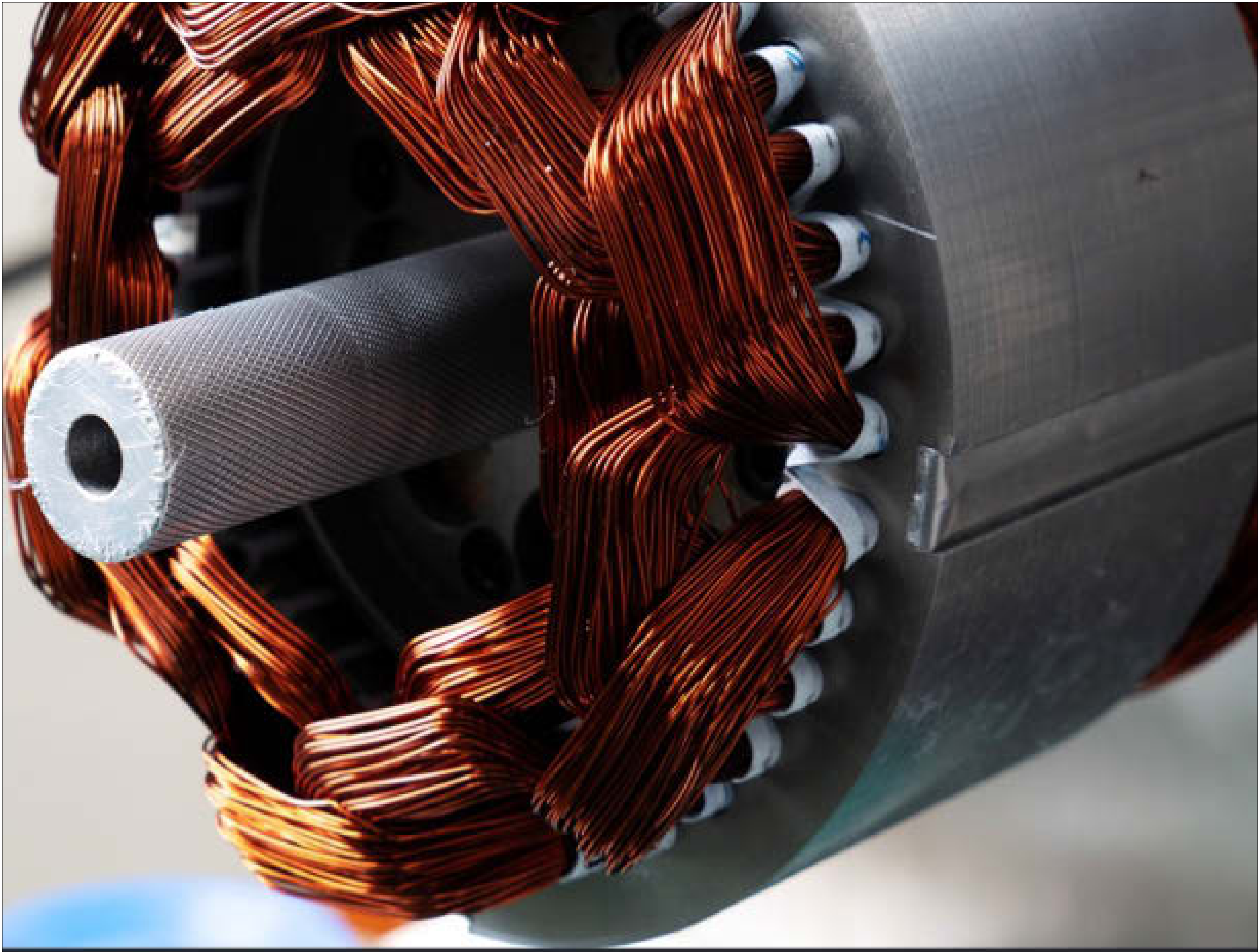

Principles of Electrical Machines

Savitha R
Vivek Kumar Jain

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BOOKS ARCADE
Regd. Office:
F-10/24, East Krishna Nagar, Near Vijay Chowk, Delhi-110051
Ph. No: +91-11-79669196, +91-9899073222
E-mail: info@booksarcade.co.in, booksarcade.pub@gmail.com
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CONTENTS

CHAPTER 1

Introduction of Electrical Transformers

Savitha R, Assistant Professor
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology,
JAIN (Deemed-to-be University), Karnataka – 562112
Email Id- r.savitha@jainuniversity.ac.in

A transformer is an electrical device that transfers energy from one electric circuit to another using the electromagnetic induction principle. It is intended to change the AC voltage between the circuits while keeping the current's frequency constant. Transformers do this without establishing a conductive link between the two circuits. This is made feasible by using Faraday's Law of Induction, which explains how an electric circuit will interact with a magnetic field to create Electromotive Force (EMF). The magnetic core, the primary winding, and the secondary winding are the three components that make up a simple transformer. A live supply of AC power is connected to the main winding. The winding is encircled by an oscillating magnetic field as a result. As a result, the secondary winding experiences an EMF. AC electricity will flow via the secondary winding if its circuit is closed. The magnetic core, which is typically constructed from laminated steel sheets and offers a low resistance route for the magnetic field, is shared by these windings. The ratio of the number of turns between the two windings and the output voltage to the input voltage is the same. The secondary winding will have fewer turns than the primary in a step-down transformer and more turns than the primary in a step-up transformer.

Fundamental Transformer Design

The first transformer was created in England in 1884, and it completely changed how AC electricity might be used. The steam-powered Rome-Cerchi power plant, which was the first AC power plant, employed this transformer in 1886. With the help of the transformer, AC electricity could be produced and provided at high voltages between 1,400 and 2000 volts before being stepped down to a lower, safer level for usage in residences and commercial buildings. While contemporary transformers are still employed for a broad range of applications, the original fundamental design is still in use. They may reach many storeys in height and are used in electrical power plants to transport electricity at high voltages, which is more effective than doing so at low voltage since it lowers power loss from heat. Signal and audio transformers, which are considerably smaller, are used to match the input of amplifiers to the output of microphones and other audio equipment. Measurement transformers reduce a main power line's power to a lower voltage so that its output may be monitored without causing damage to delicate equipment. For the purpose of conveying digital information to logic gates or drivers in electronic devices, pulse transformers transport pulses from a main circuit to a secondary circuit.The majority of the aforementioned uses are for single-phase transformers. One main winding and one secondary winding are included in this kind of transformer. However, three-phase transformers are also available. Transformers with three phases have three sets of windings. These transformers provide three-phase electricity and are used to power industrial loads.

Fundamentals of a Transformer:

1. A transformer employs electromagnetic induction to increase or decrease voltage while transferring AC current from one circuit to another.
2. The magnetic core, secondary winding, and primary winding are the three components that make up a simple transformer.

3. Transformers come in a wide range of shapes and sizes, from enormous ones used in power plants to microscopic ones found in electronics.

Types of Transformer

Types of transformers according to voltage level

Based on the operating voltage, there are essentially two kinds of transformers, as shown in below Figure 1.1:

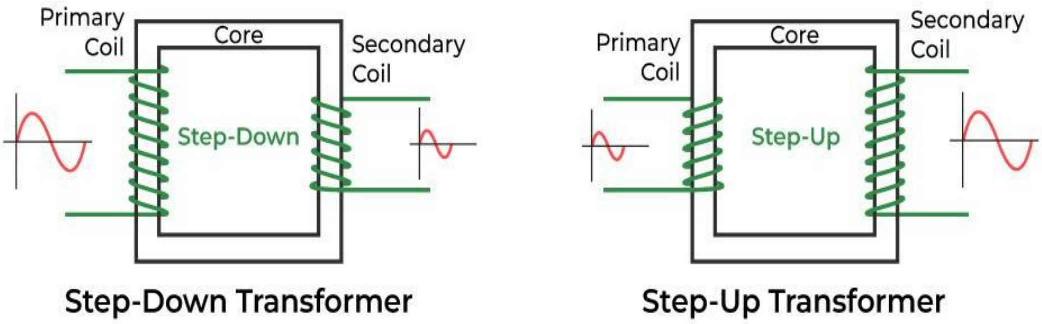


Figure 1.1. Step-up down and step-up transformer

Step-down Transformer:

A step-down transformer is used to change the main voltage across the secondary output to a lower voltage. A step-down transformer has more windings on its primary side than its secondary side. The total secondary to primary winding ratio will always be less than one as a consequence. In order to provide minimal loss and cost-effective solutions, step-down transformers are employed in electrical systems that distribute power over great distances and run at very high voltages. High-voltage supply lines are converted into low-voltage supply lines using a step-down transformer.

Step-up Transformer:

A step-up transformer raises the low primary voltage to a higher secondary voltage. In this kind of transformer, the ratio of the primary to secondary winding will be larger than one since the primary winding has less turns than the secondary winding. Electronics stabilisers, inverters, and other devices that convert low voltage to a much greater voltage typically include step-up transformers. In the process of distributing electricity, a step-up transformer is also used. High voltage is required for applications linked to power distribution. A step-up transformer is used in the grid to increase the voltage level before distribution.

Transformer based on Core Material

In the electricity and electronics sectors, many kinds of transformers are used based on the primary materials, which include:

Iron Core Transformer

The core of an iron core transformer is composed of several soft iron plates. The iron core transformer's powerful magnetic characteristics have a very high flux linkage. The iron core transformer has a high efficiency as a consequence. The soft iron core plates are available in a range of dimensions and forms. E, I, U, and L are a few common shapes.

Ferrite Core Transformer

A ferrite core transformer makes use of one due to its high magnetic permeability. This kind of transformer has exceptionally low losses in high-frequency applications. Therefore, ferrite core transformers are utilised in high-frequency applications such as Switch Mode Power Supply (SMPS), RF-related applications, etc.

Toroidal Core Transformer

Two examples of toroid-shaped core materials used in transformers are iron core and ferrite core. Toroids, which feature a ring- or donut-shaped core material, are commonly employed due to their high electrical performance. Very little leakage inductance and exceptionally high inductance and Q factors are produced by the ring shape.

Air Core Transformer:

An air core transformer's core is made of a substance that is not really magnetic. Only the air-core transformer flux connection uses the air. An electromagnetic field is created everywhere around an air-core transformer's main coil as it produces an alternating current.

Transformer based on Winding Arrangement

Auto Winding transformer:

While the primary and secondary windings have traditionally been fixed, an auto-winding transformer allows for the center-tapped node to be relocated and the secondary and primary windings to be linked in series. By moving the central tap, the secondary voltage may be adjusted. The term "auto" is not an acronym for "automatic"; rather, it is used to alert the self or a single coil. By combining its primary and secondary parts, this coil generates a ratio. The position of the central tap node, which alters the output voltage, affects the main and secondary ratio. The most popular device is the VARIAC, which produces variable AC from a constant AC input.

Transformer types depending on use exist in a large variety of variations, each of which works in a particular industry. Transformers may thus be grouped into the following groups according to their intended use:

Power Transformer: A bigger power transformer is used to transport the energy to the substation or the main electrical supply. This transformer acts as a connection between the main distribution grid and the power generator. According to their power rating and specifications, power transformers may be further split into three groups: small, medium, and large power transformers.

Measurement Transformer: Another term for this kind of transformer is an instrument transformer. Another measuring instrument that is often used in the power domain is this one. A measuring transformer is used to separate the main power and convert the current and voltage in a lower ratio to its secondary output.

Distribution Transformer: This step-down transformer lowers the high grid voltage to the required voltage for the end user, usually 110V or 230V. The size of the distribution transformer may vary depending on the ratings or conversion capability.

Pulse transformers: These are among the most widely used PCB-mounted transformers for producing electrical pulses with constant amplitude. It is used in many digital circuits when isolated pulse generation is required.

Audio Output Transformer: The audio transformer is another common transformer used in the electronics sector. It is primarily used in audio applications where impedance matching is required.

Operation of a Transformer

Mutual electromagnetic induction between the two coils, or Faraday's Law of Electromagnetic Induction, is the basic concept governing how the transformer operates. An explanation of the transformer's functioning is provided below. Two different windings cover the transformer's laminated silicon steel core. The main winding is the one to which the AC supply is linked, while the secondary winding is the one to which the load is connected, as shown in the picture below. Because mutual induction between the two windings needs an alternate flux, only alternating current may be employed, as shown in below mention Figure 1.2.

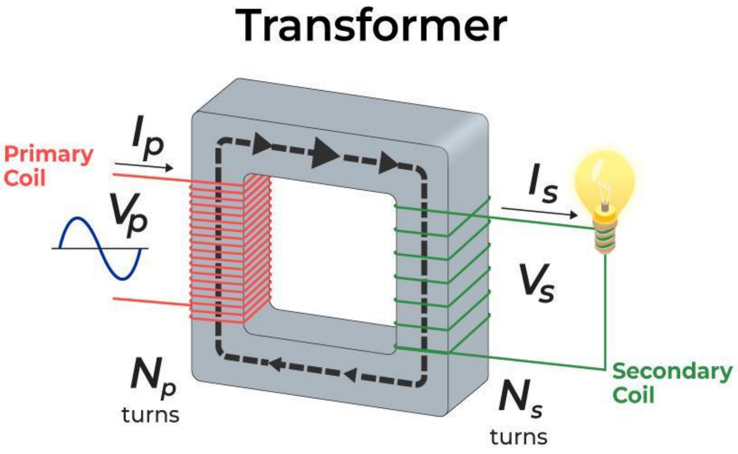


Figure 1.2 shows the operation of transformer.

