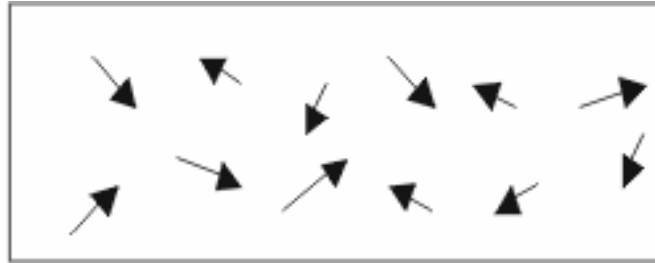


Figure 2.5
Typical magnetic fields in a non-magnetic material

The magnetic materials can be classified further as Permanent and Ferro Magnetic. A permanent magnet will have its magnetic fields aligned in one direction and hence always exhibits the magnetic property irrespective of any external source. On the other hand, ferro-magnetic materials have the magnetic fields of individual atoms aligned in one direction but the orientation of a domain is random. Hence they do not show magnetic properties under normal conditions. When an external magnetic field is applied to them (through an electric source), the magnetic fields of the individual domains tend to line up in the direction of this external field, which causes the external magnetic field to be enhanced.

This property of magnetic materials is important in building up the core of a transformer, which is the path of magnetic flux as will be seen in this chapter. It is necessary that the core of a transformer be built with magnetic material.

2.3 Electro-magnetic induction

In the previous clause it is noted that external electric force is required to produce a magnetic field. In a similar way it is possible to use the magnetic field to produce an electrical force when the magnetic flux is in the vicinity of a good conductor. This is basically called the emf (electromotive force) induced in the conductor due to an external magnetic field.

Induced emf can be further classified as dynamically induced emf and statically induced emf. Dynamically induced emf basically refers to the potential force induced in a moving conductor located within the vicinity of a strong magnetic field. This is the fundamental principle of

generators where a prime mover is used to rotate the armature rotor surrounded by a magnetic field.

The other type, statically induced emf, refers to the voltage induced in a static conductor where a magnetic flux is allowed to pass through its vicinity. This statically induced emf can be further classified as mutually induced emf and self-induced emf. Mutually induced emf is the voltage induced in a static conductor when an external magnetic flux produced by another coil cuts through it. Self-induced emf is the emf induced in a conductor when a magnetic flux produced by the current flowing through it varies.

The above self-induction is the basic action in a transformer. If a coil with N turns carries a current I , it produces a flux which is normally identified by Φ and the unit of flux is Weber. Multiplying the flux density (Normal unit B) and the cross section area (A) gives the value of flux (Φ). The unit of B is indicated in tesla and one weber of flux is obtained when one tesla is linked with a cross sectional area of one square metre. Alternatively 1 tesla is equal to 1 weber per square metre.

The coefficient of self-induction in a coil is identified by the symbol L that is by definition 'the Weber-turns per ampere' in the coil.

$$\text{i.e.} \quad L = \frac{N\Phi}{I} \dots\dots\dots (2.2)$$

The basic unit of L is expressed in Henry and 1 Henry is obtained when 1 weber links 1 turn of a coil for each ampere flowing. The value of L increases proportionately as the value of any of the above three figures increases.

Mutual inductance is also expressed in the same way except that the current is flowing in the other coil. Consider two coils, where the magnetic flux Φ_1 is produced by the current I_1 flowing in the first coil. If N_2 is the number of turns in the second coil, then the mutual inductance of the second coil expressed by the letter M is given by,

$$M_2 = \frac{N_2\Phi_1}{I_1} \text{ Henry} \dots\dots\dots (2.3)$$

Before going into the details of transformer a brief understanding is required on the terms used in the magnetic circuits. An Electrical Engineer's study starts normally with Ohm's law and progresses later on in day to day life mostly coming across terms like Voltage, Current, Resistance, etc., expressed in Volts, amperes, ohms, etc. However the factors of magnetism are not so much familiar and are not used frequently. With magnetism being the main property for the transformer operation, it is necessary to have a brief understanding on the magnetism by comparing its factors analogous to the most familiar electrical units. Table 2.1 gives the analogous values between some of these important parameters.

Table 2.1
Electrical and magnetic parameters

Electrical Terms	Magnetism Terms
Electro magnetic force between two conductors - related in terms of Voltage. Its value is expressed in volts.	Magneto motive force between two coils - related in terms of flux. Its value is expressed in terms of Ampere-Turns. The term ampere shows that a current has to flow to create this force.
The current is produced when these two conductors are connected through a resistive material or when they come in contact (Short circuit). Expressed in amperes.	The medium to which these two coils are connected decide the value of magnetic flux linked between the coils. It is necessary to have the presence of magnetic material to get a considerable flux density value.
Conductivity, the inverse of resistivity is the factor decides the Current flowing in the conductor. Conductivity is expressed in inverse of Ohms. Higher the conductivity, higher is the current.	Permeability is the factor, which decides the magnetic property of a material. The higher the permeability, the better is its magnetic property.
Current value depends on the magnitudes of voltage and resistance	Magnetic flux value depends on the magnitudes of MMF and the permeability
Resistance is the force opposing the flow of current. Higher the resistance the lower the current	Reluctance is the property, which affects the flow of magnetic flux in a magnetic material, which means a low reluctance path is required to ensure higher magnetic flux.

However it is to be remembered that the current flowing through a resistor dissipates energy in the form of heat whereas the flux flowing through reluctance does not dissipate the energy in the form of heat.

2.4 Transformer principle

Consider a single-phase generator generating a sinusoidal AC voltage $V \sin 2\pi ft$ and this voltage is applied across the conductor terminals A_2 and A_1 , with the conductor wound on a limb as shown in Figure 2.6. The conductor is generally termed as winding. The limb shall be made of magnetic material to derive its magnetic properties when an electric current flows in the conductor.

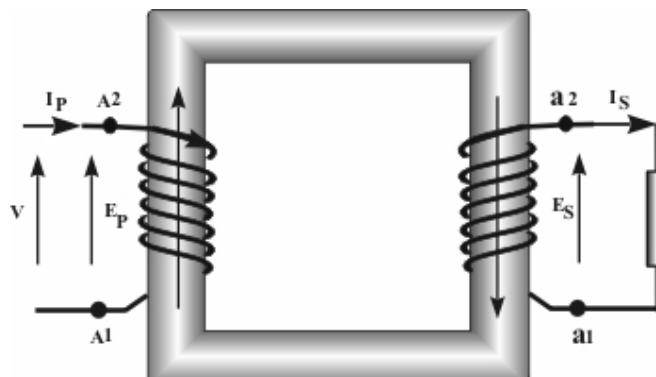


Figure 2.6 (a)
Single phase transformer principle of operation

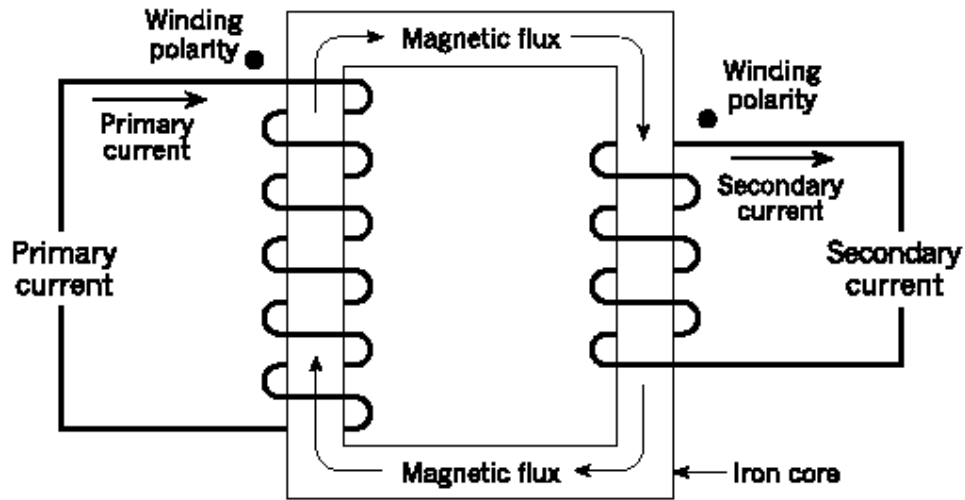


Figure 2.6 (b)
Single phase transformer principle of operation

As per the fundamentals, the applied voltage V will allow a small current to flow in the first winding based on its resistance. The current goes on varying as per the supply frequency from a positive peak value to a negative peak value continuously. This variation in current in each turn creates a magnetic flux in the core material. For a current increasing from 0 to its peak value while entering at A_2 with the winding connections as shown, the magnetic flux will increase to its peak value in the core as identified. The flux returns as the current becomes a negative value. Since the voltage is varying in magnitude sinusoidally, the flux is also sinusoidal and the directions will change vectorially in line with applied voltage/resulting current.

In the above window arrangement the magnetic flux can flow continuously in the limb since it forms a closed circuit. Now imagine that another conductor is wound on the other limb as shown, with its terminals a_2 and a_1 open. Now the magnetic flux produced by the first conductor will start cutting the second conductor, which in turn will produce a voltage E_s across terminals a_1, a_2 . This voltage also follows a sinusoidal waveform in line with the flux produced by the first winding.

The above phenomenon is the basic principle of a transformer. Now if a load is connected across terminals a_2 and a_1 , an AC current will start flowing in the load with its magnitude depending upon the voltage E_s and the load impedance. In the above case the winding, which is connected to the source, is called the PRIMARY winding and the winding, which gets its voltage induced from the magnetic linkage, is called the SECONDARY winding. The parameters of these two windings are suffixed with letters 'p' or '1' for primary and 's' or '2' for secondary to identify the winding to which the parameter is referred.

In the above case the voltage that is induced in the secondary winding purely depends on its number of turns in relation to the number of turns in the primary winding. How? First, it shall be remembered that the magnetic flux is common for both the windings. Further, assuming that both the conductor materials are identical and the whole of the flux produced by the primary winding passes through the secondary winding, then the emf produced in each turn of the primary shall be the same as the emf produced in each turn of the secondary. If there are N_1 turns in the primary and there are N_2 turns in the secondary then,

$$\frac{\text{Total emf induced in } S}{\text{Total emf induced in } P} = \frac{\text{emf per turn} \times N_2}{\text{emf per turn} \times N_1} = \frac{N_2}{N_1} \dots\dots\dots (2.4)$$

When the secondary end terminals are open, then the voltage across its terminals will be the same as the total induced emf produced by the common magnetic flux. The primary current is small under open circuit conditions so that the applied voltage is almost equal and opposite to the emf induced in P. Hence,

$$\frac{V_2}{V_1} \cong \frac{N_2}{N_1} \dots\dots\dots (2.5)$$

Assuming minimum losses in the windings and the magnetic material linking the windings (which is of course the case) the secondary output power is almost equal to the primary input power and can be expressed as

$$V_1 I_1 \cos \phi_1 = V_2 I_2 \cos \phi_2 \dots\dots\dots (2.6)$$

The cosine factors refer to the power factor of the respective sides. These power factors are equal because the loads deciding the power factor are connected on the secondary side, which is also the load for the primary, except that the primary feeds some magnetic load as well. Hence the above equations can be combined to indicate,

$$\frac{V_1}{V_2} \cong \frac{N_1}{N_2} \cong \frac{I_2}{I_1} \dots\dots\dots (2.7)$$

$$\text{Alternatively, } I_1 N_1 = I_2 N_2 \dots\dots\dots (2.8)$$

i.e. Primary Ampere Turns = Secondary Ampere Turns.

It will be seen that in the above case, the magnetic flux is the connecting link between the two windings and the secondary voltage can be reduced or increased by simply changing the turns ratio between the primary and secondary winding. Any change in the secondary current due to the load variation is accompanied by a small variation in the flux and hence the emf induced on the primary also varies only a little. But to ensure the balance of equation, the primary current increases or decreases as per the secondary load current. This balance of ampere-turns on the primary and secondary windings of a transformer holds the key for the transformer action and design.