According to the mutual inductance principle, when an alternating voltage is applied, the transformer primary winding generates an alternating flux known as the mutual flux.This alternating flux creates EMFs E1 in the main winding and E2 in the secondary winding in accordance with Faraday's law of electromagnetic induction. It also magnetically connects the transformer's primary and secondary windings. The main EMF is known as the EMF (E1), while the secondary EMF is known as the EMF (E2).

$$E_1 = -N_1 \frac{\mathrm{d}\phi_m}{\mathrm{d}t}$$

And,

$$E_2 = -N_2 \frac{\mathrm{d}\phi_m}{\mathrm{d}t}$$

Divide the aforementioned equations to get the ratio as:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

It is obvious from the formula above that the number of turns in the primary and secondary windings of the transformer affect the magnitude of EMFs E1 and E2, respectively. If E2 > E1 and N2 > N1, respectively, the transformer will be a step-up transformer; if E2 E1, it will be a step-down transformer.

If a load is now connected across the secondary winding, the EMF E_2 will cause the load current I_2 to flow through the load. As a consequence, a transformer enables the transmission of electricity between electric circuits with a change in voltage level.

Transformer Components

Three components make up the majority of a transformer:

A. Core

The winding is supported by the transformer core. It furthermore provides a low resistance magnetic flux flow path. The winding is wrapped around the core, as indicated in the figure. A laminated soft iron core is included in a transformer to reduce losses. Operational voltage, current, and power, among other factors, all affect the composition of the core. The core diameter has a direct negative correlation to copper losses and a direct positive correlation to iron losses.

B. Windings

Windings are the copper wires that are wrapped around the core of a transformer. Copper cables are utilised because of their high conductivity, which minimises transformer loss since conductivity increases with a decrease in flow resistance. Additionally, copper's high degree of ductility allows for the production of very thin wires.

The main and secondary coil windings are the two fundamental kinds of windings. The set of winding turns that receive supply current is known as the main winding. Secondary winding is the quantity of winding turns from which output is obtained. The main and secondary windings are isolated from one another using coatings that act as insulation.

C. Insulating Materials

Insulation is necessary in transformers to keep the windings separate and avoid short circuits. This facilitates mutual induction. Insulation agents affect the stability and longevity of transformers. The following materials are used as insulating media in transformers: Paper, tape, insulating fluid, and wood-based lamination.

D. Tank

The core and the windings of a transformer are shielded from the elements, such as rain and dust, and all other transformer attachments are supported by the main tank, which also acts as an oil container.

E. Transmission Fluid

The vast transformer is mostly covered with oil. The transformer oil enhances heat dissipation from the coils, provides insulation between the conductors, and offers fault-finding capabilities. Mineral oil with hydrocarbons often makes up transformer oil.

F. Conservators of oil

The transformer tank and bushings are above the oil conservator. A rubber bladder is a component of several transformer oil conservers. When a transformer is loaded, the temperature outside increases, which raises the internal oil pressure. The additional transformer oil may fit in the transformer conservator tank. Additionally, it acts as a storage area for the oil used to insulate houses.

G. Breather

It is a feature of any oil-immersed transformer with a conservator tank. It helps to safeguard the oil from dampness.

H. A/C units and fans

The transformer loses a lot of power, most of which is lost as heat. The transformer's heat is dissipated by radiators and fans, which also provide protection against failure. Most dry transformers use fresh air to cool them.

A perfect transformer

A pure theoretical transformer with zero losses, including zero core losses, copper losses, and additional transformer losses, is a perfect transformer. It is believed that this transformer is entirely effective.

When developing the ideal transformer model, it is assumed that the transformer's core is loss-free and that its windings are totally inductive. The transformer also has no leakage reactance (reactance is the opposition to the flow of current from the circuit element due to its inductance and capacitance). This shows that there is a 100% flux connection between the transformer's main and secondary windings. However, there must be some inductive resistance in every winding, which causes a voltage drop and I_2R loss. The windings of a model of an ideal transformer are thought to be perfect (completely inductive), meaning that they have no resistance.

Equation for the Ideal Transformer's EMF

Let Np be the number of turns on the primary winding and Ns be the number of turns on the secondary winding. An alternating magnetic flux that links the secondary coil and produces an emf is produced when an AC voltage is applied to the transformer's main coil. The magnitude of this emf depends on the secondary coil's number of turns. Consider a perfect (lossless) transformer with no flux in the core linking the main and secondary windings, zero primary coil resistance, and no voltage drop across the coil. Let be the flux linkage in each turn of the core at time t as a result of the current in the primary coil when the voltage Vp is applied to the primary coil (Figure 1.3).

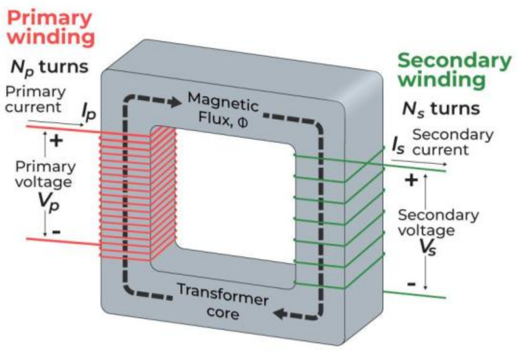


Figure 1.3 shows the emf equation of the transformer

The induced emf or voltage (εs) in the secondary with Ns turns is then calculated.

$$\varepsilon s = -Ns \times d\phi /dt \qquad (1)$$

In addition, the alternating flux generates a reverse emf in the main. This is it.

$$\varepsilon p = -Np \times d\phi /dt \qquad (2)$$

And for an ideal transformer, $\varepsilon p=Vp$

By approximation, if the secondary is an open circuit or the current drawn from it is modest, $\varepsilon s=Vs$.

The voltage across the secondary coil is Vs. As a result, Equations (1) and (2) may be written as

$$Vs = -Ns \times d\phi /dt \qquad (3)$$

$$Vp = -Np \times d\phi /dt \qquad (4)$$

From Equations (3) and (4), we have

$$Vs / Vp = Ns / Np \qquad (5)$$

The above equation is known as Transformer Equation or Transformer Formula.

To determine the prior connection, the following three presumptions are used:

Electrical resistances of the main and secondary coils are negligible.

The secondary current is negligible; the flux connectivity to the main and secondary coils is the same; or very few fluxes escape from the core.

Turning Ratio

Turn Ratio is a metric used to assess whether a transformer's secondary coil has more or fewer windings than its main coil. A primary coil has "Np" number of windings, but a secondary coil has "Ns" number of windings, which denotes the number of turns.

In the event of a perfect or 100% efficient transformer, the power input and output will be equal (no energy losses).

$$ipVp = isVs(6)$$

Equations (5) and (6) together give us $ip/is = Vs/Vp= Ns/Np=K$.

The equation before defines the turn ratio, K. The voltage is increased (Vs>Vp) if the secondary coil has more turns than the main coil (Ns>Np). Such a set up is known as a step-up transformer. A transformer is said to be a step-down transformer if the secondary coil has fewer turns than the primary coil (NsNp).

Performance of the Transformer

Commercial efficiency is another name for a transformer's efficiency. The output to input ratio of a transformer is referred to as its efficiency (in W or kW). As a result, the transformer's efficiency may be stated as follows:

Efficiencyis defined as (Power Output / Power Input).

The aforementioned equation may be used to a transformer that is perfect, meaning that there are no transformer losses and that all input energy is converted to output. Therefore, if transformer wastes are included and the transformer's efficiency is assessed throughout its practical states, the following equation is often utilized.

Efficiency is equal to 100% or ((Power O/P) / (Power O/P + Losses))

Efficiency is defined as (Power i/p - Losses) / (Power i/p - Losses) 100 = 1 (Losses/ i/p Power) 100.

Transformer Energy Losses

In the preceding calculations, an ideal transformer was employed (without any energy losses). In real transformers, some energy losses do take place for the following reasons:

Flux Leakage: Not all of the flux produced by the main coil makes it to the secondary coil because some flux leaks from the core. This happens because the core was poorly designed or because it has air holes. Wrapping the main and secondary coils around one another will allow you to lower it. If the core is well-designed, it may also be decreased.

Windings Resistance: The heat produced in the windings wastes energy since the wire used for the windings has some electrical resistance. By using thick wire with a high conductive material in high current, low voltage windings, these are reduced.

Eddy Currents: The iron core experiences energy losses due to heating as a consequence of eddy currents produced by the alternating magnetic field. The impact is lessened by the use of a laminated core.

Hysteresis Loss: During each AC cycle, the core's magnetization is reversed by the alternating magnetic field. By using a magnetic material with a low hysteresis loss, the loss of energy in the core, which happens as heat due to hysteresis loss, is reduced to a minimum.

The Use of Transformers

Some of the most popular applications for transformers include the following:

Altering the voltage level in an AC circuit to make sure all of its electrical components are functioning properly.It prevents DC from moving between circuits.It divides into two distinct electrical circuits.The electric power plant's voltage level has to be raised before transmission and distribution can happen.Electrical power is transformed from one circuit to another circuit using a static electrical device called an electrical transformer without affecting the frequency. Transformers have the ability to change the voltage while also changing the current.

Operating Principle of a Transformer

The fundamental phenomena that drives a transformer's operation is mutual induction between two windings connected by a shared magnetic flux. The simplest type of a transformer is seen in the image to the right. A transformer's main winding and secondary winding are two inductive coils. While the coils are electrically isolated from one another, they are magnetically connected. A source of alternating voltage must be connected to the main winding in order to create an alternating magnetic flux around the winding. The core provides magnetic path for the flux, to get linked with the secondary winding. The majority of the flux is referred to as "useful flux" or "main flux" when it is connected with the secondary winding, while the flux that is not linked with the secondary winding is referred to as "leakage flux" when it is not. According to Faraday's law of electromagnetic induction, EMF is generated in the secondary winding as a result of the flux produced being alternating (its direction continually changing). This emf is referred to as "mutually induced emf," and its frequency is identical to that of supplied emf (Figure 1.4). Electrical energy is transmitted from one circuit (primary) to another circuit if the secondary winding is closed circuit and is thus conducting mutually induced current (secondary).

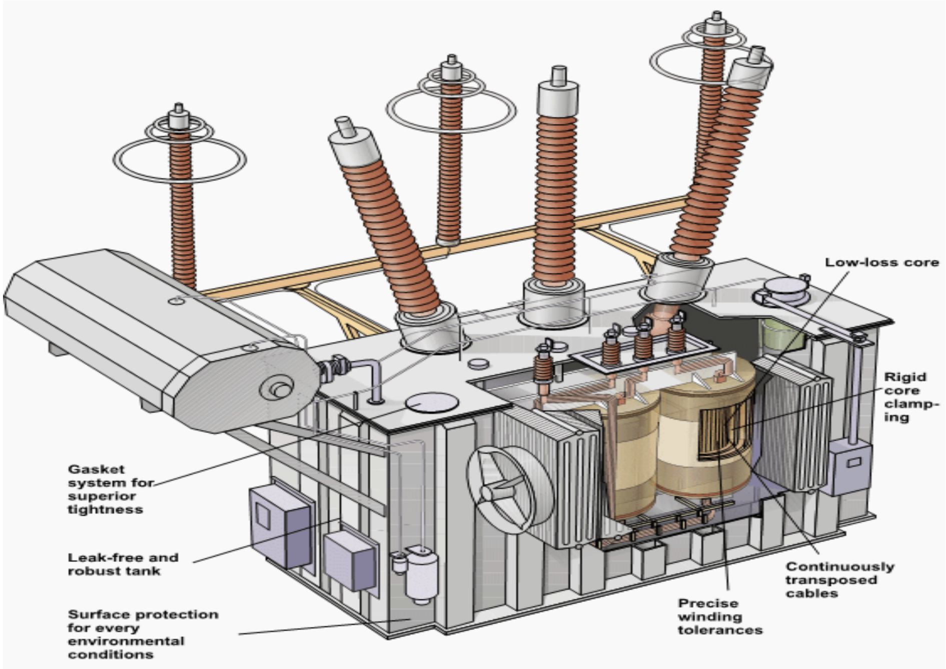


Figure 1.4 internal design of the electric transformer

A transformer is made up of a laminated steel core and two inductive windings. Both the steel core and the coils are isolated from one another. A transformer may additionally have an oil conservator to provide oil in the transformer tank for cooling reasons, adequate bushings to take out the terminals, and a container for the winding and core assembly (referred to as a tank). The diagram on the left shows how a transformer is made in its most basic form.The core of all kinds of transformers is built by stacking steel sheets that have been bonded together with the least amount of space between them possible (to achieve continuous magnetic path). In order to offer high permeability and little hysteresis loss, the steel utilised has a high silicon concentration and is sometimes heat treated. Steel sheets that have been laminated are utilised to reduce eddy current loss. The sheets are shaped into letters E, I, and L. Laminations are piled by switching the sides of joints in order to prevent excessive resistance at joints. In other words, if the first sheet assembly's joints are on the front face, the next assembly's joints will be on the rear face.

CHAPTER 2

Classification, Equation and Diagram of Transformer

Spoorthi B, Assistant Professor
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka – 562112
Email Id- spoorthi.b@jainuniversity.ac.in

Transformer Types

Transformers may be categorised using a variety of criteria, such as construction type, cooling method, etc.Transformers may be categorised into two groups based on their construction: (i) Core type transformers and (ii) Shell type transformers.