2.5 EMF equation of a transformer

Assume that the flux produced by the AC voltage has a peak value of ϕ_m at a supply frequency of 'f' cycles per second. The flux will change from $+\phi_m$ to $-\phi_m$ in half a cycle which is $1/2f$ second.

$$\begin{aligned} \text{Hence average rate of change of flux} &= 2 \phi_m \text{ per every } 1/2f \text{ second} \\ &= 4f \phi_m \text{ Webers/ second} \dots\dots\dots (2.9) \end{aligned}$$

Accordingly the average emf induced per one turn = $4f \phi_m$ Volts

For a sine wave, the effective value or rms value is equal to 1.11 times the average value.

Hence the rms value of voltage induced per one turn = $1.11 \times 4f \phi_m = 4.44 f \phi_m \dots (2.10)$

Accordingly the rms value of voltage induced on primary with N_1 turns

$$= E_p \text{ or } V_1 = 4.44 N_1 f \phi_m \dots\dots\dots (2.11)$$

The rms value of voltage induced on secondary = $E_s \text{ or } V_2 = 4.44 N_2 f \phi_m \dots\dots (2.12)$

The above equation can be arrived by an alternate method given below:

Faraday's law establishes that the magnitude of the induced voltage in a winding is proportional to the rate of change of flux linkage associated to the winding. Further, Lenz's law proves that the polarity of the induced voltage is such as to oppose that flux linkage change if current were allowed to flow, and this is expressed as:

$$e = -N (d\phi/dt) \dots\dots\dots (2.13)$$

$$\text{where } \phi = \phi_m \sin 2\pi f t \dots\dots\dots (2.14)$$

$$\begin{aligned} \text{Hence } (d\phi/dt) &= - (2\pi f \phi_m) \cos 2\pi f t \\ &= 2\pi f \phi_m \sin (2\pi f t - \pi/2) \dots\dots\dots (2.15) \end{aligned}$$

Hence instantaneous voltage induced per turn

$$e/N = - 2\pi f \phi_m \sin (2\pi f t - \pi/2) \dots\dots\dots (2.16)$$

Maximum value of induced emf per turn will be reached when sine factor is 1.

$$= 2\pi f \phi_m \text{ volts } \dots\dots\dots (2.17)$$

Accordingly RMS value of voltage induced per turn

$$\begin{aligned} &= 0.707 \times 2\pi f \phi_m \\ &= 4.44 f \phi_m \text{ volts/turn } \dots\dots\dots (2.18) \end{aligned}$$

For design calculations, the same can be expressed in terms of volts per turn and flux density in the core:

$$E / N = 4.44 B_m A f \times 10^{-6} \dots\dots\dots (2.19)$$

Where

E / N = Volts per turn, which is the same in both the windings

B_m = Maximum value of flux density in the core, tesla

A = Net cross-sectional area of the core, mm^2

f = Frequency of supply, Hz

The above equation is basically used to decide the transformer construction parameters, Viz., Voltage, number of turns, core area, etc.,

2.6 Transformer core

In the earlier section we have come across the term B , which is basically the flux density in the core and can be varied by changing the source voltage. It is necessary to understand the properties of the transformer core and its importance in transformer construction, which results in this flux density.

The Core is usually comprised of a silicon steel stamping shaped like an "E" and an "I".

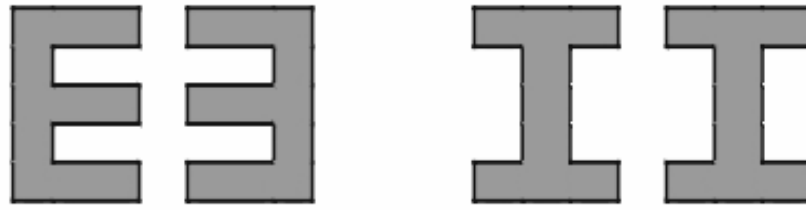
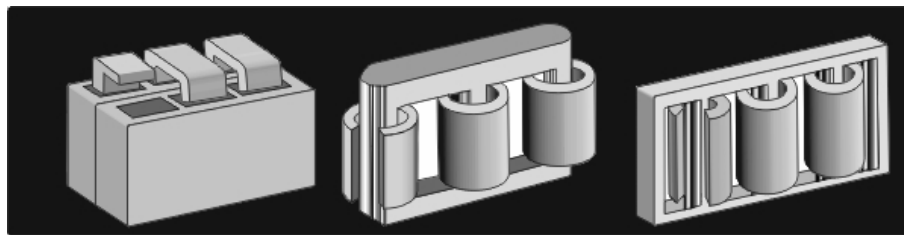


Figure 2.7
Typical Transformer Stampings

The E & I are joined together to form into square or rectangular loop to provide limbs for the transformer windings as shown in Figure 2.8. These constructions ensure a closed path or circuit for the lines of magnetic flux to travel. The primary coil and secondary coil are around the limbs depending on the construction of the core, which divides the type of transformers as core type and shell type.



Shell type transformer

Core-type transformer

Five limb core-type transformer

Figure 2.8
Transformer construction types

In the above picture, the windings are the concentric portions and the solid portions refer to the metallic part of a transformer, which either surround the windings (Shell type) or which is surrounded by windings (Core type). The windings are normally made of electrolytic grade Copper and the metallic parts are basically made of steel. The metallic part linking the windings is referred to as the magnetic core of a transformer. The transformer in general is referred as air core transformers.

In shell type transformers, the flux-return paths of the core are external to, and enclose the windings. The shell-type arrangement provides intrinsically better magnetic shielding that is well suited for supplying power at low voltages and heavy currents. This design is widely used in arc furnace transformers.

The core-type designs are extensively used throughout the world for other types of power and distribution transformers. These have concentric windings around the various limbs. This design possesses top and bottom yokes of cross-section equal to the wound limbs, thereby not requiring separate flux-return paths. In the event of very large transformers, where transportation becomes a problem, the cross-section of the top and bottom yokes is reduced to almost 50% of that of the wound limbs. This necessitates additional flux-return paths which are achieved by adopting a 5-limb transformer design illustrated in Figure 2.8.

The core of a transformer produces a magnetic flux typically as per Figure 2.9, where B is the flux, H is the magnetizing force and V is the input voltage. The values indicated are indicative for a particular transformer and the values will vary depending upon the source, material and construction features.

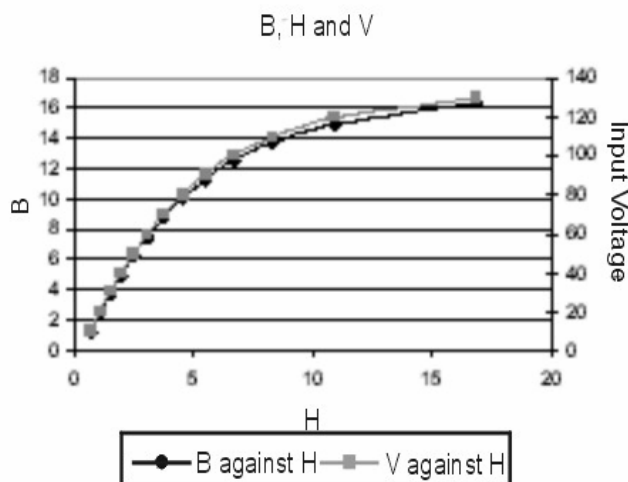


Figure 2.9
Typical B-H curve of a magnetic core

The permeability of the core material is termed in terms of its ability to conduct magnetic flux compared to air. Air's capability is taken as 1 tesla and the flux density of magnetic materials is measured in tesla, comparing with the property of air. For example the transformer core steel can have a permeability of about 10,000 tesla.

The permeability of the magnetic material is the ratio of magnetic flux density to the magnetizing force, which can be expressed as

$$\text{Permeability} \quad \mu = B/H \dots\dots\dots (2.20)$$

Referring to the graph it can be seen that the permeability is almost constant only for a fixed zone and after which it is not possible to get higher flux density irrespective of any amount of increase in H.

For efficiency reasons transformers are generally operated near to the “knee-point” of the magnetic characteristic. Any increase above the rated terminal voltage tends to cause core saturation and therefore demands an excessive increase in magnetization current.

When a transformer is energized, it follows the classic magnetization curve as per Figure 2.10.

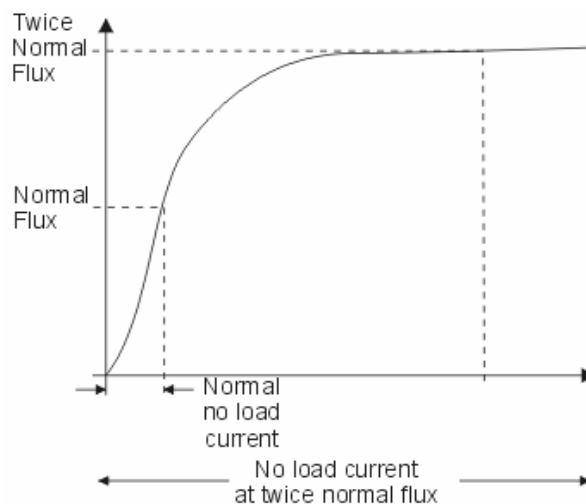


Figure 2.10
Transformer magnetizing characteristics

The point at which the flux density reaches its maximum value is called the saturation point and different materials have different saturation values based on its permeability value.

Assume that the material reaches its maximum flux density $B_{\max}$ at value equal to $H_{\max}$. When H is brought back to zero, the B value does not reduce to zero and a negative H has to be applied externally to bring the value of B to zero. When the H is decreased further in the negative direction, the B value reaches a negative saturation value $B_{\min}$. Once again if H is applied in the positive direction, it will be seen that the B value does not become zero but retains a negative B . This is in effect the famous hysteresis loop of the magnetic material as given in Figure 2.11.

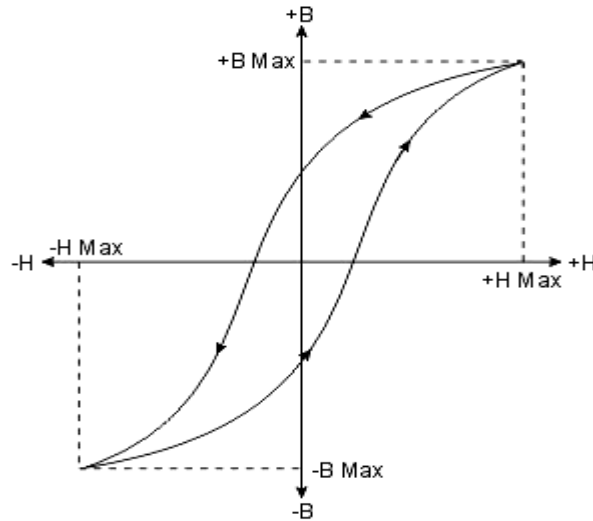


Figure 2.11
Hysteresis Loop of magnetic material

2.7 Vector or phasor diagram of transformers

The vector/phasor diagrams of transformer voltages and currents at no load and load conditions give a better picture on the happenings inside a transformer and the relevance of the equivalent circuit. For easy understanding, single-phase connections are being considered.

When an alternating current is applied to the primary winding, an alternating magneto motive force (mmf) is induced into the magnetic core and subsequently sets up an alternating flux passing through its body. This alternating flux in the core that links both the primary and secondary windings induces an electro motive force (emf) in both the windings. In the primary winding this emf is referred to as the back-emf and in an ideal situation, it would oppose the applied voltage to the primary windings such that there would be no flow of current. However the impedance in the windings causes a low current to pass in the primary winding and the current that flows in the primary winding is termed as the transformer magnetizing current. In the open secondary winding, this induced emf is referred to as the secondary open-circuit voltage, which basically refers to the voltage measured between the two ends of the winding.

Figure 2.12 depicts the vectorial representation of the voltages, flux and currents that flow in a simple single-phase transformer neglecting its impedances. The descriptions of the parameters are identified by the side, which will give a clear idea on the phase angle differences between the voltages, currents and flux in a typical single-phase transformer windings and its core.

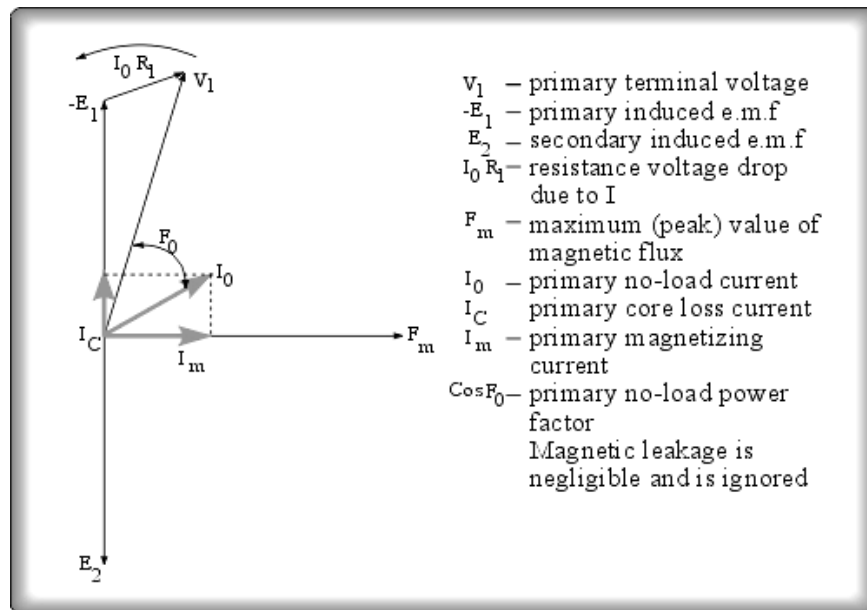


Figure 2.12
Phasor diagram for a single-phase transformer on open circuit

If a load is connected to the secondary winding across its two ends it will result in a flow of current through the load, the value of which depends upon the open circuit voltage across the secondary winding and the load impedance. This load current creates a demagnetizing mmf in the magnetic core upsetting the balance between the primary applied voltage and the already induced back-emf. To re-establish this equilibrium an additional current must be drawn from the primary supply source to provide an exactly equivalent mmf. Figure 2.13 shows the phasor diagram for a single-phase transformer supplying a pure resistive load, where the current I_2 in the secondary winding is in phase with its induced emf E_2 . (Unity power factor)

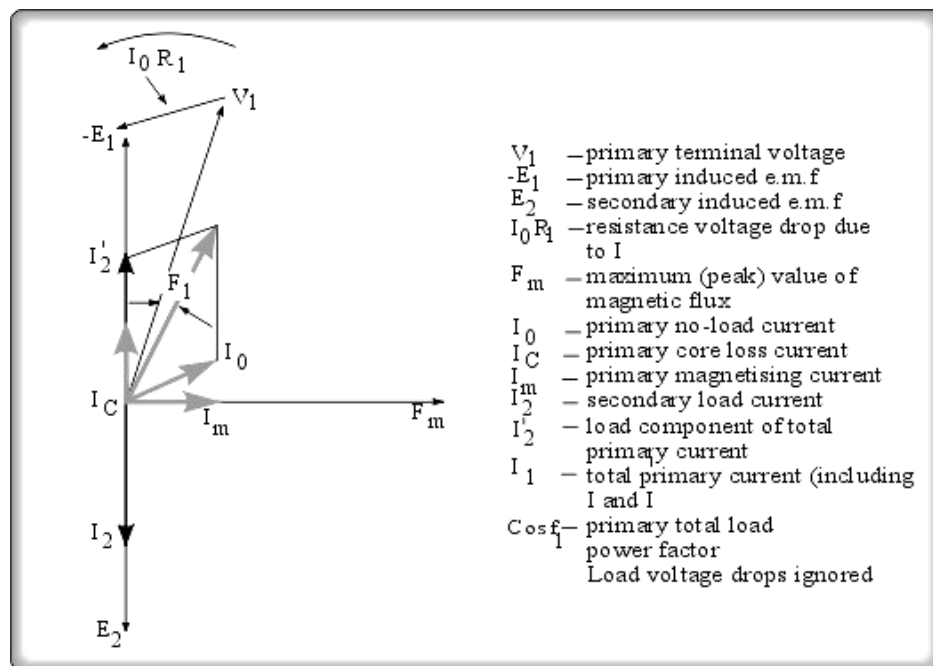


Figure 2.13
Phasor diagram for a single-phase transformer supplying a unity power factor load

2.8 Transformers connected to load

The earlier sections referred to characteristics of a transformer with a simple resistive load connected to the secondary resulting in secondary current to be in phase with its voltage. However in practical terms, the loads connected to a transformer are inductive in nature. Assume a transformer connected to a load of Z_2 across its secondary. In vectorial representation, the following diagram shows the various parameters of a transformer, which is connected with an inductive load consisting both resistive and reactive components. R and X, the primary parameters are identified with suffix 1 while the secondary winding parameters are suffixed with 2.

Figure 2.14 gives the vector diagram with a resistive and reactive load combination, which is the most common type of load in electrical distribution.

It is to be noted that the basic phasor diagram still looks the same except for the lagging power factor introduced in the currents of both primary and secondary windings. In fact, the sum total effect is a reduction in the secondary terminal voltage. The drops due to primary resistance and leakage reactance can be converted in terms of the secondary voltage using the transformer equations.

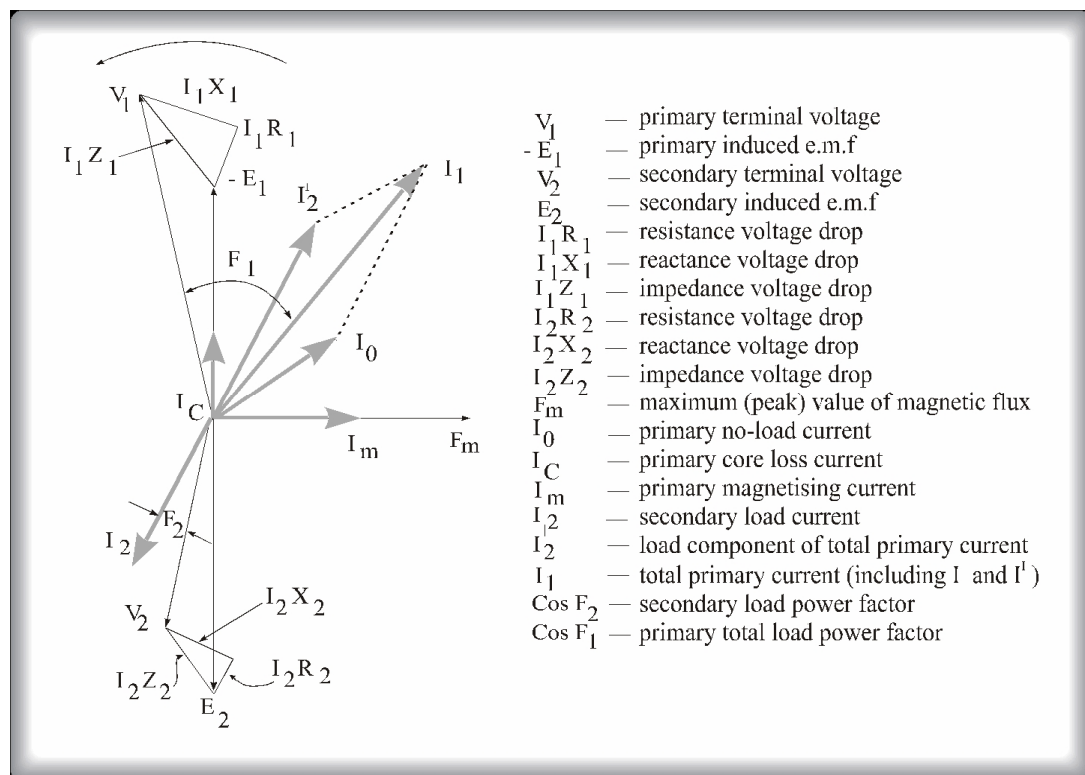
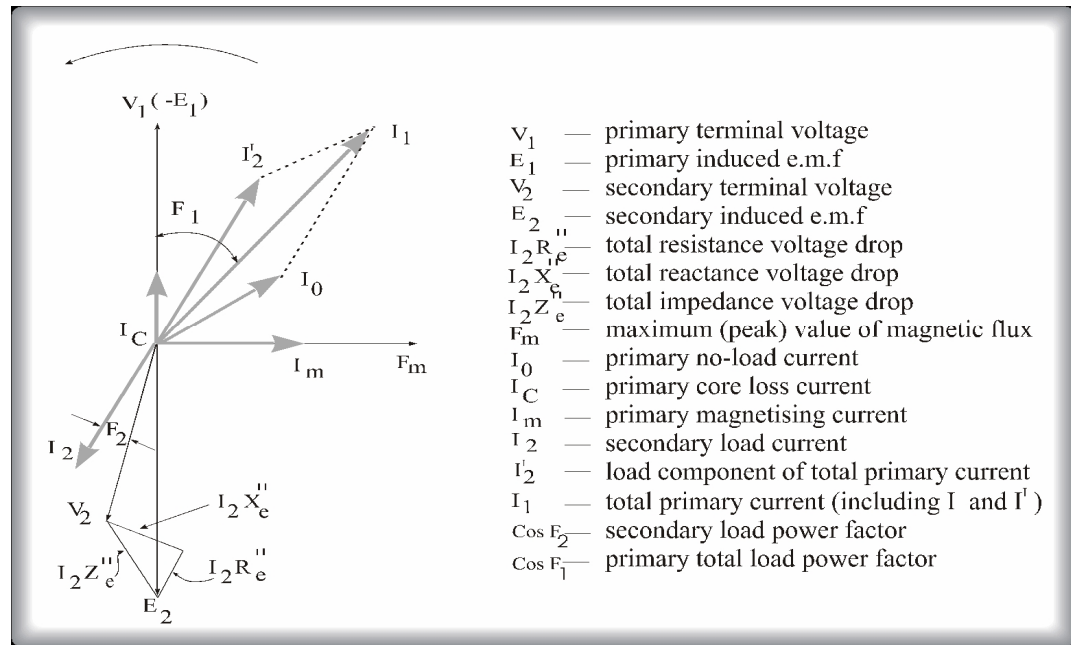


Figure 2.14

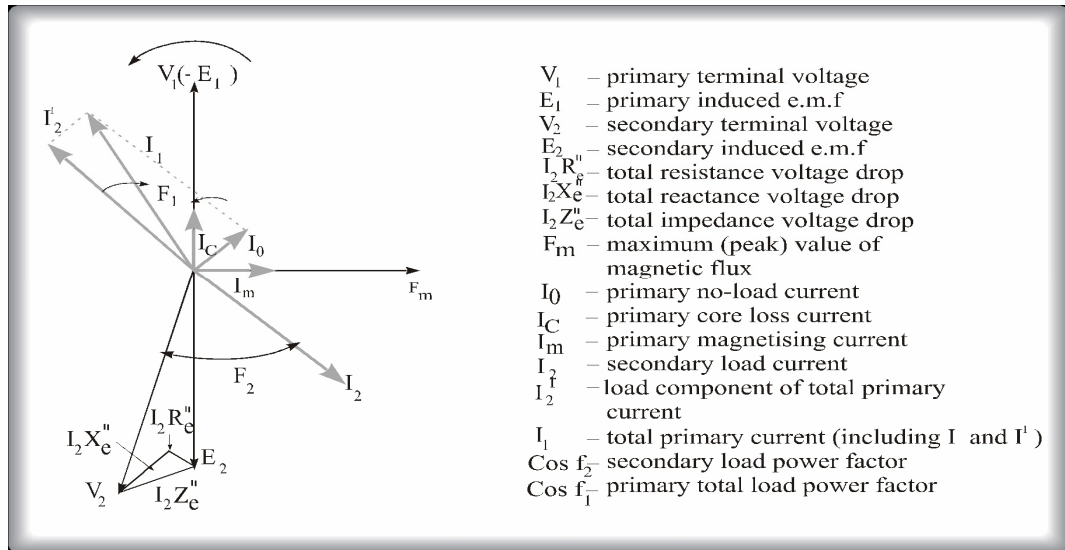
Phasor diagram for a single-phase transformer supplying an inductive load of lagging power factor $\cos \phi_2$ Voltage drops divided between primary and secondary sides

Figure 2.15 shows the phasor conditions where the resistance and leakage reactance drops are shown as occurring on the secondary side with all parameters transferred to secondary side adopting the transformer equations.