Transformer of the Core Type

Transformers of the core type have windings that are positioned on the core limbs and are cylindrically former wound, as shown in the illustration above. Each layer of the cylindrical coils is isolated from the others and has a varied number of layers. For insulation, materials like paper, linen, or mica may be employed. Because they are simpler to insulate, low voltage windings are positioned closer to the core.

Shell Type Transformer

The coils are sandwiched between layers of insulation and are former wrapped. A shell type transformer might have a scattered shape or a basic rectangular form, as shown in the belowFigure 2.1.

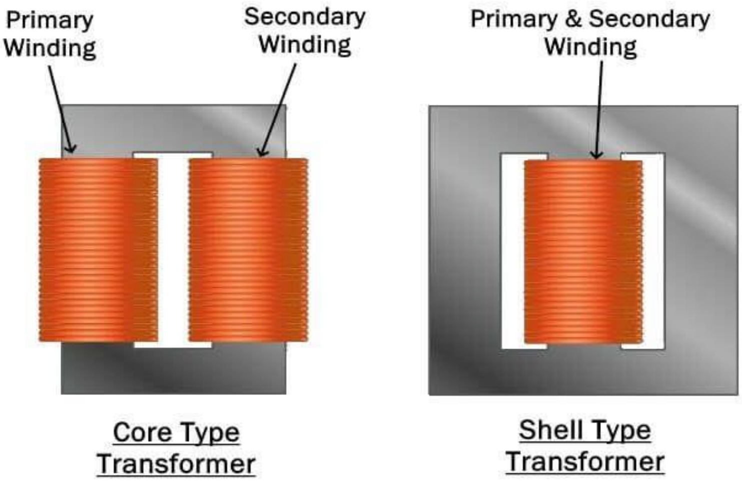


Figure 2.1 core and shell type of transformer

Based on the purpose behind them

Step-up transformer: Secondary voltage rises (with a corresponding fall in current).

Step-down transformer: At the secondary, the voltage drops (with a corresponding rise in current).

Based on the types of supply

A. Transforms one phase only

B. Two-phase transformer (D) based on how they are used

1. Power transformer: High-rated, used in transmission networks

2. Distribution transformer: This kind of transformer, which has a lower rating than power transformers, is used in distribution networks.

3. Instrument transformer: Used in many instruments in industries for relay and protection purposes.

Transformers: Current (CT), Potential (PT), and (PT)

Based on the cooling method used

A. The self-cooling, oil-filled kind

B. An oil-filled, water-cooled design

C. An air blast (air cooled)

Equation for a Transformer's EMF

Alternating flux m forms in the iron core of a transformer when a sinusoidal voltage is given to the primary winding. Both the main and secondary windings are connected by this sinusoidal flux. A sine function describes the flow function.Mathematically, the rate of change of flow with respect to time is obtained.Below is a Figure 2.1 illustrating how the transformer's EMF Equation was derived

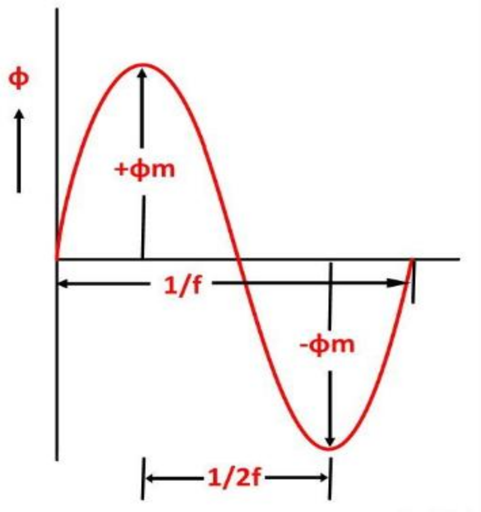


Figure 2.2 derivation of transformer equation

Let

- ϕ_m be the maximum value of flux in Weber
- f be the supply frequency in Hz
- N_1 is the number of turns in the primary winding
- N_2 is the number of turns in the secondary winding
- Φ is the flux per turn in Weber

As shown in the above figure that the flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.

By Faraday’s Law

Let E_1 be the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt} \dots\dots\dots (1)$$

Where $\Psi = N_1\phi$

$$E_1 = -N_1 \frac{d\varphi}{dt} \dots\dots\dots (2)$$

Since ϕ is due to AC supply $\phi = \phi_m$ Sinwt

$$E_1 = -N_1 \frac{d}{dt} (\varphi_m \, \text{Sinwt})$$

$$E_1 = -N_1 \, w\varphi_m \, \text{Coswt}$$

$$E_1 = N_1 w\varphi_m \, \text{Sin}(wt - \pi/2) \dots\dots\dots (3)$$

So the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 max = N_1 w\varphi_m \dots\dots\dots (4)$$

But $w = 2\pi f$

$$E_1 max = 2\pi f N_1 \varphi_m \dots\dots\dots (5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \dots\dots\dots (6)$$

Putting the value of E_1max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \text{........}(7)$$

Putting the value of π = 3.14 in the equation (7) we will get the value of E_1 as

$$E_1 = 4.44 f N_1 \varphi_m \dots \dots \dots (8)$$

Similarly

$$E_2 = \sqrt{2}\pi f N_2 \varphi_m$$

Or

$$E_2 = 4.44 f N_2 \varphi_m \dots \dots \dots (9)$$

Now, equating the equation (8) and (9) we get

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \varphi_m}{4.44 f N_1 \varphi_m}$$

Or

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

The above equation is called the turn ratio where K is known as the transformation ratio.The equation (8) and (9) can also be written as shown below using the relation, (ϕ m = B_m x A_i) where A_i is the iron area and B_m is the maximum value of flux density.

$$E_1 = 4.44 N_1 f B_m A_i \ \text{Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \ \text{Volts}$$

For a sinusoidal wave

$$\frac{\text{R.M.S value}}{\text{Average value}} = \text{Form factor} =$$

Transformer Phasor Diagram

There are a few key considerations that must be made before moving on to the transformer phasor diagram. We will create the phasor diagram for the transformer's No Load, Lagging Load, and Leading Load conditions based on these considerations.

Important Points for the Transformer Phasor Diagram

A. A transformer's excitation current, when there is no load applied, merely leads the working flux by a hysteretic angle.
B. The excitation current has two components: a core loss component (Ic) that is phase-locked to the applied voltage and a magnetising current that is phase-locked to the working flux (Im).
C. The Electromotive Force (EMF), which is produced by working flux, lags it by 90 degrees.
D. When a transformer is connected to a load, it draws additional current (I') from the source, resulting in the equation $N_1I' = N_2I_2$, where I' stands for the load component of primary current I.

Transformer operation in a loaded state

The following describes how the transformer operates when it is loaded:

The transformer pulls the no-load current from the main supply while the secondary is left open. The magnetomotive force N_0I_0 is induced by the no-load current, and this force createshe flux in the transformer core. The diagram below depicts the transformer's circuit when there is no load.

The secondary winding of the transformer experiences I_2 current flow when the load is connected to the secondary. The transformer's secondary winding experiences the magnetomotive force N_2I_2 as a result of the secondary current. The flux 2 in the transformer core was created by this force. Lenz's law states that the flux 2 opposes the flux (Figure 2.2).

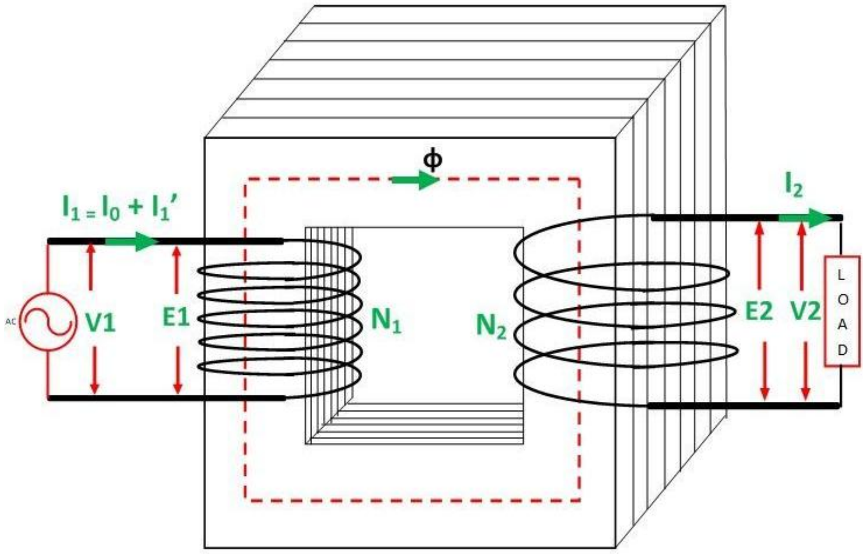


Figure 2.2. Transformer operation in load condition

The transformer's resulting flux diminishes when flux 2 opposes flux 1, and this flux lowers the induced EMF E_1. As a result, the V_1 has greater strength than both E1 and the extra primary current I'_1 that is pulled from the main supply.The extra current is utilized to bring the flux in the transformer's core back to its initial value such that $V_1 = E_1$. The main current I'_1 and secondary current I_2 are in phase opposition. It is referred to be the major counter-balancing current as a result.

The magnetomotive force $N_1I'_1$ is produced by the extra current I'_1. This force also created the flux '1. The flux's direction is the same as that of the, and it cancels the flux 2 that the MMF N_2I_2 produces.

Now, $N_1I_1' = N_2I_2$

$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

Therefore,

The power factor angle 1 of the primary side of the transformer is determined by the phase difference between V_1 and I_1.

The kind of load connected to the transformer affects the power factor on the secondary side. The power factor will be trailing if the load is inductive, as indicated in the phasor diagram above, and leading if the load is capacitive. The vector sum of the currents I_0 and I_1 yields the total primary current, I_1. i.e

$$\overline{I_1} = \overline{I_0} + \overline{I_1'}$$

Transformer Phasor Diagram with Inductive Load

Below is a picture of the real transformer's phasor diagram as it is being loaded inductively.

Phasor Diagram for No Load Condition:

Transformer at no load means that its secondary winding is open and primary is energized from voltage source. Figure following displays this circumstance (Figure 2.3).

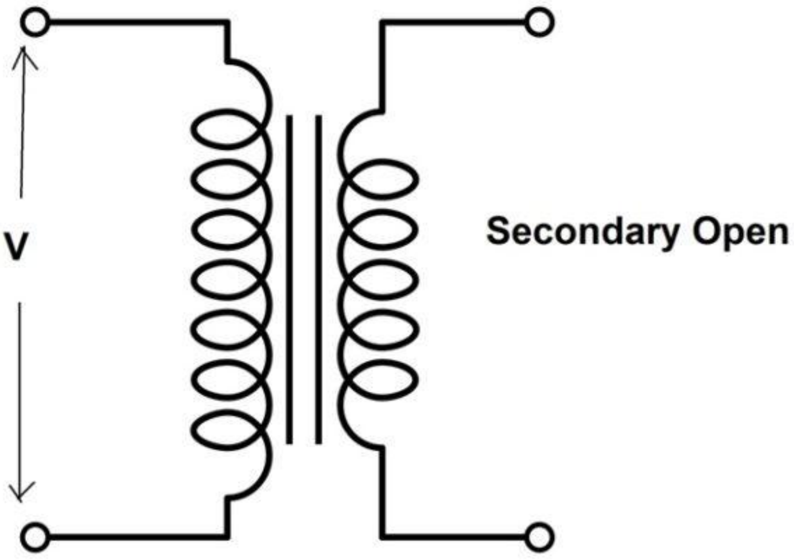
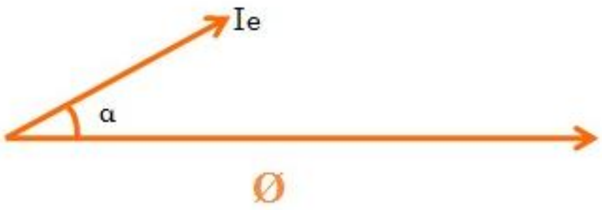


Figure 2.3 No Load Condition

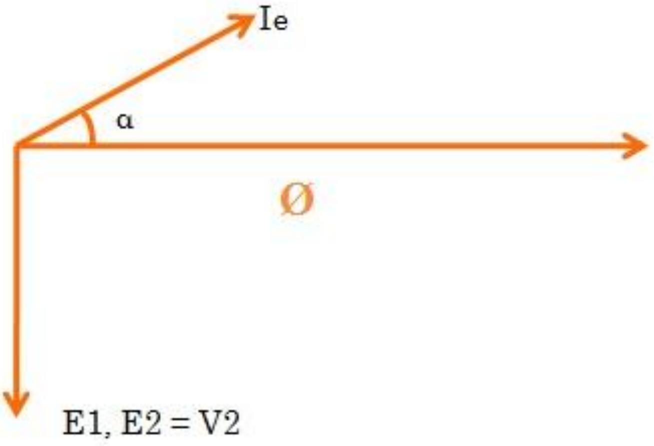
The methods listed below should be followed for a transformer's phasor diagram under no-load conditions:

Working Flux is used as Reference in the examples below.