**Figure 2.15**

Phasor diagram for a single-phase transformer supplying an inductive load of lagging power factor $\cos \Phi_2$ Voltage drops transferred to secondary side

What happens when the load on the secondary is capacitive in nature? In fact, there will be a rise in the voltage as can be seen in the following Figure 2.16. This happens when a leading current passes through an inductive reactance (which is the transformer itself).

**Figure 2.16**

Phasor diagram for a single-phase transformer supplying a capacitive load of leading power factor $\cos \Phi_2$ Voltage drops on primary are transferred to secondary side

The preceding phasor diagrams have illustrated the relationship between the various voltages and currents and the phase angles between them on a single-phase basis. These phasor diagrams are applicable for poly-phases, except that there will be an angular difference between the parameters (phase difference of 120° between the phase wise parameters in a 3-phase transformer). In all other respects, the individual phases emulate almost same type of characteristics as single phase basis.

2.9 Rated quantities

The transformer rating is specified in Volt-amperes (VA) indicating the amperes A it can handle at a rated voltage V. Depending on the magnitude of power being transferred or handled, the transformer rating or output can be expressed in mega volt-amperes (MVA) or in kilovolt-amperes (kVA), and are determined by the following equations depending on whether the source is single phase or three phase.

Single-phase transformers

$$\text{Output} = E_2 \times I_2 \text{ in VA} \dots\dots\dots (2.21)$$

$$\text{or} = (4.44 f \Phi_m N_2) \times I_2 \dots\dots\dots (2.22)$$

with the multiplier 10^{-3} for kVA and 10^{-6} for MVA

It may be noted that normally single-phase transformers are rated for smaller VA values. At the same time, it is also a common practice to connect three single-phase transformers with each transformer connected to each phase to neutral to provide a three-phase common output. Though this practice is not so common, there are some installations where the use of single-phase transformers is adopted to generate three phase distribution.

Three-phase transformers

A three-phase transformer basically consists of three windings and is used to transmit the 3-phase power produced by a generator. The three-phase transformer also has primary and secondary windings (same as a single phase transformer but the windings of each phase are separately wound and brought out for both primary and secondary with the primary terminals connected to the three phase source). The three windings of the primary and secondary can be connected in the form of either Star or Delta. However in a 3-phase transformer whether connected in Star or Delta form,

$$\text{Output} = 4.44 f \Phi_m N I \times \sqrt{3} \dots\dots\dots (2.23)$$

$$\text{or} = E_2 I_2 \times \sqrt{3} \dots\dots\dots (2.24)$$

with the multiplier 10^{-3} for kVA and 10^{-6} for MVA

Where I_2 is the full-load current in the transformer secondary winding. The constant $\sqrt{3}$ is a multiplier for the conversion of phase voltage to line voltage in case of star-connected windings and is a multiplier for the conversion of phase currents to line currents in case of delta-connected windings. E_2 and I_2 are the rated secondary (no-load) voltage and the rated full-load secondary current, respectively.

2.10 Transformer equivalent circuit

In the single-phase transformer connection shown in Figure 2.6 it is well known that both the primary and secondary windings have a resistance value R and inductance value L. Because of the inductive nature of the windings, the inductance value dominates the resistance value. For calculation purposes, it is necessary to express the inductance L in ohms which is equal to $2\pi fL$ and is designated as X. Typically the primary and secondary resistance values of the two windings are expressed as below.

$$\text{Primary Resistance and reactance} = R_1 \text{ and } X_1$$

$$\text{Secondary Resistance and Reactance} = R_2 \text{ and } X_2$$

The windings are interlinked by the magnetic core, which also incurs losses similar to that spent on the windings. Accordingly the factors contributing these losses can be termed in terms of resistance and reactance. We have noted that the transformer core losses basically comprise of hysteresis losses and eddy current losses. Hence in practical terms the current spent on core losses can be considered to flow divided into resistance R_m and magnetizing reactance X_m .

Assuming a primary voltage of V_1 and a secondary voltage of V_2 , the transformer can be represented as per the circuit shown in Figure 2.17 taking into consideration resistance and reactance values of the windings and core.

An ideal transformer is one that has all the magnetic flux linked equally among its windings. However in practice there is a loss, which is basically due to an effect called Leakage Reactance. It can be noted that the magnetic path is common for both the windings of a transformer and hence the magnetic flux produced in the transformer is also getting divided to the two windings. It is convention to allocate half the leakage flux to both the windings, as it is difficult to quantify exactly the leakage flux contribution to the primary and the secondary windings.

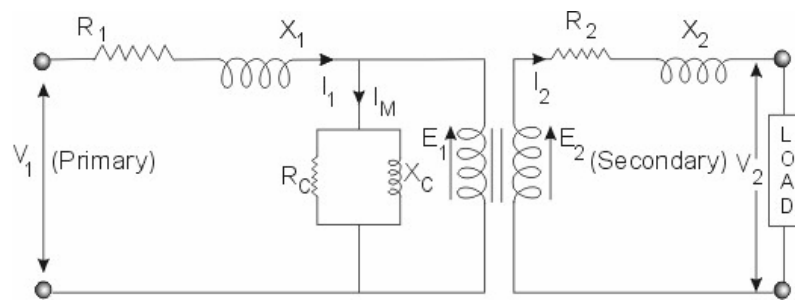


Figure 2.17
Transformer Equivalent Circuit

It is not practically possible to ensure that all of the flux produced by the primary winding source is getting linked to the secondary winding. So the transformer can be said to possess an in built resistive force which is contributing to the imperfections in the transformation (between primary and secondary). This resistive phenomenon is termed as the leakage reactance of a transformer. Then a simple circuit shown below with resistance R and reactance X can represent the equivalent circuit.

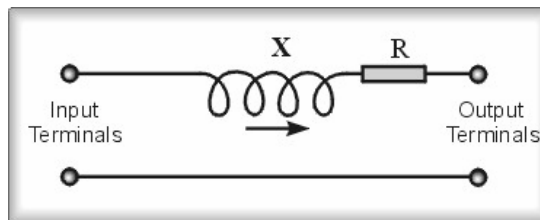


Figure 2.18
Transformer simple Equivalent Circuit

When a full load current is flowing in the windings, there is a voltage drop due to the currents flowing in the above resistance and reactance. The net value of R and X is expressed in practical terms as transformer impedance, and is normally expressed as a percentage voltage drop in the transformer at full load current. Expressed mathematically this is:

$$V_z = \%Z = [\{ I_{FL} Z \} / E] \times 100 \dots\dots\dots (2.25)$$

Where Z is $\sqrt{R^2 + X^2}$, R and X being the transformer resistance and leakage reactance respectively and I_{FL} and E are the full-load current and open-circuit voltage of either primary or secondary windings.

The transfer of primary impedance on to the secondary is done as follows:

Let

Z_s = total impedance of the secondary circuit including leakage and load characteristics

Z'_s = equivalent value of Z_s when referred to the primary winding

$$\begin{aligned} \text{Then } I'_2 &= N_2/N_1 \cdot I_2 \\ &= N_2/N_1 \cdot E_2/Z_s \dots\dots\dots (2.26) \end{aligned}$$

$$\text{But } E_2 = N_2/N_1 \cdot E_1$$

$$\text{So } I'_2 = (N_2/N_1)^2 \cdot E_1/Z_s \dots\dots\dots (2.27)$$

$$\text{Also, } V_1 = E_1 + I_2' Z_1$$

$$\text{Where } E_1 = I_2' Z'_s$$

$$\text{Therefore } I'_2 = E_1/Z'_s \dots\dots\dots (2.28)$$

Comparing the above equations it will be seen that $Z'_s = Z_s (N_1/N_2)^2$.

Figure 2.19 gives the transformer equivalent circuit by converting the values of resistance and reactance to a common base.

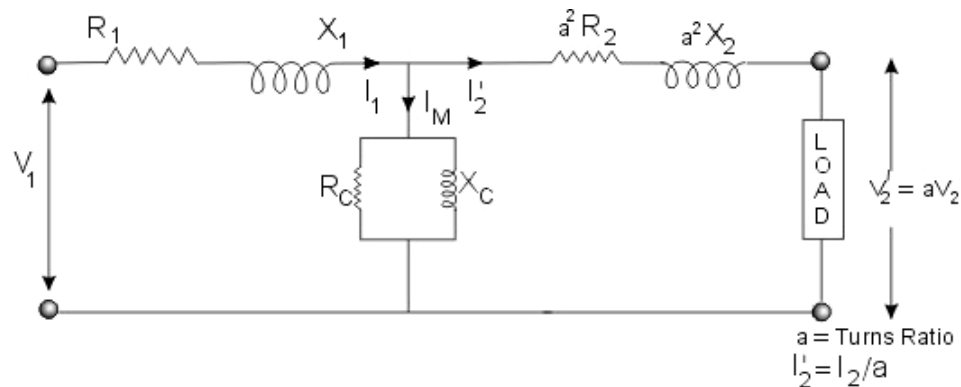


Figure 2.19
Equivalent Circuit with conversion of parameters

2.11 Three-phase transformers

The earlier sections mainly referred to single-phase transformers, but all the principles can be extended to three-phase transformers as well. The typical connection of a three-phase transformer is shown in Figure 2.20

Normally there occurs a phase shift phenomenon in a two-winding three-phase transformer, when one winding is delta connected and the other is star connected (A-B-C refer to primary terminals and a-b-c refer to secondary terminals). These will be covered in a separate chapter.

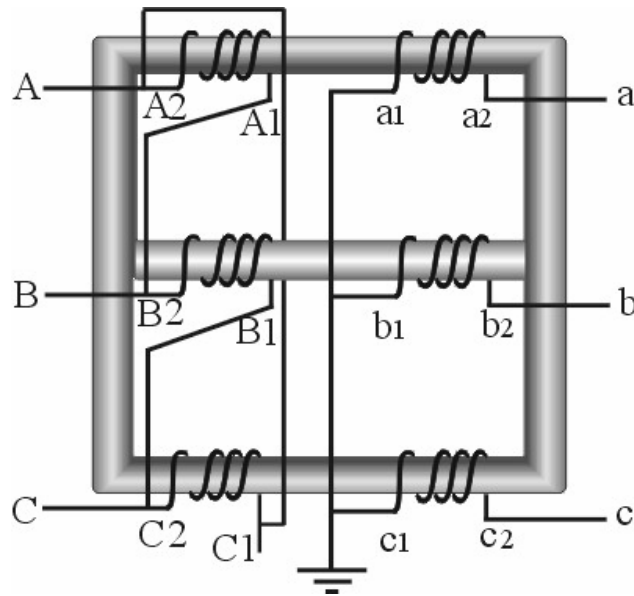


Figure 2.20
Physical connection of Delta (D) or Star (Y) configuration

2.12 Transformer core losses

Each time the magnetizing force produced by the primary (of the transformer) changes because of the applied AC voltage the atoms realign themselves in the direction of the force. The energy to accomplish this realignment of the magnetic atoms comes from the input power to keep the transformer operational but it is not used in any way for the voltage induced in the secondary winding; it is therefore a loss. These losses are spent on the transformer core for its correct operation and these losses are referred to as core losses. Because various types of core materials have different magnetizing abilities, the selection of core material is an important factor in reducing core losses.