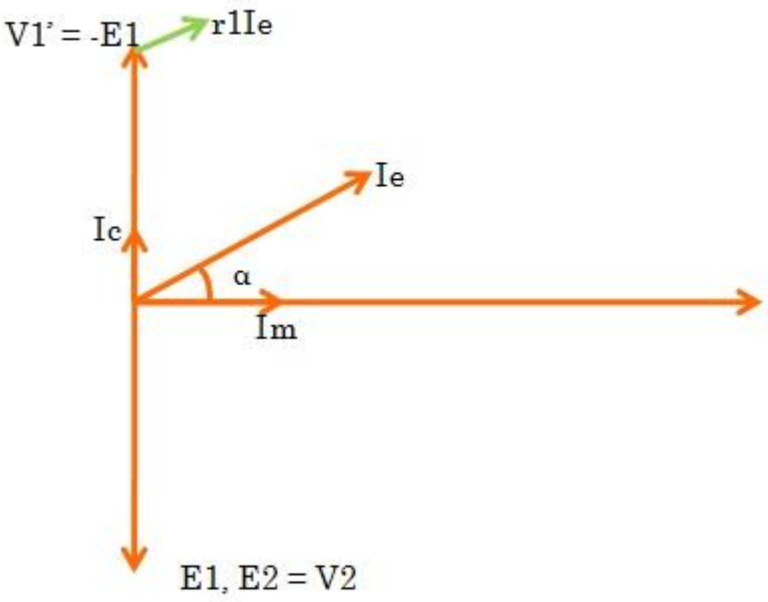
Excitation Current I_e leading Ø by α.



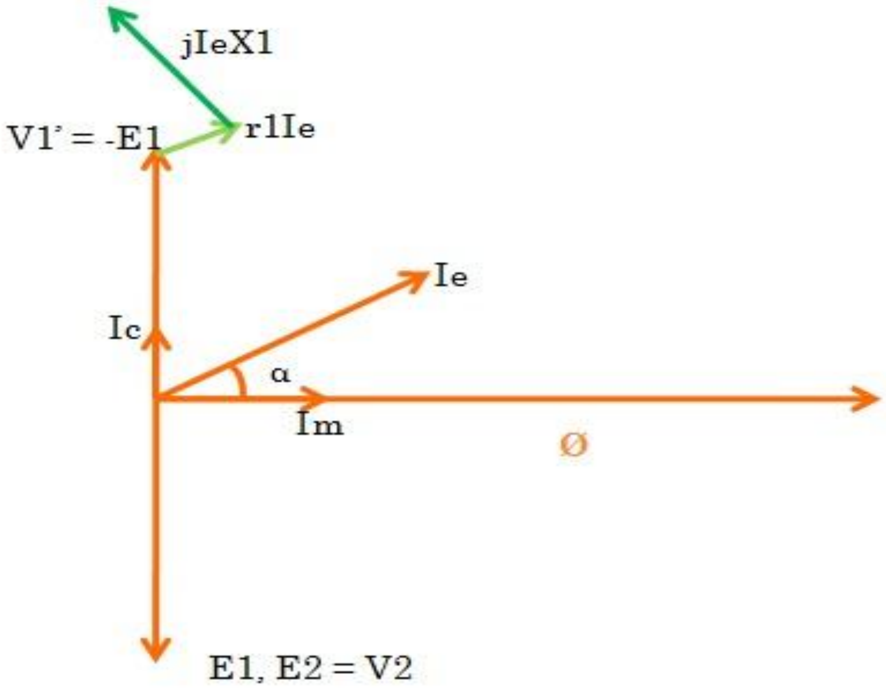
Induced EMF E_1 and E_2 lagging Flux by 90 degree.



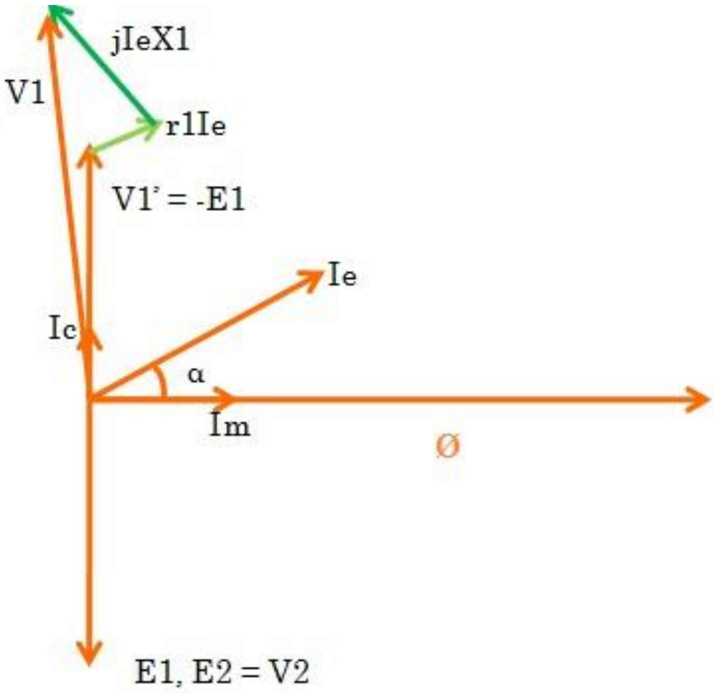
Voltage drop r_1I_e in Primary. This will be in phase with the I_e and hence shown parallel to it in the figure below.



Voltage drop I_eX_1 in Primary due to reactance. This will be perpendicular to I_e as shown below.



Source Voltage $V_1 = V_{1'} + r_1I_e + jI_eX_1$, phasor sum. Thus the complete phasor diagram of transformer at no load will be as shown below.



Phasor Diagram of Transformer for Lagging Load:

The secondary winding current lags behind the secondary terminal voltage when the transformer secondary is coupled to an inductive load. Assume for the moment that the current is behind by an angle of two (Figure 2.4).

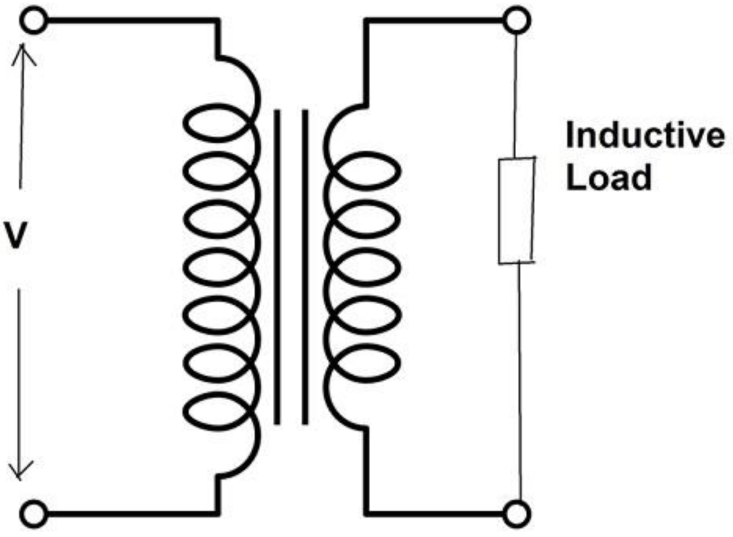


Figure 2.4 Transformer for Lagging Load

Let, r_1 = Primary winding Resistance

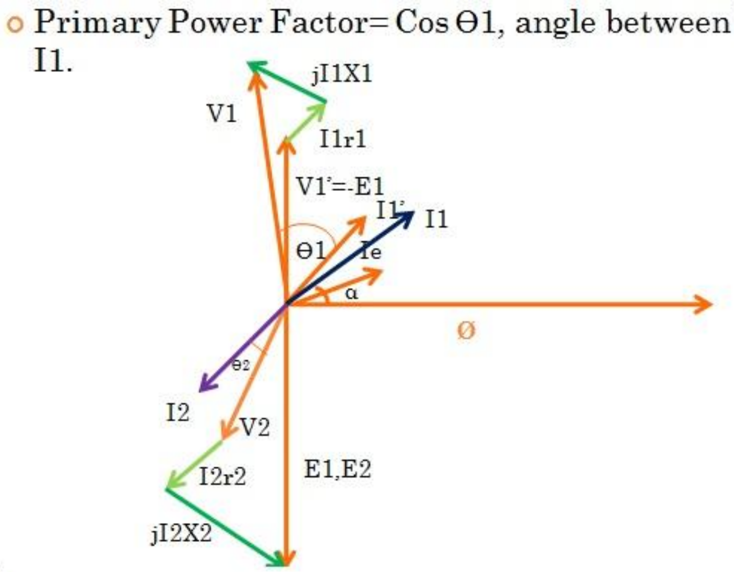
X_1 = Primary winding leakage Reactance

r_2 = Secondary winding Resistance

X_2 = Secondary winding leakage Reactance

The steps for phasor drawing will be as follows:

If we take the working flux Ø as reference, the phasor diagram of transformer will be as shown below.



- Primary Power Factor= Cos Θ1, angle between V1 & I1.

CHAPTER 3

Equivalent Circuit, Losses and Voltage Regulation of Transformer

Pradeepa P, Assistant Professor
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka – 562112
Email Id- p.pradeepa@jainuniversity.ac.in

Equivalent Circuit of a Transformer

The equivalent circuit diagram of a transformer is a condensed version of the circuit that makes it simpler to determine the impedance, resistance, and leakage reactance of the transformer.Calculating an essential parameter is the transformer equivalent impedance. The equivalent circuit of the transformer referred to the primary or equivalent circuit of the transformer referred to the secondary sides, respectively, are needed for this calculation. Another crucial transformer parameter is percentage impedance.

This characteristic should get extra consideration when constructing a transformer in an existing electrical power system. When using power transformers in parallel, the percentage impedance of each transformer should be correctly matched.Since the equivalent impedance of the transformer may be used to calculate the percentage impedance, it can be argued that the equivalent circuit of the transformer is also necessary.

Transformer equivalent circuit, known as the primary

We must first construct the general equivalent circuit of the transformer before we can change it for referring from the primary side in order to draw an equivalent circuit of a transformer referred to the primary. To achieve this, we must first remember the whole vector diagram of a transformer, which is shown in the Figure 3.1.

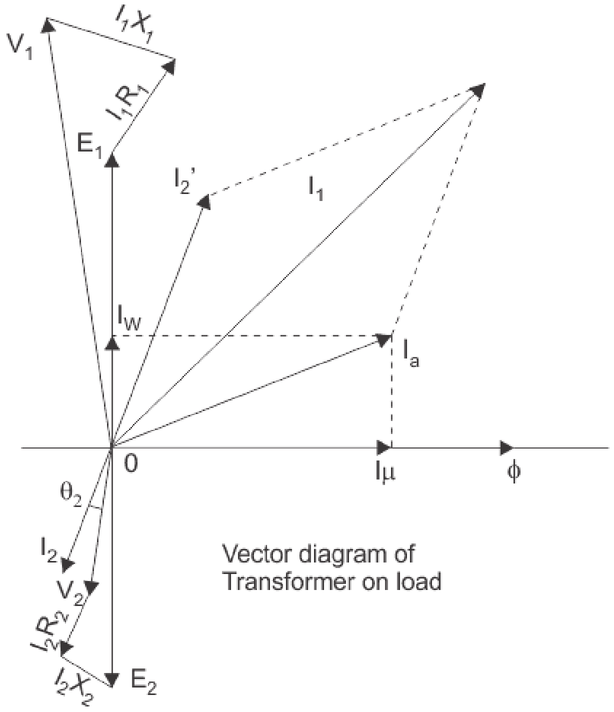


Figure 3.1 Transformer equivalent circuit

Let us consider the transformation ratio be,

$$K = \frac{N_1}{N_2} = \frac{E_1}{E_2}$$

The applied voltage to the primary is shown in the above diagram as V_1, and the voltage across the primary winding is shown as E_1. I_1 total current is sent to the primary. As a result, before the voltage V_1 supplied to the primary reaches across the primary winding, it is partially decreased by I_1Z_1 or $I_1R_1 + j.I_1X_1$.

Primary induced emf E1 balances the voltage that emerged across the coil. Consequently, this section of the transformer's voltage equation may be expressed as

$$V_1 - (I_1R_1 + jI_1X_1) = E_1$$

This is how the equation's equivalent circuit may be represented on paper (Figure 3.2):

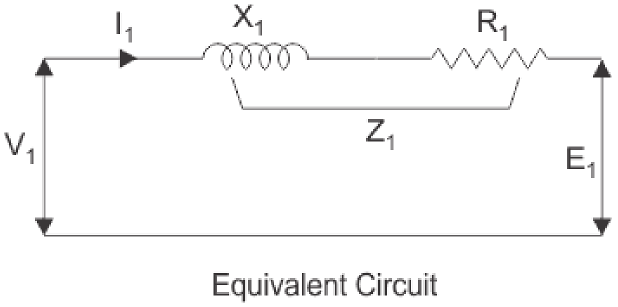


Figure 3.2 shows the circuit diagram of transformer

The total primary current I_1 contains two components, one of which is the no-load component Io and the other is the load component I_2', as shown in the vector diagram above. Since the main current includes two components or branches, the transformer's primary winding must run along a parallel route.

The excitation branch of a transformer's equivalent circuit is the name given to this parallel current route. The excitation circuit's resistive and reactive branches may be shown as Figure 3.3:

$$R_0 = \frac{E_1}{I_w} \ and \ X_0 = \frac{E_1}{I_\mu}$$

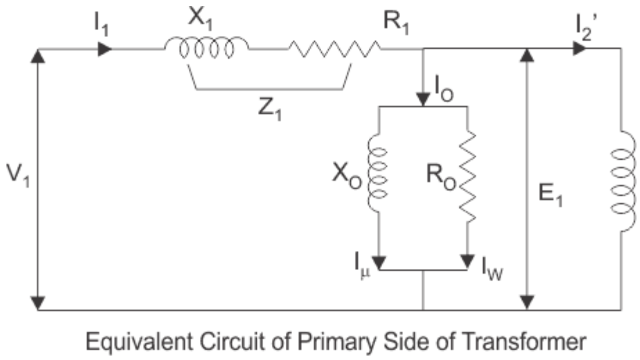


Figure 3.3 shows the circuit diagram of primary side of the transformer

Induced voltage across the transformer's main winding is E_1, as indicated in the figure to the right, when the load component I_2' passes through it.

This induced voltage E_1 changes to secondary voltage E_2, and the load component of the primary current I_2' changes to secondary current I_2 in the secondary. Secondary current is I_2.

Therefore, before it arrives across the load, the voltage E_2 across the secondary winding is partially reduced by I_2Z_2 or $I_2R_2 + j.I_2X_2$. V_2 is the load voltage.

Below is a diagram showing the transformer's whole equivalent circuit (Figure 3.4).

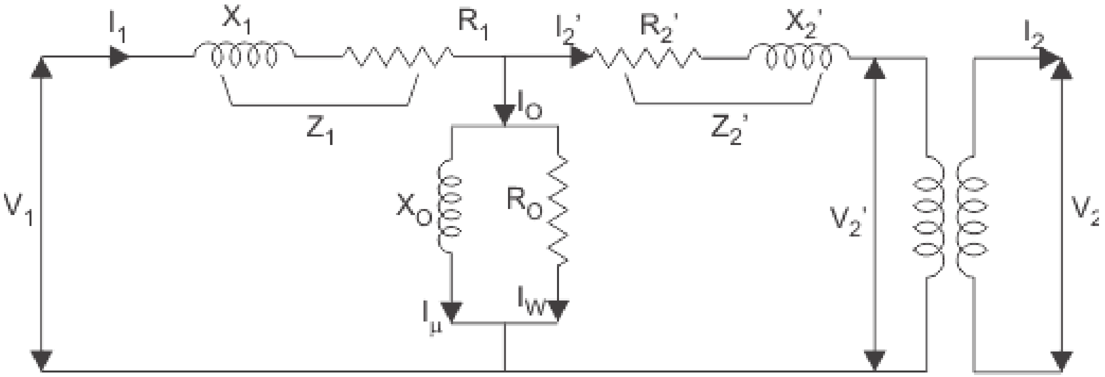


Figure 3.4 Equivalent circuit of transformer referred to primary

Now if we see the voltage drop in secondary from primary side, then it would be 'K' times greater and would be written as $K.Z_2.I_2$.
Again $I_2'.N_1 = I_2.N_2$

$$\Rightarrow I_2 = I_2'\frac{N_1}{N_2}$$

$$\Rightarrow I_2 = KI_2'$$

Therefore,

$$KZ_2I_2 = KZ_2KI_2' = K^2Z_2I_2'$$

From above equation, secondary impedance of transformer referred to primary is,

$$Z_2' = K^2Z_2$$

$$Hence,\ R_2' = K^2R_2\ and\ X_2 = K^2X_2$$

So, the complete equivalent circuit of transformer referred to primary is shown in the Figure 3.5 below:

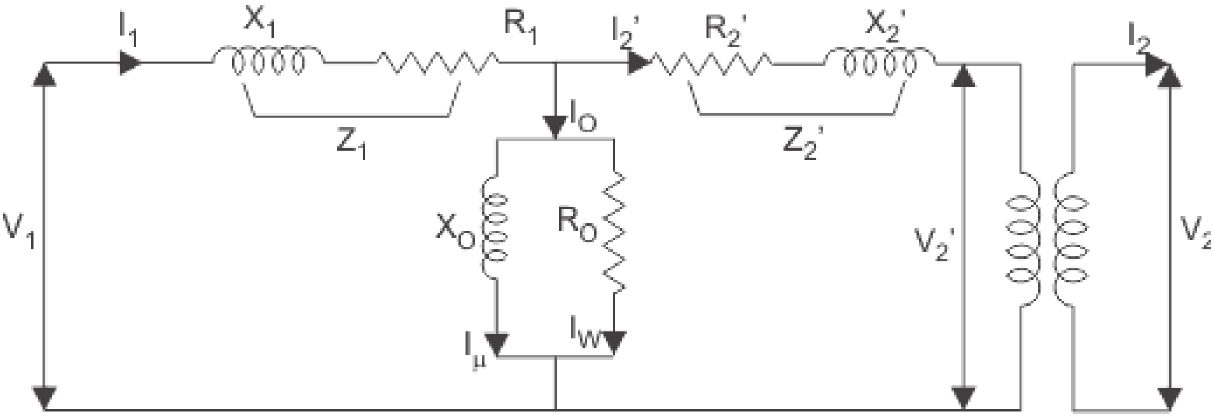


Figure 3.5 complete equivalent circuit of transformer referred to primary

Io has a negligible impact on the voltage drop since it is substantially less than I_1 and makes up less than 5% of the main current at full load.

The excitation circuit may thus be ignored in the approximate equivalent transformer circuit. Due to the series arrangement of the winding resistance and reactance, the transformer's equivalent resistance and reactance may now be referred to by any one of its sides. It is side 1, or main side, in this instance (Figure 3.6).

$$Here,\ V_2' = KV_2$$

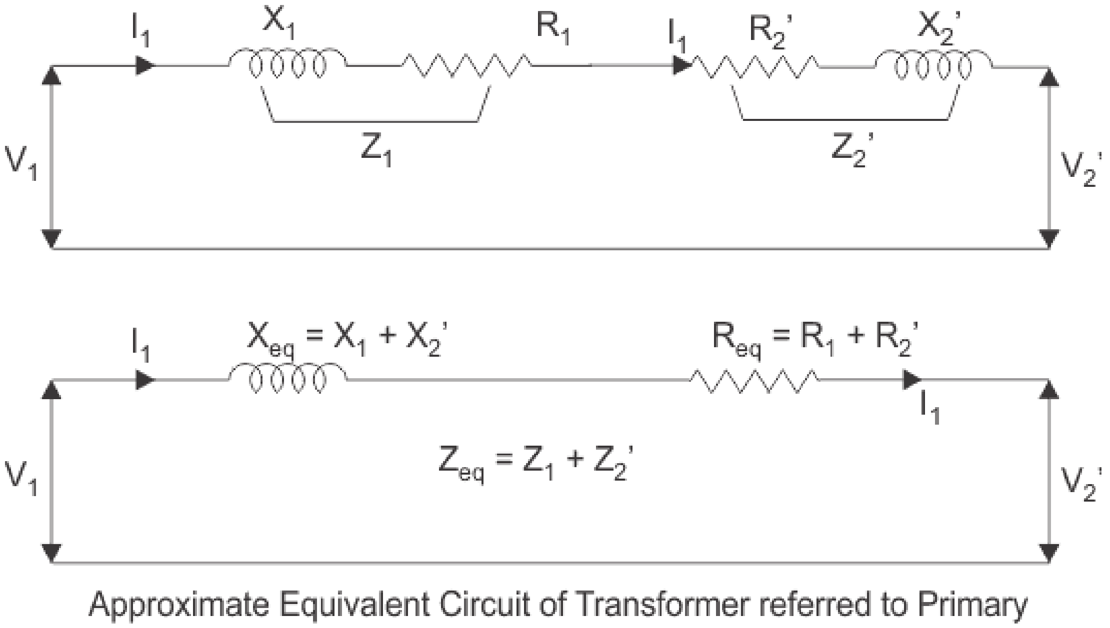


Figure 3.6 Approximate equivalent circuit of transformer referred to primary.

Transformer equivalent circuit referred regarded as secondary

Similar to this, it is possible to sketch the roughly identical transformer secondary circuit.Whereas the secondary equivalent impedance of a transformer may be obtained (Figure 3.7).

$$Z_1 = \frac{Z_1}{K^2}$$

$$Therefore,\ R_1' = \frac{R_1}{K^2}$$

$$X_1' = \frac{X_1}{K^2}$$

$$Here,\ V_1' = \frac{V_1}{K}$$

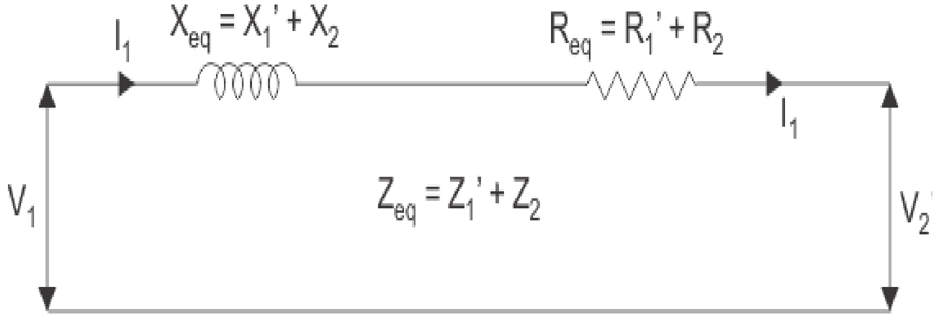


Figure 3.7 complete equivalent circuit of transformer referred to Secondary

Losses in Transformer

Loss is the difference between input power and output power in any electrical equipment. As a static device, an electrical transformer has no mechanical losses (such as windage or friction losses). All that a transformer is made of is electrical losses (iron losses and copper losses). Transformer losses are comparable to losses in a DC machine, with the exception that mechanical losses do not occur in transformers.

The following describes how transformer losses work:

Losses of Core or Iron

Depending on the magnetic characteristics of the material used to build the core, eddy current loss and hysteresis loss might occur. Thus, core losses or iron losses are other names for these losses.

Transformer hysteresis loss

The reversal of magnetism in the transformer core is what causes hysteresis loss. The amount and quality of the iron, the frequency of magnetic reversals, and the flux density value all affect this loss. Steinmetz's formula may be used to provide it.

Watts are equal to W_h=B_{max}1.6fV, where is the Steinmetz hysteresis constant.

Transformer eddy current loss

The main winding of a transformer receives AC current, which creates an alternate magnetising flux. This flux creates induced emf in the secondary winding when it interacts with it. However, a portion of this flux also interacts with other conducting components, such as the transformer's steel core or iron body, leading to induced emf and a tiny amount of circulating current in those components. Eddy current is the name given to this current. Some energy will be lost as heat as a result of these eddy currents.

Copper Loss in a Transformer

The transformer windings' ohmic resistance is what causes copper loss. Primary winding copper loss is I12R1 and secondary winding copper loss is I22R2. Where I1 and I2 are primary and secondary winding currents, respectively, and R1 and R2 are primary and secondary winding resistances, respectively. It is evident that Cu loss is inversely proportional to square of current, and current is load-dependent. As a result, copper loss in transformers varies depending on the load.

Transformer Efficiency

The output power divided by the input power may be used to describe a transformer's efficiency, just as it can for any other electrical equipment. Efficiency is calculated as output / input.The most effective electrical equipment is a transformer. Most transformers operate at full load efficiency levels of between 95 and 98.5%. It is impossible to gauge a transformer's efficiency using output / input because, due to its great efficiency, output and input are virtually equal in value. A more accurate formula to determine a transformer's efficiency is efficiency = (input - losses) / input = 1 - (losses / input).

Condition for Maximum Efficiency

Let,

Copper loss = I12R1

Iron loss = Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

η will be maximum at $\frac{d\eta}{dI_1} = 0$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{V_1I_1^2\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$I_1^2R_1 = W_i$$

As a result, a transformer's efficiency will be at its peak when copper and iron losses are equal.

Loss of Copper Equals Loss of Iron.

All-Day Transformer Efficiency

As we've seen previously, a transformer's typical or commercial efficiency may be expressed as:

$$\text{ordinary efficiency} = \frac{\text{output (in watts)}}{\text{input (in watts)}}$$

However, this efficiency cannot be used to evaluate the performance of all kinds of transformers. For instance, distribution transformers' primary are always powered. But most of the time throughout the day, their secondary generators provide little to no load (as residential use of electricity is observed mostly during evening till midnight).

That is, only the transformer's core losses are significant and copper losses are nonexistent when the secondaries of the transformer are not providing any load (or only supplying a small amount of load) (or very little). Transformer loads are the only time significant copper losses occur. Copper losses are thus considerably less significant for such transformers. On the basis of energy used in a single day, the effectiveness of these transformers is compared.

$$\text{All day efficiency} = \frac{\text{output (in kWh)}}{\text{input (in kWh)}} \quad \text{(for 24 hours)}$$

A transformer's daily efficiency is always lower than its typical efficiency.

Regulating transformer voltage

A component's ability to regulate voltage is determined by how much the voltage changes between its transmitting and receiving ends. The percentage voltage differential between the voltages at no load and full load on distribution lines, transmission lines, and transformers is a term often used in power engineering.

An explanation of transformer voltage regulation

Consider a power transformer that has an open circuit, which means the load is not connected to the secondary terminals. The transformer's secondary terminal voltage in this instance will be equal to its secondary induced EMF E_2.

When a full load is attached to the transformer's secondary terminals, rated current I_2 flows via the secondary circuit, causing a voltage drop.