Core losses, also called "iron losses", of the transformer can be classified into two kinds Viz., Hysteresis losses and eddy current losses. Hysteresis losses are the main type of core loss, comprising about three-fourths of the total core losses. "Hysteresis" describes the tendency of the core material to oppose a change in magnetism.

Hysteresis is an important factor in an iron core. Whenever the flux density is increased, additional magnetizing force is required to overcome the hysteresis. Further, after the magnetizing force has reduced to zero (at the end of an alternation cycle), a certain magnetization still remains in the core which can be decreased to zero only by the application of magnetizing force in the opposite direction. Hence during each cycle, a certain percentage of the total energy supplied to the primary winding is used to produce the additional magnetic forces to overcome the hysteresis effect, and this energy is lost as far as the transformer is concerned.

The two types of losses in the transformer can be calculated as per the following formulae.

$$\text{Hysteresis Loss} = k_1 f B_m^n \text{ Watts / Kg} \dots\dots\dots (2.29)$$

$$\text{Eddy current Losses} = k_2 f^2 t^2 B_{\text{eff}}^2 / \rho \text{ Watts/Kg} \dots\dots\dots (2.30)$$

Where

k_1 and k_2	=	Constants based on material
B_m	=	Maximum flux density in Tesla
n	=	A constant 1.6 to 2.5 based on material
B_{eff}	=	RMS value of flux density in Tesla
t	=	Thickness of material in mm
ρ	=	Resistivity of material under use

It can be seen that the losses are based on the applied frequency and the material properties.

Currents are caused in the solid metal core by induction from the magnetic field. This current is called transformer Eddy Current. In iron core transformers, the iron core carries these eddy currents similar to a conductor because it is affected by the magnetic field just as the secondary winding is. Small voltages are induced in the core by the changing magnetic field; these currents cause $I^2 R$ losses in the core. It is necessary to keep both I and R as low as possible to keep the eddy current losses to a small value.

A solid steel core is not preferred since it is prone to high losses due to eddy currents/ circulating currents when the magnetic flux is traveling. It was observed that the transformer cores made in the form of laminations are effective means to keep these losses to a minimum. By using a laminated core (thin sheets of metal instead of a solid iron core), the path of the eddy current is broken up without increasing the reluctance of the magnetic circuit. The laminations lie in the same direction as the flux. Therefore, the insulating surfaces are directly across the path of the eddy currents. The resulting eddy current reduction improves the efficiency of the transformer.

The above losses are referred to as transformer no-load losses, which need to be spent irrespective of the load current on the secondary current. The no load losses almost remain constant from 0 to 100% loading of the transformer.

2.13 Transformer efficiency

The other type of losses which is spent in a transformer is called the load loss OR COPPER LOSS basically referring to the $I^2 R$ losses spent on the transformer primary and secondary winding resistances based on the currents flowing in the respective winding, when we start loading the transformers. Copper has got its name because of the use of copper in transformers for quite a long time, though nowadays Aluminum is also used as winding material.

The efficiency of a transformer is given by the ratio of output power on the primary to input power fed by the secondary. When a transformer is loaded it incurs core losses and copper losses. Hence

$$\begin{aligned} \text{Efficiency} &= \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{Losses}}{\text{Input}} \\ &= 1 - \frac{\text{Losses}}{V_2 I_2 \cos \Phi + \text{Losses}} \quad \dots\dots\dots (2.31) \end{aligned}$$

$$= 1 - \frac{\text{Losses} \div V_2 I_2}{\cos \Phi + (\text{Losses} \div V_2 I_2)} \quad \dots\dots\dots (2.32)$$

2.14 Regulation

It has been noted that due to the load impedance, there is a drop in the secondary terminal voltage as the load current increases. ($V_2 = E_2 - I_2^2 Z$). This voltage drop varies with the load current and is termed as the regulation of a transformer.

The voltage drop in a transformer is affected by the resistive (R) and reactive (X) components which together is termed as impedance (Z) of the transformer.

The copper loss in a transformer is basically due to the resistive component when a load current passes through the windings. Hence,

$$\begin{aligned} V_R &= \text{percentage resistance voltage at full load (voltage drop due to resistive component)} \\ &= \frac{\text{copper loss} \times 100}{\text{Rated kVA}} \dots\dots\dots (2.33) \end{aligned}$$

$$\begin{aligned} \text{Similarly } V_X &= \text{percentage reactance voltage (Voltage drop due to reactive component)} \\ &= (I_2 X'_e / V_2) \times 100 \dots\dots\dots (2.34) \end{aligned}$$

Based on the above equations and referring to the phasor diagrams, it can be mathematically proved that the approximate percentage regulation at a particular load current equaling “a” times full load current of the transformer with a power factor of $\cos\phi_2$ is given by:

$$\text{Percentage regulation} = a (V_R \cos\phi_2 + V_X \sin\phi_2) + \frac{a^2}{200} (V_X \cos\phi_2 - V_R \sin\phi_2)^2 \dots\dots\dots (2.35)$$

The percentage regulation that occurs at the secondary terminals, at unity power factor load ($\cos\phi_2 = 1$ and $\sin\phi_2 = 0$) may be calculated by substituting the values of V_R and V_X the simplifying the above equations as below:

$$= \frac{\text{Copper loss} \times 100}{\text{output}} + (\text{percentage reactance})^2 \dots\dots\dots (2.36)$$

This value is always positive and indicates a voltage drop with load.

For transformers having low reactance values up to about 4%, this can simplify to:

$$\text{Percentage regulation} = a (V_R \cos\phi_2 + V_X \sin\phi_2) \dots\dots\dots (2.37)$$

For transformers with high reactance values about 20% and above:

$$\begin{aligned} \text{Percentage regulation} &= a (V_R \cos\phi_2 + V_X \sin\phi_2) \\ &\quad + \frac{a^2}{2 \times 10^2} (V_X \cos\phi_2 - V_R \sin\phi_2)^2 \\ &\quad + \frac{a^4}{8 \times 10^6} (V_X \cos\phi_2 - V_R \sin\phi_2)^4 \dots\dots\dots (2.38) \end{aligned}$$

It had been noted that the secondary voltage would increase by increasing its number of turns ratio with respect to the primary. This characteristic is used to offset the regulation in a loaded transformer. The transformer is provided with additional winding with suitable taps for external connection. Normally this provision is made on the high voltage side to keep the current to be controlled at a lower value. Whenever there is a voltage drop, the taps are changed to a lower position to get a proportional increase in the turns ratio between primary and secondary so that a higher voltage can be obtained on the secondary side.

2.15 Efficiency calculations

For the purpose of arriving at the efficiency of transformers, the following tests are done which are well known to electrical engineers.

Open Circuit test by applying standard voltage on primary with secondary open and measuring the input, which is basically the core losses/ iron losses/no load losses.

Short circuit test by shorting the secondary terminals and applying a small voltage on the primary and flow 100% rated full load current in the secondary winding. This basically gives the copper losses.

The above losses measured can be considered to be at unity power factor. Then the efficiency at any fraction of load x and a power factor $\cos \Phi$ is given by:

$$\text{Efficiency} = \frac{x \times \text{Transformer KVA} \times \cos \Phi}{(x \times \text{Transformer KVA} \times \cos \Phi) + \text{Iron Loss} + \text{Copper Loss}} \dots(2.39)$$

The above formula is used to calculate the efficiency of a transformer at any power factor and load if the no load losses and copper losses are available. The % iron loss varies indirectly with the load and the load loss varies directly with the load. Similarly the regulation of a transformer can also be arrived since VR and VX are related to the copper losses and iron losses.

It can be proven that the maximum efficiency of a transformer is achieved when:

$$\text{Iron Losses} = \text{Copper Losses}$$

$$\text{Or at a load} = \sqrt{\frac{\text{Iron Loss}}{\text{Copper Loss}}} \times 100\% \dots\dots\dots(2.40)$$

Transformer Connections and Markings

3.1 Winding Polarity

International standards define the polarity of the HV and LV windings sharing the same magnetic circuit as follows:

If the core flux induces an instantaneous emf from a low number terminal to a high number terminal in one winding, then the direction of induced emf in all other windings linked by that flux will also be from a low number terminal to a high number terminal (A1 to A2 and a1 to a2 in Figure 3.1).

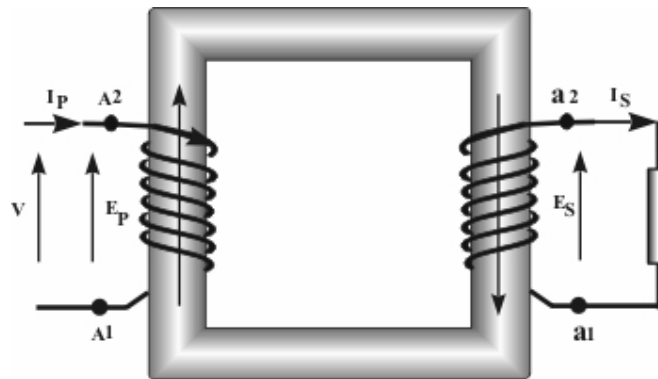


Figure 3.1
Polarity of a single phase transformer connection

From the laws of induction, it will be seen that the current flow in the windings is in the opposite direction.

Polarity forms an important requirement for connecting the current transformers in the transformer windings to ensure that the current is sensed in the correct direction of flow before deciding the fault conditions for tripping. This section will discuss phase relationships and polarities undergoing changes depending upon the phase sequence followed in the primary connections and changing the star point on the secondary side. It is necessary that the transformer winding polarities are identified by using common suffix numbers (for primary and secondary) to imply that both the terminal ends of a winding are connected to follow identical polarities.

Simple test methods are available to check the polarity of transformer connections, which will be covered in the subsequent chapter.

3.2 Terminal Markings of transformers

To ensure proper design and installation, individual phase windings are given descriptive letters and the same letter in combination with suffix numbers is then used for all windings of one phase. The HV windings are given upper case letters and the LV windings are given lower case letters for corresponding phases. The alphabets mostly used are A,B,C (ANSI) and U,V,W (IEC) with suffixes corresponding to the respective windings.

Thus for single-phase transformers:

A	:	for the HV winding
3A	:	for the third winding, if any.
a	:	for the LV winding

For two-phase windings on a common core or separate cores in a common tank:

A,B	:	for the HV windings
a,b	:	for the LV winding

For three-phase transformers:

A, B, C / U, V, W	:	for the HV winding
a, b, c / u, v, w	:	for the LV winding

Figure 3.2 shows the standard markings of a single-phase transformer. By identifying A_1 and a_1 , the user clearly knows the method of connection to be employed. For example if the primary voltage is provided from a phase to neutral ends of 3 phase transformer across A_1 and A_2 , the terminal a_2 behaves as the neutral point in the secondary side and it is a common practice to connect this end to neutral on the secondary side. Though practically there may not be any harm in interchanging a_1 and a_2 , there is a phase shift occurring in the secondary winding (with respect to the primary), which will shift by 180° .