The main winding will now additionally draw a comparable amount of full load current from the source. I_2Z_2, where Z_2 is the secondary impedance of the transformer, gives the voltage drop in the secondary.

Now, if anybody were to test the voltage across secondary terminals in this loading state, they would get voltage V_2 between load terminals, which is clearly lower than the secondary voltage E_2 when there is no load, and this is due to the I_2Z_2 voltage drop in the transformer.

Transformer Equation of Voltage Regulation

The percentage representation of the transformer voltage regulation equation, is

$$Voltage\ regulation(\%) = \frac{E_2 - V_2}{V_2} \times 100\%$$

Transformer voltage regulation for lagging power factor

We shall now thoroughly deduce the equation for voltage regulation. If the load's lagging power factor is cos2, then the angle between the secondary current and voltage is 2 (Figure 3.8).

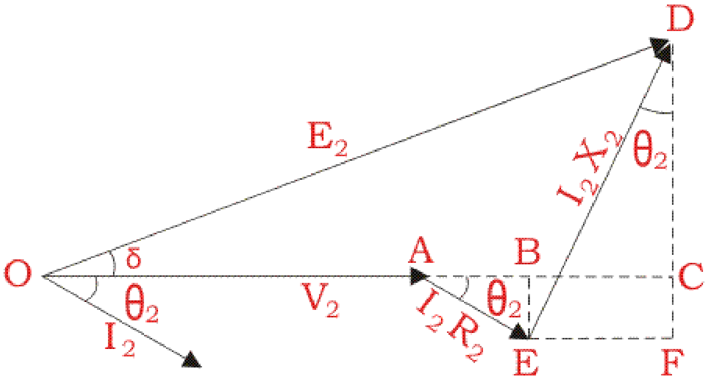


Figure 3.8 voltage regulation at lagging power factor.

Here, from the above diagram,

$$OC = OA + AB + BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB + BC$$

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2$$

Voltage regulation of transformer at lagging power factor,

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$

$$= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Transformer voltage regulation for leading power factor

Let's calculate the equation for voltage regulation using leading current. Assuming that the load's leading power factor is cos2, we can calculate the angle between secondary current and voltage as follows (Figure 3.10):

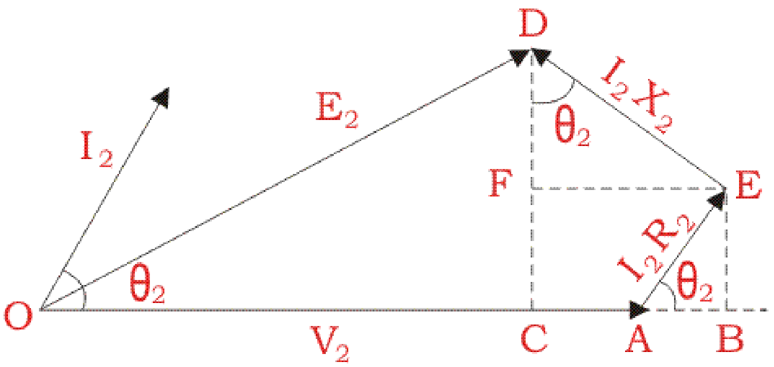


Figure 3.10 voltage regulation at leading power factor

Here, from the above diagram,

$$OC = OA + AB - BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB - BC$$

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2$$

Voltage regulation of transformer at leading power factor,

Transformer Zero Voltage Regulation

When a device has "zero voltage regulation," its "no-load voltage" and "full-load voltage" are the same. This indicates that voltage regulation is equal to zero in the equation above for voltage regulation. This is not realistic and can only theoretically be done with a perfect transformer.

CHAPTER 4

Auto Transformer, Three Phase Transformer with their Connection

Pushparajesh Viswanathan, AssociateProfessor
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka – 562112
Email Id- v.pushparajesh@jainuniversity.ac.in

An auto transformer is a transformer with a laminated core and only one winding wrapped on it. Although an auto transformer and a two-winding transformer are similar, they vary in how the primary and secondary windings are connected. The winding has a portion that is shared by the main and secondary sides.When there is a load, some of the load current comes straight from the supply and the remainder comes through the action of the transformer. A voltage regulator is an auto transformer.

Circuit diagram and Auto Transformer explanation

In a typical transformer, the main and secondary windings are magnetically coupled but electrically isolated from one another as seen in the image below. The main and secondary windings of an auto transformer are coupled electrically and magnetically. In actuality, both main and secondary windings share a portion of the one continuous winding (Figure 4.1).

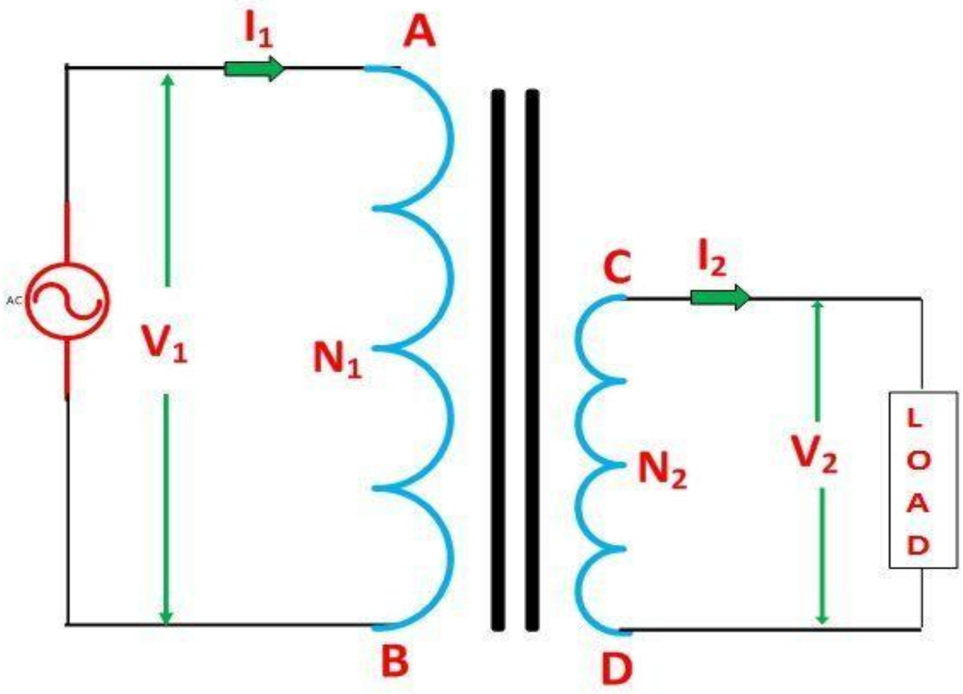


Figure 4.1 Circuit diagram of Auto Transformer

Ordinary Two Winding Transformer

Based on their structure, auto transformers come in two different varieties. One kind of transformer has a continuous winding, and taps are brought out at strategic locations based on the required secondary voltage. However, in another kind of auto transformer, a continuous winding is made up of two or more separate coils that are electrically coupled. The image below depicts the Auto transformer's construction (Figure 4.2).

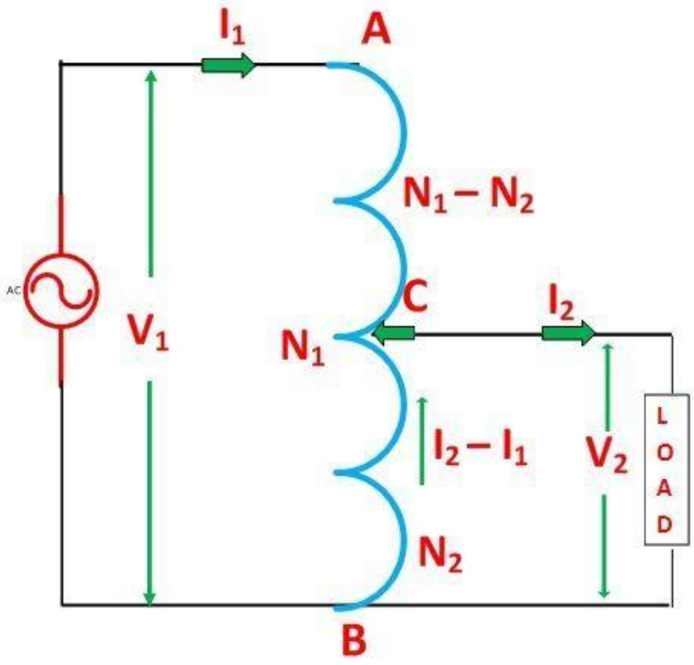


Figure 4.2 Two Winding Transformer

Auto-Transformer

The main winding, AB, from which a tap is taken at C, making CB a secondary winding. The load is linked across CB, while the supply voltage is applied across AB. Either fixed or variable tapping may be used. An alternating flux is created in the core when an AC voltage V1 is supplied across AB, and as a consequence, an EMF E1 is generated in the winding AB. This induced EMF is used in the secondary circuit in part.

Let,

V_1 – primary applied voltage

V_2 – secondary voltage across the load

I_1 – primary current

I_2 – load current

N_1 – number of turns between A and B

N_2 – number of turns between C and B

Neglecting no-load current, leakage reactance and losses,

$V_1 = E_1$ and $V_2 = E_2$

Therefore, the transformation ratio:

$$K = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

As the secondary ampere-turns are opposite to primary ampere-turns, so the current I_2 is in phase opposition to I_1. The secondary voltage is less than the primary. Therefore current I_2 is more than the current I_1. Therefore, the resulting current flowing through section BC is $(I_2 - I_1)$.

The ampere-turns due to section BC = current x turns

$$\text{Ampere turns due to section BC} = (I_2 - I_1)N_2 = \left(\frac{I_1}{K} - I_1\right) x\, N_1K = I_1N_1(1-K) \ldots\ldots\ldots (1)$$

$$\text{Ampere turns due to section AC} = I_1(N_1 - N_2) = I_1N_1\left(1 - \frac{N_2}{N_1}\right) = I_1N_1(1-K) \ldots\ldots (2)$$

Equation (1) and (2) shows that the ampere-turns due to section BC and AC balance each other which is characteristic of the transformer action.

Saving of Copper in Auto Transformer as Compared to Ordinary Two Winding Transformer

The weight of the copper is proportional to the length and area of a cross-section of the conductor.

The length of the conductor is proportional to the number of turns, and the cross-section is proportional to the product of current and number of turns.

Now, from the above figure (B) shown of the auto transformer, the weight of copper required in an auto transformer is

W_a = weight of copper in section AC + weight of copper in section CB

Therefore

$$W_a \propto I_1(N_1 - N_2) + (I_2 - I_1)N_2$$

$$W_a \propto I_1N_1 + I_2N_2 - 2I_1N_2$$

If the same duty is performed with an ordinary two winding transformer shown above in the figure (A), the total weight of the copper required in the ordinary transformer,

W_0 = weight of copper on its primary winding + weight of copper on its secondary winding

Therefore,

$$W_o \propto I_1N_1 + I_2N_2$$

Now, the ratio of the weight of the copper in an auto transformer to the weight of copper in an ordinary transformer is given as:

$$\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2 - 2I_1N_2}{I_1N_1 + I_2N_2}$$

OR

$$\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2}{I_1N_1 + I_2N_2} - \frac{2I_1N_2}{I_1N_1 + I_2N_2}$$

$$\frac{W_a}{W_o} = 1 - \frac{2\,I_1N_2/I_1N_1}{I_1N_1/I_1N_1 + I_2N_2/I_1N_1} = 1 - K$$

OR

$$W_a = (1 - K)W_o$$

Saving of copper affected by using an auto transformer = weight of copper required in an ordinary transformer weight of copper required in an auto transformer

$$\text{Saving of copper} = W_O - W_a = W_o - (1 - K)W_0 = KW_O$$

Therefore,

Saving of copper = K x weight of copper required for two windings of the transformer

Hence, saving in copper increases as the transformation ratio approaches unity. Hence the auto transformer is used when the value of K is nearly equal to unity.

Auto transformer benefits include lower cost, better control, and lower losses as compared to conventional two-winding transformers of the same rating.

Negative aspects of the auto transformer

The secondary winding is not isolated from the main winding, which is one of the key drawbacks of the auto transformer and the reason it is not used more often.In the event that an auto transformer is utilised to deliver low voltage from a high voltage and the secondary winding fails, the whole primary voltage will pass the secondary terminal, endangering both the user and the apparatus.

Therefore, linking high voltage and low voltage systems shouldn't utilise the auto transformer.Only used in a small number of locations where a modest deviation between the input and output voltage is necessary.

Applications of an auto transformer include starting squirrel cage induction motors by applying up to 50% to 60% of their full voltage to the stator during startup, boosting voltage drops in distribution cables with a small boost, acting as a voltage regulator, and distributing power to railways and audio systems.

Three phases Transformers

To create and transfer electric power over great distances for usage by businesses and industry, a three-phase electrical system is employed. Three phase transformers are used to increase or reduce three-phase voltages (and currents) because the three phase transformer's windings may be linked in a variety of ways.We have examined the design and functioning of the single-phase, two-winding voltage transformer up to this point, which may be used to alter the secondary voltage's relationship to the primary supply voltage. However, voltage transformers may also be built to link to two, three, six, or even intricate combinations of up to 24 phases for certain DC rectification transformers, in addition to only one single phase.