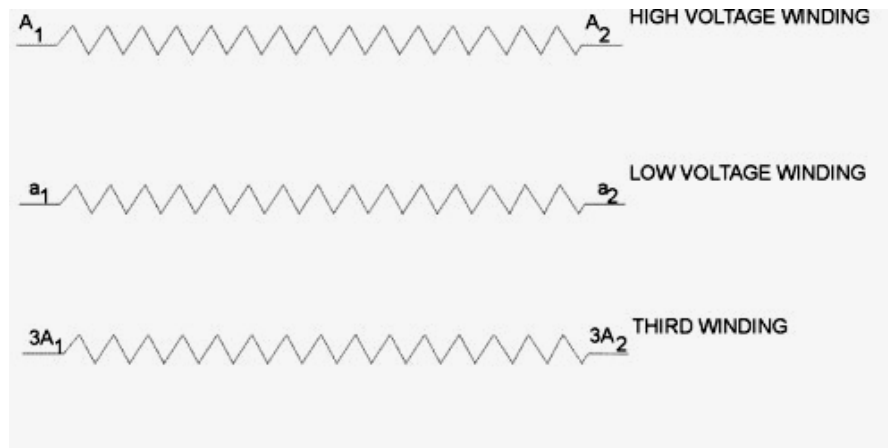


Figure 3.2
Terminal marking of a single-phase transformer having a third winding

Figure 3.3 shows the relative markings in two winding transformers (single-phase and three-phase).

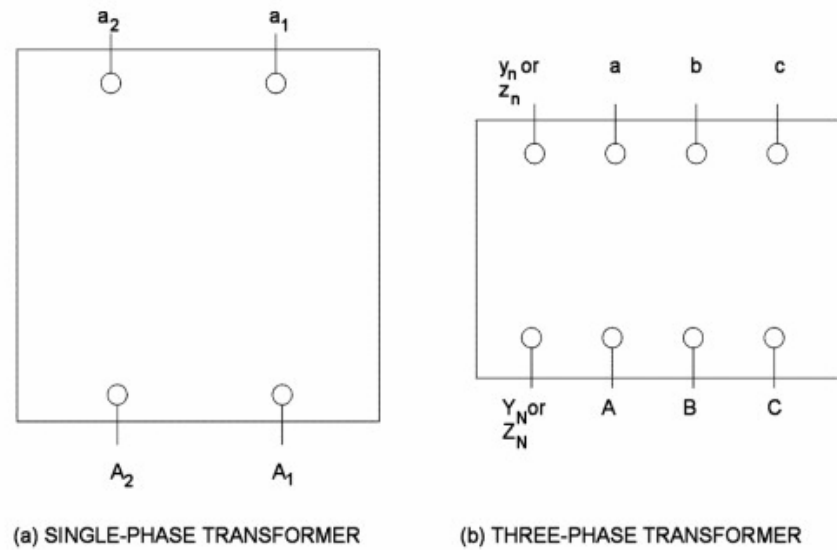


Figure 3.3
Relative position of terminals of two-winding transformers

In addition to the letters marking the terminals, suffix numbers are given in sequence, relative to the direction of the induced emf, on all the tapping points and the ends of the winding. In the case of three-phase star connected transformers, A1 would be connected to the star's neutral point and A2 would be the line terminal. Figure 3.4 illustrates typical terminal markings of tappings.

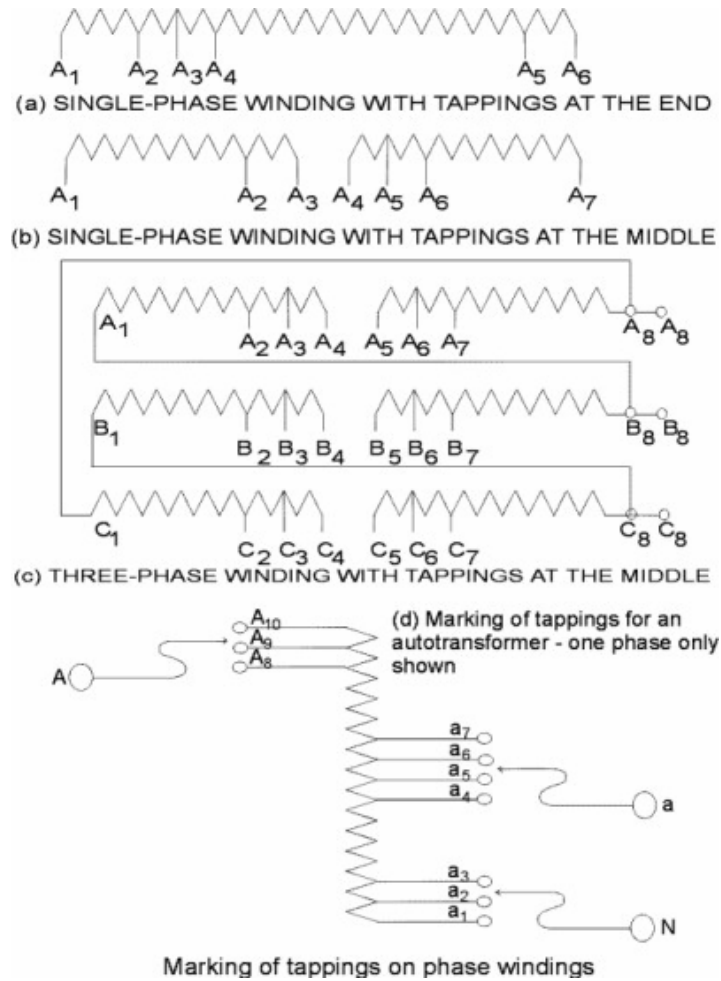


Figure 3.4
Marking of tapings on phase windings

3.3 Transformer winding connections and phasor relationships

The most common arrangement for any transformer is to have only two windings per phase, a high voltage winding and a low-voltage winding (primary and secondary). As already noticed, a 3-phase transformer can have its windings connected either in Star or in Delta with 120° displacement between each phase supply. Following paragraphs explain the different characteristics of transformers depending upon the connection method adopted. Based on the method chosen for the primary and the secondary connections, a phase-shift can take place through the transformer from primary to secondary.

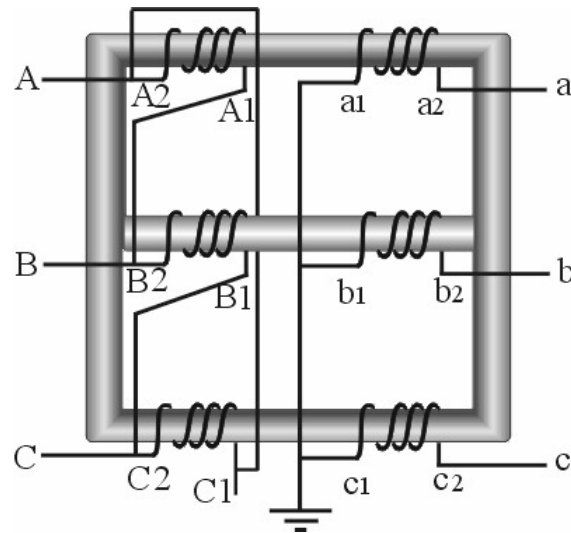


Figure 3.5 (a)
Physical connection of Delta (D) or Star (Y) configuration

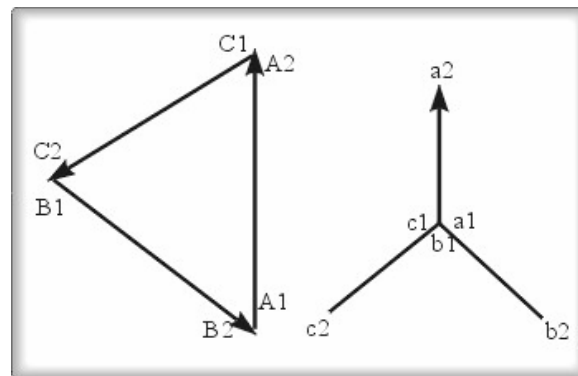


Figure 3.5 (b)
Vectorial representation of Delta and Star configuration

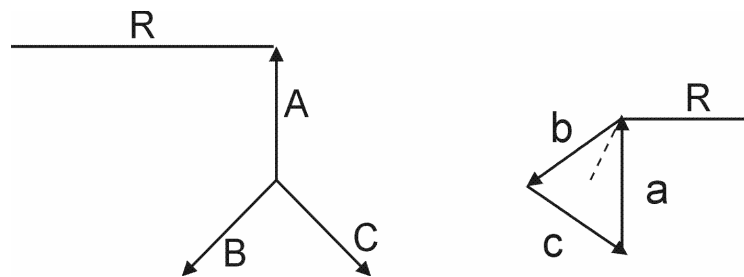


Figure 3.5 (c)
Phase shift of a three phase transformer

In the example shown, the phase shift of secondary winding is $+30^\circ$ with respect to the corresponding primary winding. i.e. the a-n voltage leads A-N by 30° , b-n voltage leads B-N by 30° and so on. The vector diagram is considered analogous to a clock whose hour hands also rotate 360° (same as the full cycle of a vector). Considering a clock with 12 hour positions, each hour position corresponds to a 30° shift when you start looking after the 12 o'clock position. Hence the above connections achieve an equivalent of 11 o'clock position on the secondary side with respect to its corresponding primary voltage. This connection is referred to as the 11 o'clock position. In simple terms this is referred to as Dyn11. (small n represents a connection where secondary neutral is brought out for external connection), which is named as VECTOR GROUP

of a three-phase transformer. The vector group of a transformer helps the user to identify the relative phase displacements between primary and secondary windings.

The letter n in the above marking refers to the secondary-side neutral, which is brought out externally for earth connection. If the primary is star connected and brought out for source connections, N represents the primary neutral.

The transformer winding connections can be expressed in different ways. For example:

YNd1= HV winding connected in star with Primary neutral (Capital N) brought out.
LV winding connected in delta.

Phase shift 30° i.e. from 12 to 1 o'clock.

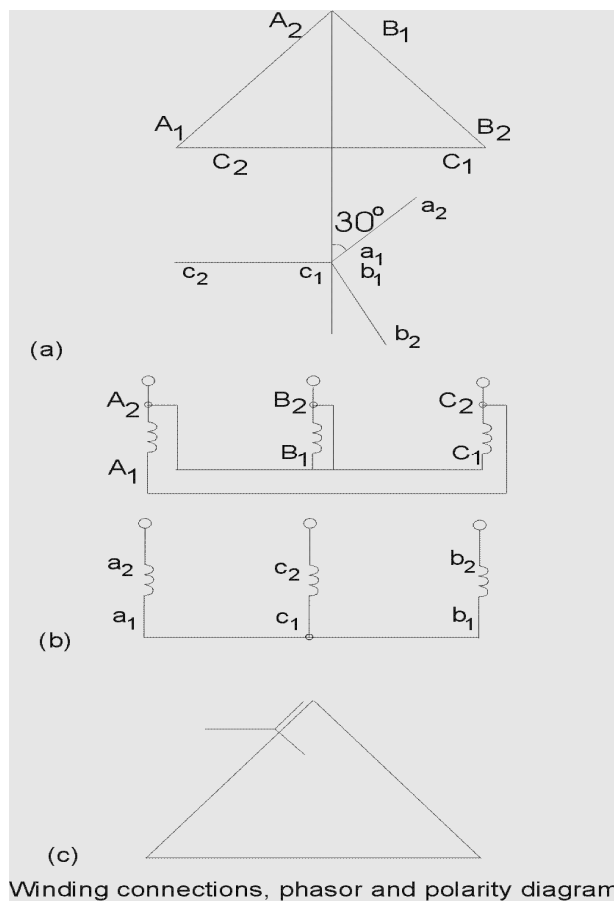
Table 3.1 lists the various group numbers that transformer phasors can be categorized into, representing the induced emfs and the counter clockwise direction of rotations.