Three-phase, also written as 3-phase or 3φ supplies are used for electrical power generation, transmission, and distribution, as well as for all industrial uses. While compared to single-phase power, three-phase supplies offer several electrical benefits. However, when thinking about three-phase transformers, we must deal with three alternating voltages and currents that have 120 degree phase-time differences.

Three Phase Voltages and Currents as shown in Figure 4.3

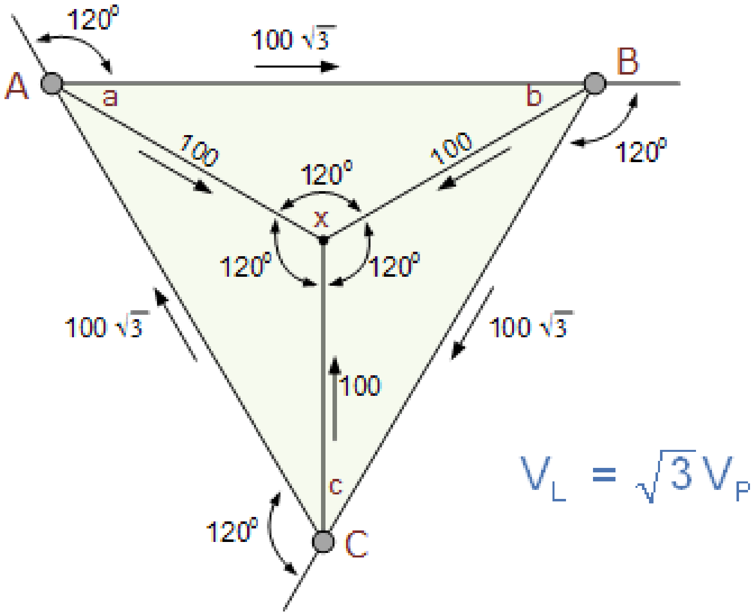


Figure 4.3Three Phase Voltages and Currents

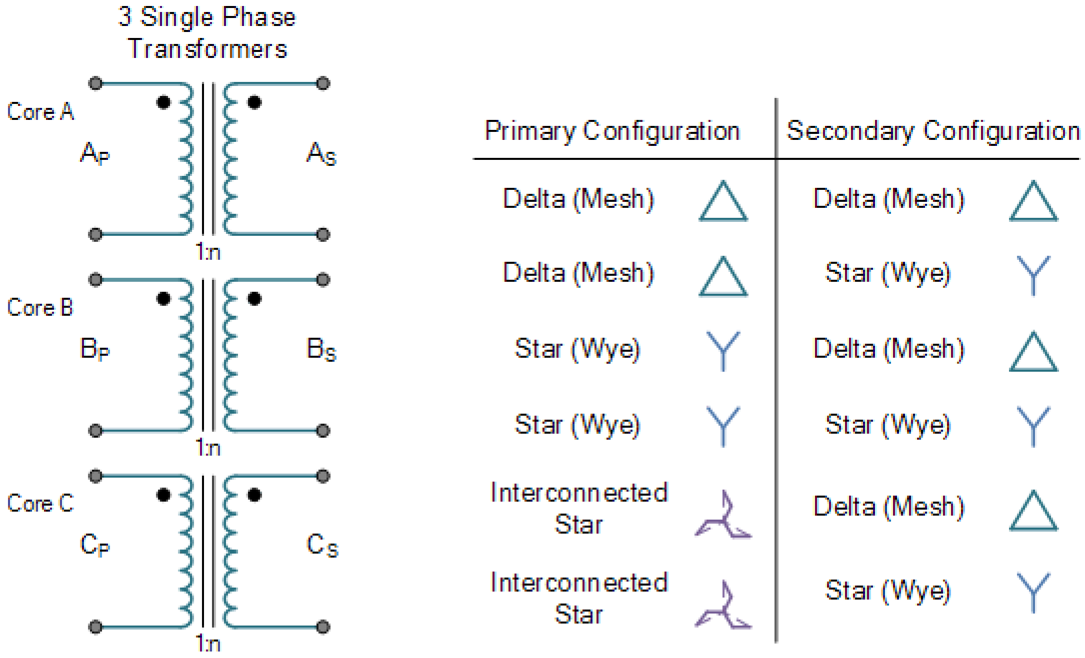
Where: VP stands for phase-to-neutral voltage and VL for line-to-line voltage.

A transformer cannot convert from one phase to another, either from one phase to three phases or from three phases to one phase. We must link the transformer connections in a certain manner to create a three phase transformer configuration in order to make them work with three-phase supply.

A three phase transformer, also known as a three phase transformer bank, can be built by joining three single-phase transformers together, or it can be built using a pre-assembled, balanced three phase transformer that consists of three pairs of single phase windings mounted onto a single laminated core.

Because the copper and iron core are utilised more efficiently when designing a single three phase transformer, it will be smaller, less expensive, and lighter than three separate single phase transformers coupled together for the same kVA rating. Whether employing a single three-phase transformer or three separate single-phase transformers, the procedures for connecting the main and secondary windings are the same (Figure 4.4).

Three Phase Transformer Connections



Primary Configuration	Secondary Configuration
Delta (Mesh) △	Delta (Mesh) △
Delta (Mesh) △	Star (Wye) Y
Star (Wye) Y	Delta (Mesh) △
Star (Wye) Y	Star (Wye) Y
Interconnected Star	Delta (Mesh) △
Interconnected Star	Star (Wye) Y

Figure 4.4Three Phase transformer connection

A transformer's main and secondary windings may be linked in a variety of ways, as illustrated, to satisfy just about any need. Three types of connections are conceivable for three phase transformer windings: "star" (wye), "delta" (mesh), and "interconnected-star" (zig-zag).Depending on the function of the transformer, the three winding combinations may be star-delta, star-star, or delta-delta with the primary linked in a delta pattern and the secondary in a star pattern. Transformers are often referred to as polyphase transformers when they are utilised to provide three or more phases.

Configurations for Three Phase Transformers in Star and Delta

But when discussing three-phase transformer connections, what do we mean by "star" (also referred to as Wye) and "delta" (also referred to as Mesh). Three separate sets of primary and secondary windings make up a three phase transformer. The kind of connection a star or delta configuration depends on how these sets of windings are linked to one another.In addition to deciding the sort of electrical connections utilized on both the primary and secondary sides, the three possible voltages each of which is separated from the other by 120 electrical degrees also control the direction of the transformer currents.

The magnetic fluxes in the three single-phase transformers have a 120 time-degree phase difference when they are coupled together. Three magnetic fluxes with a 120 degree difference in time-phase are present in the core of a single three-phase transformer.

The three main windings of a three-phase transformer are often marked with the capital (upper case) letters A, B, and C, which stand for the three distinct phases of RED, YELLOW, and BLUE. The letters a, b, and c in tiny (lower case) font are used to identify the secondary windings. For example, the second winding of the primary will have ends that will be named B1 and B2, while the third winding of the secondary will be labelled c1 and c2, as illustrated. Each winding has two ends that are typically labelled 1 and 2.

Transformer Star and Delta Configurations (Figure 4.5)

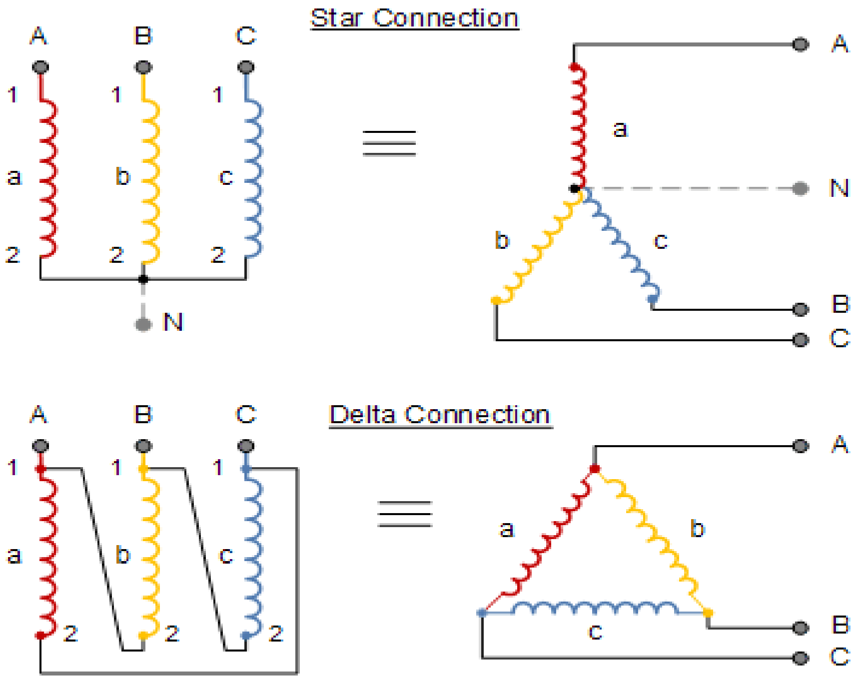


Figure 4.5 Transformer Star and Delta Configurations

On a three-phase transformer, the type or types of connections are often denoted by symbols: upper case letters Y for star connected, D for delta connected, and Z for interconnected star primary windings; lower case letters Y, D, and Z for the corresponding secondaries. For the same sorts of linked transformers, Star-Star would then be labelled Yy, Delta-Delta would be labelled Dd, and Interconnected Star to Interconnected Star would be labelled Zz (Figure 4.1).

Table 4.1 Transformer Winding Identification

Connection	**Primary Winding**	**Secondary Winding**
Delta	D	d
Star	Y	y
Interconnected	Z	z

The four possible connections between the main and secondary three-phase circuits of three single-phase transformers are now clear to us. Delta-Delta (Dd), Star-Star (Yy), Star-Delta (Yd), and Delta-Star are the four typical combinations (Dy).

Transformers for high voltage operation with star connections have the benefit of lowering the voltage on a single transformer, requiring fewer turns and larger conductors, which makes insulating the coil windings simpler and less expensive than with delta transformers.However, the delta-delta connection has a significant advantage over the star-delta configuration in that if one of a group of three transformers were to malfunction or become disabled, the two remaining ones would still be able to deliver three-phase power with a capacity equal to roughly two thirds of the transformer unit's initial output.

Transformer Delta and Delta Connections as shown in Figure 4.6

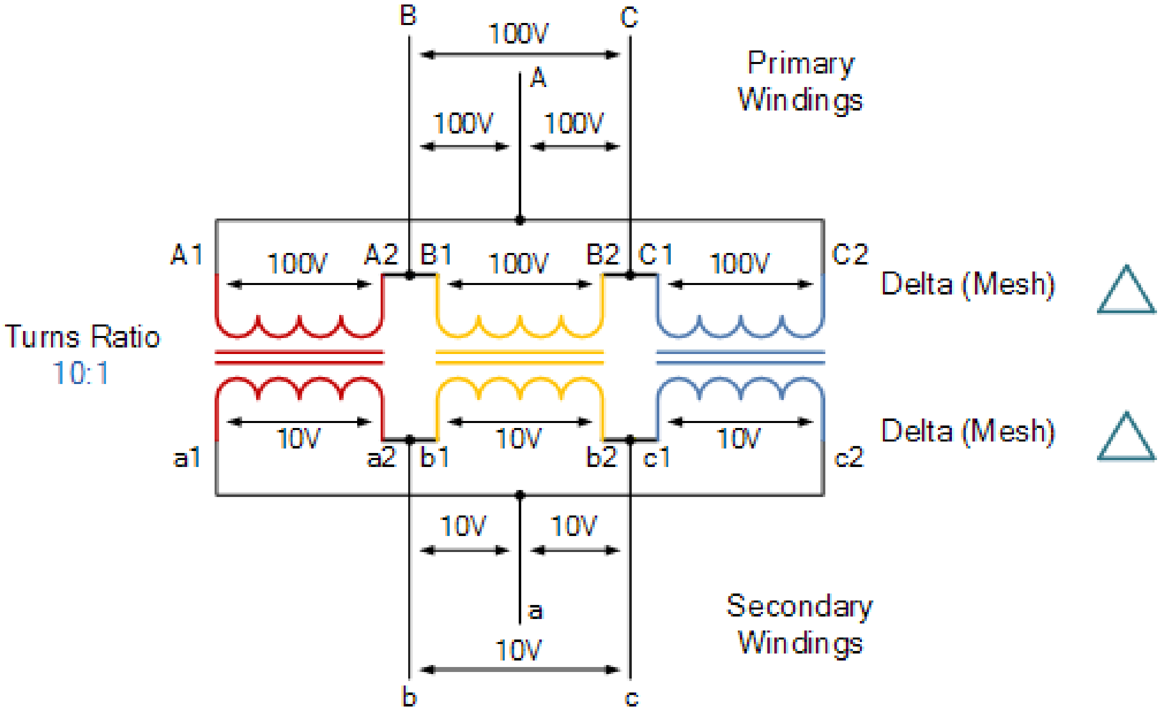


Figure 4.6Transformer Delta and Delta Configurations

The line voltage, VL, in a set of transformers coupled in a delta fashion (Dd), equals the supply voltage, VL = VS. But the current in each phase winding is given as:

1/√3 × IL of the line current, where IL is the line current.

The need that each transformer be wrapped for the entire line voltage (in our case, over 100V) and for 57.7% of the line current is a drawback of delta linked three phase transformers.

The winding requires a bigger and more costly coil than the star connection due to the winding's higher turn count and the insulation between turns.

The lack of a "neutral" or common connection with delta-connected three-phase transformers is another drawback.