Table 3.1
Transformer Group numbers

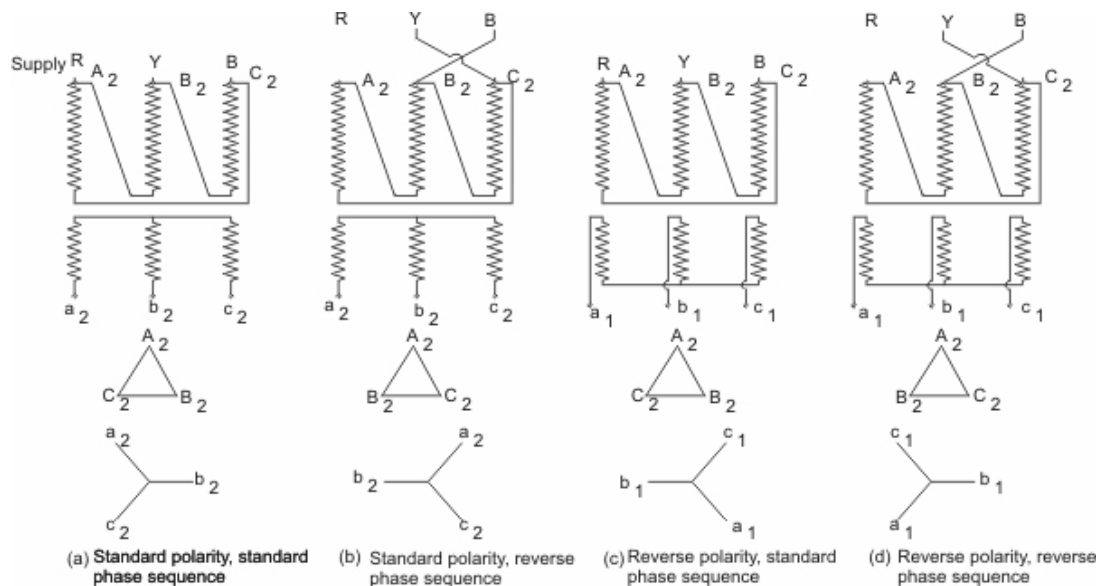
Group Number	Phase Displacement	Clock Hour Number
I	0°	0
II	180°	6
III	-30°	1
IV	$+30^\circ$	11

Considering the same example, if the primary delta connection had been made by connecting A_2B_1 , B_2C_1 and C_2A_1 , this would have resulted in a phase displacement of 30° clockwise (lagging) on the secondary side, i.e. the 1 o'clock position. This type of connection is termed as Dy1 (Or Dyn1)

It is also possible to interchange phase inputs on the primary side. That is, the phase sequence R, Y, B of the source may be connected to transformer windings A,C,B respectively. Figure 3.7 gives the four possible ways of connecting the Delta and the source which in turn results in different combinations of secondary voltage phase sequence/clock positions.

**Figure 3.6**

Winding connections, phasor and polarity diagram with modified connections on Primary

**Figure 3.7**

Diagrams showing four examples of a three-phase delta/star-connected transformer having different polarity and phase sequence with different input / delta connections

Inter-phase connections of the HV and LV windings are indicated in Table 3.2.

Table 3.2
Winding connection designations

Winding connection		Designation
high voltage	Delta	D
	Star	Y
	Interconnected star	Z
low voltage	Delta	d
	Star	y
	Interconnected star	z

3.4 Delta–Star and Star–Delta connections

As seen above these connections result in a phase shift on the secondary side with respect to the primary source. The Delta–Star connections are employed in HV transmission systems at the generator end where the voltages are stepped up from the generator to quite a high value. These are also employed where single-phase loads are to be fed on the secondary side by having single-phase loads connected between phase and neutral. Normally the neutral end is grounded to avoid floating neutral and flow of third harmonic currents need to be taken care on the Delta connected end.

The Star Delta combination is used where the line-to-line voltage is to be stepped down considerably because of the introduction of $\sqrt{3}$ factor on the line-to-line voltage in the Y connection.

It is to be noted that the Delta connection requires $\sqrt{3}$ times more turns on each limb compared to a star connection. At the same time due to the difference in the phase and line currents of a 3 phase system, the star connected winding requires $\sqrt{3}$ times cross section of the delta connected conductor. Hence the size and economy decides the connection methods to be employed on the transformers.

At the same time since the low voltage distribution in most of the cases require single-phase loads to be fed, the Y connection is more common on the secondary side of distribution transformers. The other advantage of the Y connection on the secondary side is the possibility to earth the neutral to limit the fault current and reduce the touch potential levels with resistive earthing.

3.5 Star–Star connected transformers

The other type of connection possible in a three-phase transformer is to have both primary and secondary connected in Y. This type of connection normally achieves two possible vector groups Yy0 and Yy6. Yy0 is achieved when the transformer is having the neutral connections of primary and secondary formed by grouping $A_1 B_1 C_1$ and $a_1 b_1 c_1$ to form the neutral point in the respective windings. Yy6 is achieved when the primary is undisturbed but grouping $a_2 b_2 c_2$ to form the secondary neutral.

Normally the star-star connection is mostly used in the case of bigger power transformers and for transformers having less single-phase connections. This is because the neutral of these transformers cannot be loaded beyond 10% of the rated current. It is also to be noted that the number of turns per phase and the insulation requirements are lower because the phase voltage is $1/\sqrt{3}$ times the line voltage.

The major disadvantage of the Y-Y connection is the introduction of third harmonic currents to the loads, which requires the use of a tertiary winding to allow path for third harmonics. The advantage of the Y-Y connection is that the insulation can be graded towards the neutral end, which makes the cost comparatively lower. The disadvantage is of course the limitation for connecting single-phase loads. Also, when the generator is connected in Y the Y connection on primary side of transformers eliminates the distortions in the secondary voltage by interconnecting the neutrals of the generator and Y connected primary.

3.6 Delta-delta connections

These connections are employed in large power rated transformers used in low voltage applications because the insulation cost does not become a major economical issue in low voltage applications. This connection ensures that the third harmonic current can flow in the delta windings without flowing on the line side. The secondary voltages will not have any phase displacement with respect to the primary end.

This connection does not pose any floating neutral issues as experienced with Y connections when load unbalances are encountered.

3.7 Zig zag connections

These are extensions of a star connection to introduce two-phase shifts on the star connected portion of the windings. This connection requires two sets of windings on the primary or secondary which are to be star connected with the interconnection between these two sets of windings modified in different ways to introduce an additional phase shift in a part of the windings.

Figure 3.8 shows the typical zig zag connection of a three-phase transformer along with the vector relation between the primary and secondary winding. Here the zig zag connection is represented by the letter z.

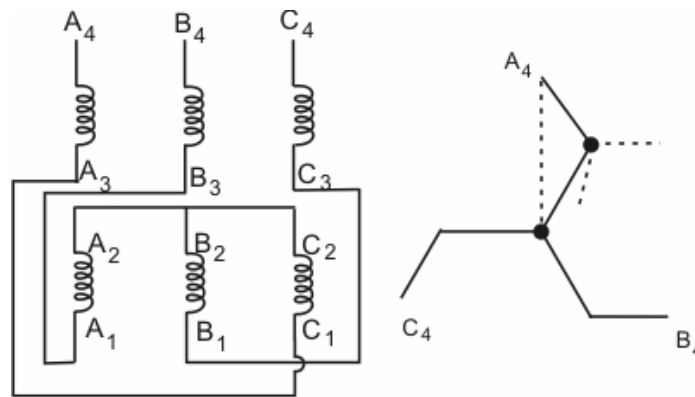


Figure 3.8
Zig zag connection of a transformer and the vector group.

3.8 Transformers with tertiary windings

It is most common to come across transformers with a third winding called tertiary winding in addition to primary and secondary windings. This is adopted in large size transformers in power stations and large switching substations. The most common reason for the additional third set of windings to a three-phase transformer is for the provision of a delta-connected tertiary winding to provide path for the third harmonics. Other reasons are:

- To limit the fault level on the LV system by sub-dividing the in-feed – i.e. double secondary transformers
- The interconnection of several power systems operating at different supply voltages
- The regulation of system voltage and of reactive power by means of a synchronous capacitor connected to the terminals of one winding

As has been mentioned earlier in this chapter, it is desirable that a three-phase transformer has one set of three-phase windings delta-connected, thus providing a path for third-harmonic currents. The presence of delta-connected windings also allows current to circulate around the delta in the event of an imbalance in the loading between the phases, so that this imbalance is reduced.

If the neutral of the supply and the star-connected winding are both earthed, then although the transformer output wave form will be undistorted, the circulating third-order harmonic currents flowing in the neutral can cause interference with telecommunications circuits and other electronic equipment. Further it can cause unacceptable heating in any neutral earthing resistors, so this provides an added reason for the use of a delta-connected tertiary winding.

If the neutral of the star-connected winding is unearthed then, without the use of a delta tertiary, this neutral point can oscillate above and below earth at a voltage equal in magnitude to the third-order harmonic component. Because the use of a delta tertiary prevents this, it is sometimes referred to as a stabilization winding.

The load currents in the primary phases corresponding to a single-phase load on the secondary of a star-star transformer with a delta tertiary are typically as shown in Figure 3.9 assuming a one-to-one turn ratio for all windings.

This leads to an ampere-turns rating of the tertiary approximately equal to one-third that of the primary and secondary windings and provides a rule-of-thumb method for rating the tertiary in the absence of any more specific rating basis.

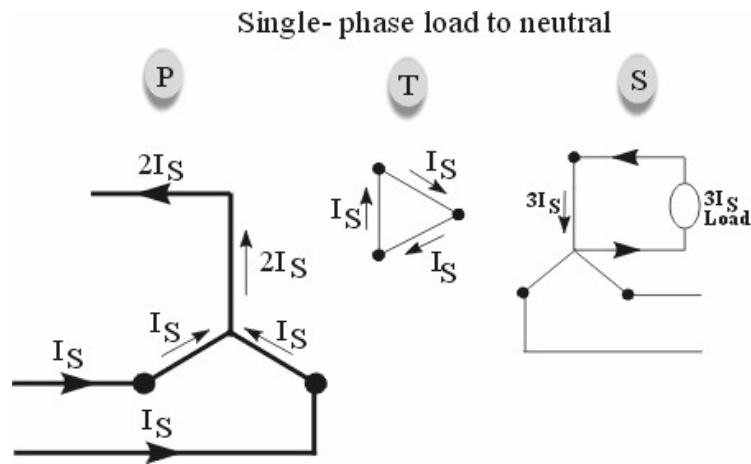


Figure 3.9
Single-phase load to neutral

3.9 Double secondary transformers

This is another type of multi-winding transformers where it is required to split the number of supplies from a HV feeder to economize on the quantity of HV switchgear and at the same time limit the fault level of the feeds to the LV switchgear.

In designing the double secondary transformer, it is necessary that both LV windings are disposed symmetrically with respect to the HV winding so that both have identical impedances to the HV. The two possible arrangements to achieve this, is as shown in Figure 3.10 (in both instances there is a crossover between the two LV windings half way up the limb.)

The leakage reactance LV1 to LV2 in the first case would be high as the LV windings of Figure 3.10(a) are loosely coupled due to the fact that the inner LV upper half crosses to the outer upper half and the inner lower half crosses to the outer lower half.

The leakage reactance LV1 to LV2 in the second case would be low as the LV windings of Figure 3.10(b) are closely coupled due to the fact the upper inner crosses to lower outer and upper outer crosses to lower inner. Thus, the equivalent circuits for these two arrangements are as in Figure 3.11 wherein the transformer is represented by a three-terminal network and typical values of impedance (leakage reactance) are marked.

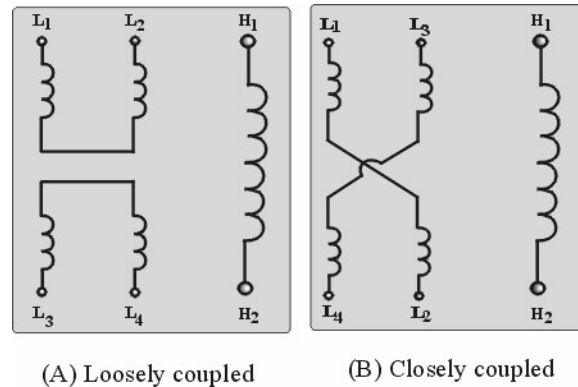


Figure 3.10
Transformers with two secondary windings

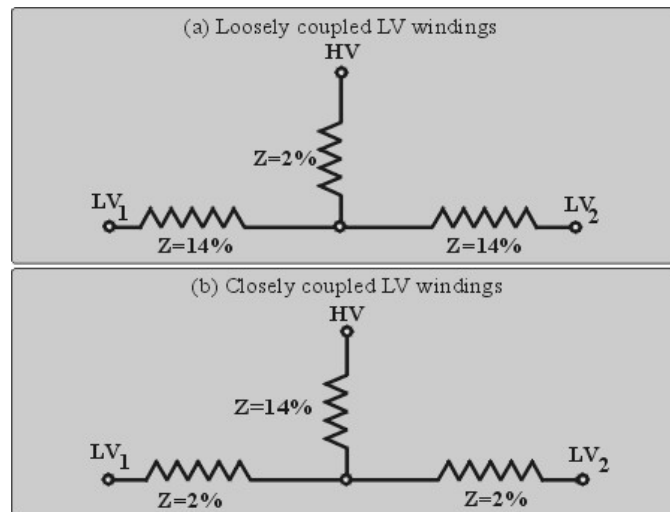


Figure 3.11
Equivalent circuits for loosely coupled and closely coupled double secondary transformers

3.10 Three-phase banks using single phase transformers

The connections in the preceding clauses refer to having all the three-phase windings connected inside a common tank with magnetic core formed in the form of 3 or 5 limbs to accommodate all the three sets of windings on both primary and secondary. In the above arrangements the connections on the primary and secondary are fixed though it is possible to change the phase relationships by interchanging the input phase connections.

It is also possible that we can have independent single-phase transformers with two terminals for each transformer. Then it is possible to choose the vector groups of any combination by just modifying the connections on the primary and secondary sides either in Delta or Star and to get any desired phase shift.

The major deciding factor to go for such an arrangement is the space and cost. In earlier days it was common to have such arrangements keeping one spare single-phase transformer. Hence it is possible to have better redundancy with such a group of single-phase transformers when space permits. However because of the improved reliability of three-phase transformers due to design improvements, the use of single-phase transformers for three-phase conversion is not so common.

3.11 Scott connections

These are employed where it is required to convert a three-phase voltage to three-phase voltage with two windings without resorting to 3-phase connections seen earlier. This is also called a T-T connection because of the way the connections look. In these connections we have two windings in which one of the windings has a center tap point to which the end of the first winding is connected. Figure 3.12 shows the method of Scott connection with center taps on primary and secondary sides.

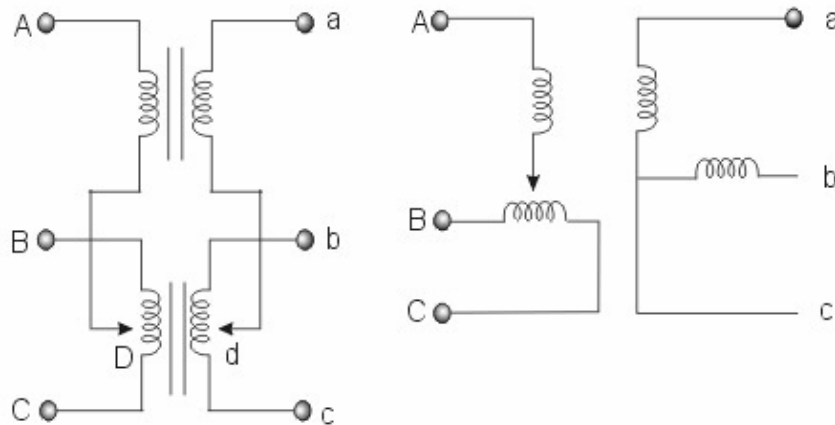


Figure 3.12
Typical Scott Connection

A similar connection can be employed with tapplings at a different point instead of center point. The common use is 0.866 tap which is called a teaser transformer.

These connections are generally useful when there is a requirement to convert three-phase to two-phase and vice versa, which are some times used to feed two-phase furnaces

3.12 Autotransformers

These are transformers, which use common winding for both primary and secondary with a common neutral end. It can be either single-phase or three-phase. The connections we studied earlier are basically termed as isolation transformers where isolated secondary winding is used. Autotransformers on the other hand have common primary and secondary windings except for the tapping on the winding (to get the required voltage).

Typical applications for these transformers are in Motor starting circuits, Testing transformers, Interconnecting two utility substations transmitting at different kV, etc.,. The connections are obviously economical in terms of cost and space compared to two-winding isolation transformers.

The main disadvantage of this type is that all interference on the supply side is transferred to loads without isolation.



Figure 3.13
Typical connections in autotransformer vis-à-vis isolation transformer

3.13 Parallel operation of transformers

Parallel operation of transformers occurs when two or more transformers are connected to the same HV and LV busbars, especially on the load side. This is widely followed in power stations and continuous process plants, to ensure that in the event of transformer or generator failures, redundancy is built in the distribution to maintain power supply through healthy transformers.

Five principal characteristics shall be met by each of the transformers to be operated in parallel:

- Same inherent phase angle difference between primary and secondary terminals
- Same voltage ratio
- Same percentage impedance (10% tolerance is acceptable)
- Same polarity
- Same phase sequence
- Capacity not differing beyond 1:3 with respect to each other.

Figure 3.7 earlier showed four instances of delta-star-connected transformer under different conditions of polarity and phase sequence. There could be cases where the phase sequence required in the secondary side of one transformer could be different with respect to the other transformer.

In such a case, reversing the internal connections on one side of the transformer can change polarities but interchanging two of the primary supply leads can reverse the phase sequence. Referring to the same figure, transformers in diagrams in (a) and (d) can be paralleled so long as the secondary leads from a_1 and c_1 to the busbars are interchanged.

Referring to Figure 3.14 below that typically represent a power station auxiliary system, we have a 660 MW generator generating at 23.5 kV that is stepped up to 400 kV via a generator transformer and with a unit transformer providing a supply to the 11 kV unit switchboard. While the unit is being started up, the 11 kV switchboard will normally be supplied via the station transformer that takes its supply directly from the 400 kV system. At some stage during the loading of the generator, supplies will be changed from the station transformer to the unit transformer, which will briefly involve paralleling these sources so it is imperative that the supplies are in phase.

The generator transformer will probably be connected star-delta with the 23.5 kV phasor at 1 o'clock; i.e. YNd. The 23.5-11kV unit transformer will be connected delta-star with its 11 kV phasor at the 11 o'clock position, i.e. Dyn1. This means that the 11 kV system now has a zero phase shift compared to the 400 kV system. Thus, the station transformer must now connect the 400 kV system to the 11 kV system without any phase shift, and therefore this is achieved by utilizing a star-star connected transformer.

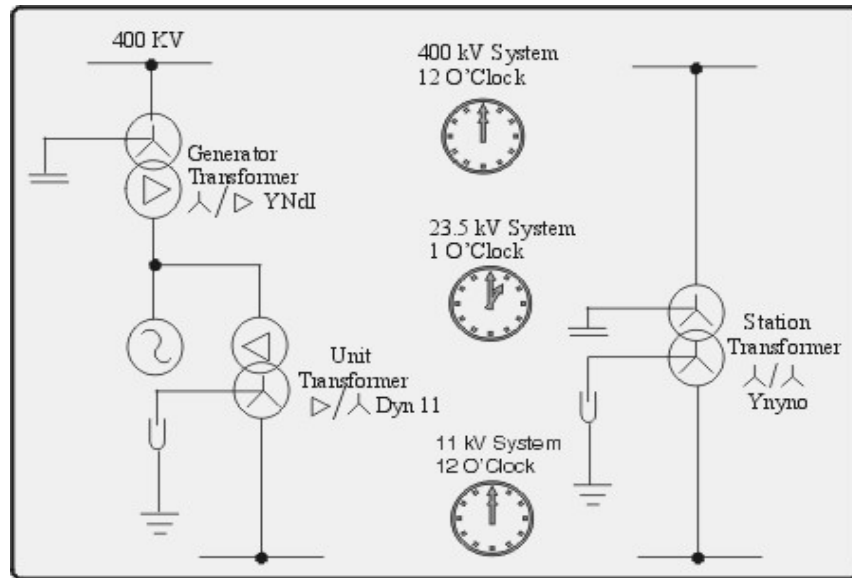


Figure 3.14
Power station auxiliary system

3.14 Impedances for parallel connected transformers

Paralleling of two identical transformers reduces the combined impedances to half that of the individual transformers, resulting in the increase of the fault level of the LV busbar. This is to be taken into consideration while designing distribution equipment and protective relaying for transformers operated in parallel.

Take an example where there are n transformers to be operated in parallel with all the basic conditions met by each of them. Assume the individual capacities as $S_1, S_2, \dots, S_n$ and individual percentage impedances as $Z_1, Z_2, \dots, Z_n$ for these transformers. S is the total capacity of the transformers and Z is the combined % impedance of the group.

Then the combined percentage impedance voltage offered by the parallel operation will be arrived by using the formula

$$\frac{S}{Z} = \frac{S_1}{Z_1} + \frac{S_2}{Z_2} + \dots + \frac{S_n}{Z_n} \dots \dots \dots (3.1)$$

The transformers cannot be assumed to share the loads proportionate to the individual capacity, since the individual impedance also holds the key for the load carried by individual transformers. This is given by

$$S'_1 = S_1 \times \frac{Z}{Z_1} \dots \dots \dots (3.2)$$

where S'_1 is the permissible full load capacity of the transformer having a capacity of S_1 .

3.15 Vector groups and connections

The tables on the following pages give the various vector groups and their connections depending on the interconnection chosen in the respective primary and secondary phase terminals. It is mandatory to identify the internally adopted connections as one of these diagrams, on the transformer nameplate as part of transformer main data.

Table 3.3
Group I Vector Diagrams

Typical Group-I Zero Degree Phase Displacement Transformers

Vector Group	Line Terminals & Induced Voltages Phasor Diagram		Winding Connections
	H.V.Winding	L.V.Winding	
YNyn0			
Dd0			
Dz0			
ZNd0			

Table 3.4
Group II Vector Diagrams

Typical Group-II 180 Degree Phase Displacement Transformers

Vector Group	Line Terminals And Induced Voltages Phasor Diagram		Winding Connections
	H.V. Winding	L.V. Winding	
$Y_N y_n 6$			
Dd6			
Dz6			
Zd6			

Table 3.5
Group III Vector Diagrams

Typical Group-III (-30) Degree Phase Displacement Transformers

Vector Group	Line Terminals And Induced Voltages Phasor Diagram		Winding Connections
	H.V. Winding	L.V. Winding	
Dy1			
Yd1			
Yz1			
Zy1			

Table 3.6
Group IV Vector Diagrams

Typical Group IV +30 Degree Phase Displacement Transformers

Vector Group	Line Terminals & Induced Voltages phasor Diagram		Winding Connections
	H.V.Winding	L.V.Winding	
Dy11			
Yd11			
Yz11			
Zy11			

Table 3.7
Single/Two Phase Vector Diagrams

Typical 1/2 phase, Scott connected Transformers

Type	Line Terminals And Induced Voltage Phasor Diagram		Winding Connections
	H.V. Winding	L.V. Winding	
Single Phase			
Two Phase			
SCOTT Transformer			