In the star-star arrangement (Yy), (WYw, Wye) each transformer has one terminal connected to a common junction, or neutral point with the three remaining ends of the primary windings connected to the three-phase mains supply.

A transformer winding needs 57.7% more turns for a star connection than it does for a delta connection.

Three transformers are needed for the star connection, and if any of them malfunctions or stops working, the whole group might stop working.

However, the star-connected three-phase transformer is very practical and cost-effective in power distribution systems since a fourth wire may be attached as a neutral point, (n), of the three secondaries that are star-connected as indicated.

Transformer Star and Star Connections (Figure 4.7)

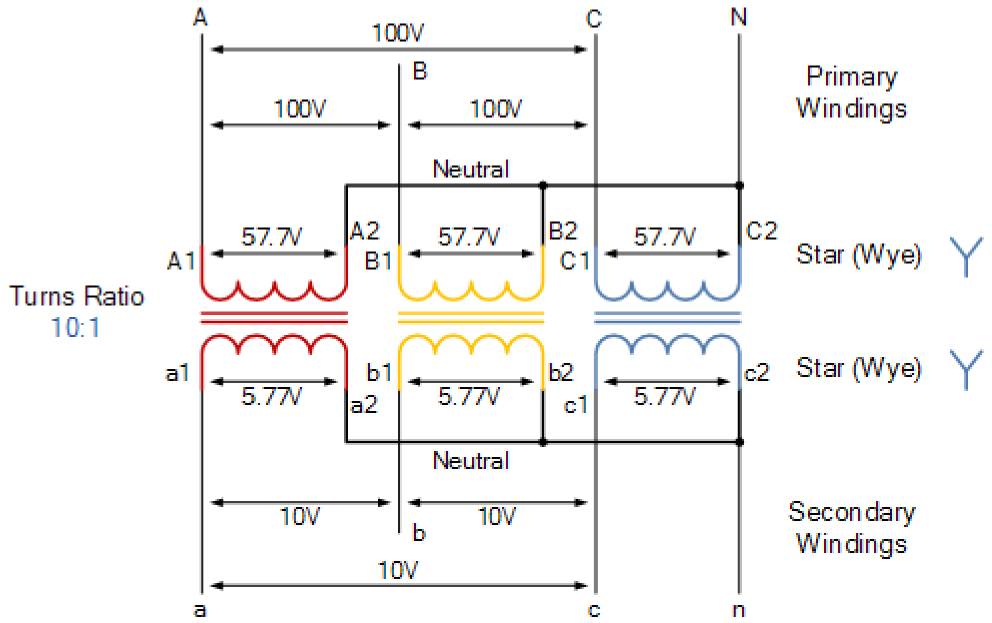


Figure 4.7Transformer Star and Star Configurations

The voltage between any lines of the three-phase transformer is called the "line voltage", VL, while the voltage between any line and the neutral point of a star connected transformer is called the "phase voltage", VP. This phase voltage, which is 1/3 of the line voltage, exists between the neutral point and any one of the line connections. The major side phase voltage, abbreviated VP, is then presented above.

$$V_P = \frac{1}{\sqrt{3}} \times V_L = \frac{1}{\sqrt{3}} \times 100 = 57.7 \text{ Volts}$$

Since the line current of the supply and the secondary current in each phase of a set of transformers linked in a star are the same, IL = IS.In a three-phase system, the relationship between line and phase voltages and currents may be summarised as follows (Table 4.2):

Table 4.2 Three-phase Voltage and Current

Connection	Phase Voltage	Line Voltage	Phase Current	Line Current
Star	$V_P = V_L \div \sqrt{3}$	$V_L = \sqrt{3} \times V_P$	$I_P = I_L$	$I_L = I_P$
Delta	$V_P = V_L$	$V_L = V_P$	$I_P = I_L \div \sqrt{3}$	$I_L = \sqrt{3} \times I_P$

Where,

Once again, VP is the phase-to-neutral voltage on either the main or secondary side and VL is the line-to-line voltage.Other alternative connections for three phase transformers are star-delta Yd, where the main winding is linked in a star pattern and the secondary is connected in a delta pattern, and delta-star Dy, where the primary and secondary are both connected in a delta pattern.

With the main windings giving a three-wire balanced load to the utility company and the secondary windings providing the necessary fourth-wire neutral or ground connection, delta-star linked transformers are often employed in low power distribution.

The total turns ratio of the transformer gets more complex when the primary and secondary have distinct winding connections, such as star or delta. A three-phase transformer might theoretically have a 1:1 turns ratio if it is linked as delta-delta (Dd) or star-star (Yy). In other words, the windings' input and output voltages are identical.

The phase voltage, VP, of the supply, which is equal to 1/3 VL, will instead be received by each star-connected main winding if the 3-phase transformer is connected in star-delta, or (Yd).

The voltage 1/3 VL will then be induced in each matching secondary winding, becoming the secondary line voltage since these secondary windings are delta-connected. A star-delta linked transformer will thus give a 3:1 step-down line voltage ratio with a 1:1 turns ratio.

The turns ratio for a transformer linked to a star-delta (Yd) thus becomes:

Star-Delta Turns Ratio

$$TR = \frac{N_P}{N_S} = \frac{V_P}{\sqrt{3}V_S}$$

The transformer will produce a 1:3 step-up line-voltage ratio for a delta-star (Dy) linked transformer with a 1:1 turns ratio. The turns ratio for a linked delta-star transformer thus becomes:

Delta-Star Turns Ratio

$$TR = \frac{N_P}{N_S} = \frac{\sqrt{3}V_P}{V_S}$$

The secondary voltages and currents of the transformer with regard to the primary line voltage, VL, and its primary line current, IL, may then be listed for the four fundamental configurations of a three-phase transformer, as illustrated in the accompanying Table 4.3.

Table 4.3 Three-phase Transformer Line Voltage and Current

Primary-Secondary Configuration	**Line Voltage Primary or Secondary**	**Line Current Primary or Secondary**
Delta – Delta	$V_L \Rightarrow nV_L$	$I_L \Rightarrow \frac{I_L}{n}$
Delta – Star	$V_L \Rightarrow \sqrt{3}.nV_L$	$I_L \Rightarrow \frac{I_L}{\sqrt{3}.n}$
Star – Delta	$V_L \Rightarrow \frac{nV_L}{\sqrt{3}}$	$I_L \Rightarrow \sqrt{3}.\frac{I_L}{n}$

Star – Star	$V_L \Rightarrow nV_L$	$I_L \Rightarrow \frac{I_L}{n}$

Where VL is the line-to-line voltage and VP is the phase-to-neutral voltage, respectively, and n is the transformer's "turns ratio" (T.R.) calculated as the number of secondary windings NS divided by the number of primary windings NP (NS/NP).

CHAPTER 5

Construction and Need of Isolation in Three Phase Transformers

G. Ezhilarasan, Professor
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka – 562112
Email Id- g.ezhilarasan@jainuniversity.ac.in

Construction of Three Phase Transformers

As previously stated, the three-phase transformer is really three linked single phase transformers on a single laminated core. By merging the three windings onto a single magnetic circuit as depicted, significant cost, space, and weight reductions may be realised.The three magnetic circuits of a three-phase transformer are typically interlaced to provide a consistent distribution of the dielectric flux between the high and low voltage windings. Transformers of the three-phase shell type are the exception to this rule. Despite being connected, the three cores are not interwoven in the shell form of construction (Figure 5.1).

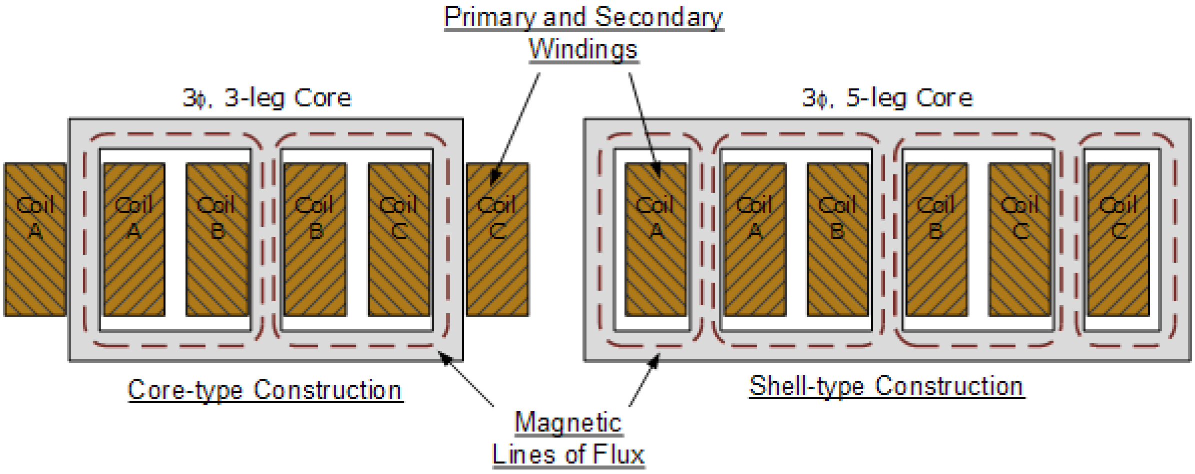


Figure 5.1 construction of 3 phase transformer

The most typical design for a three-phase transformer that enables magnetic coupling of the phases is one with a three-limb core. The three magnetic fluxes in the core are produced by the line voltages, and their time-phase differences are 120 degrees, with the flux of each limb using the other two limbs as its return route.

As a result, the flux in the core stays approximately sinusoidal, resulting in a secondary supply voltage that is sinusoidal.Construction of the five-limb, three-phase shell-type transformer is heavier and more costly than that of the core-type.

Since five-limb cores can be manufactured with less height, they are often utilised for extremely large power transformers. The core components, electrical windings, steel housing, and cooling of a shell-type transformer are largely the same as those of bigger single-phase models.

Impedance Matching Cause

Impedance matching, in essence, ensures that the input impedance of the stage after the source, known as the load, and its output impedance, known as the source, are equal. Both maximal power transmission and minimal loss are possible with this combination. If you see this notion as a sequence of light bulbs connected to a power source, it will be simple to comprehend. The first lightbulb serves as stage one's output impedance (for example, a radio transmitter), while the second lightbulb serves as the load, or more precisely, as the second bulb's input impedance (an antenna, for example). In our example, this would entail transmitting the greatest power into the air so that a radio station can be heard from a distance. We want to ensure that the most power is given to the load. When the source's output impedance is equal to the load's input impedance, the greatest amount of power may be transferred; otherwise, more power is lost in the source (the first light bulb shines brighter).

Isolation-transformer

Alternating current (AC) electrical energy is transformed from the primary to the secondary side by transformers, which are electromagnetic devices. The energy is transformed with equal frequency and approximately equal power by means of the transformer core magnetic field. As a result, they provide the electrical system galvanic separation. The same principles that apply to other transformer types also apply to isolation transformers. But the major job is to provide the electrical system galvanic isolation. They can work as step-up transformer or step-down transformers but often operate with turn’s ratio. This means that the primary and secondary voltage values are equal. This is obtained with a same number of turns on the primary and secondary windings.

The isolation transformers are used in many electrical devices as computers, measurement devices or specific industry power electronic devices.It is very important to use isolating transformers when an oscilloscope measures signals in an electrical circuit which is not galvanically isolated from the network.

Because the current circuit can be closed (short-circuited) between oscilloscope common point and grounding. The main purpose of the isolation transformer is safety and protection of electronic components and the persons against electrical shock. It physically separates the power supplying from primary side and a secondary side circuit connected to electronic components and grounded metal parts which are in contact with the person. Basically, the transformer secondary side is isolated from the grounding.

This means that the isolation transformer secondary side must not be grounded. It would create a physical connection between the primary and secondary transformer side. The auto transformer with common winding cannot be used as isolation transformer because it has a connection between primary and secondary side. Isolation transformer provides available supplying even if the device is broken.

The primary side remains under voltage which can be used to supply some alarm or warning beep circuits when the device is broken.The transformers suppress the electrical noise from supplying or electromagnetic induction. That is very important in case of sensitive devices as measurement or medical devices. This transformer is built with electrostatic shields which additionally increase the electrical noise suppression. The proper isolation transformer design avoids ground loops. Ground loops create an additional current path where the current created by electromagnetic induction can flow. This is the main reason for noise and interference in the signal.

When the isolation transformer is designed it is very important to pay attention to windings capacitance values which create capacitive coupling. This enables AC signal to pass from primary to the secondary side which significantly increased the noise level. For this purpose, the windings are surrounded by a metal strip which is grounded (creating a Faraday shield).The isolation transformers are used as instrument transformers when the high voltage should be measured.

The high voltage is dangerous for the person who tries to measure high voltage but it can also harm the measurement circuits. In this case, the step-down isolation transformer is used to reduce the high voltage to the safe level and for measurement range.

Application of Isolation Transformer

There is also some special application of isolating transformers, such us pulse transformers which transmit rectangular pulse signals and provide the electrical isolation. This type is suitable in some computer network designs.

Design and Customization of Isolation Transformers

An isolation transformer may be toroidal, or donut-shaped, in configuration. Toroid transformers provide several benefits, including their small size and light weight, which enable them to be used in various applications. A toroidal transformer's windings are spread uniformly across the whole thing since they pass through the center of the core. Silicon iron or a nickel-iron alloy can be used to make the core (Figure 5.2).

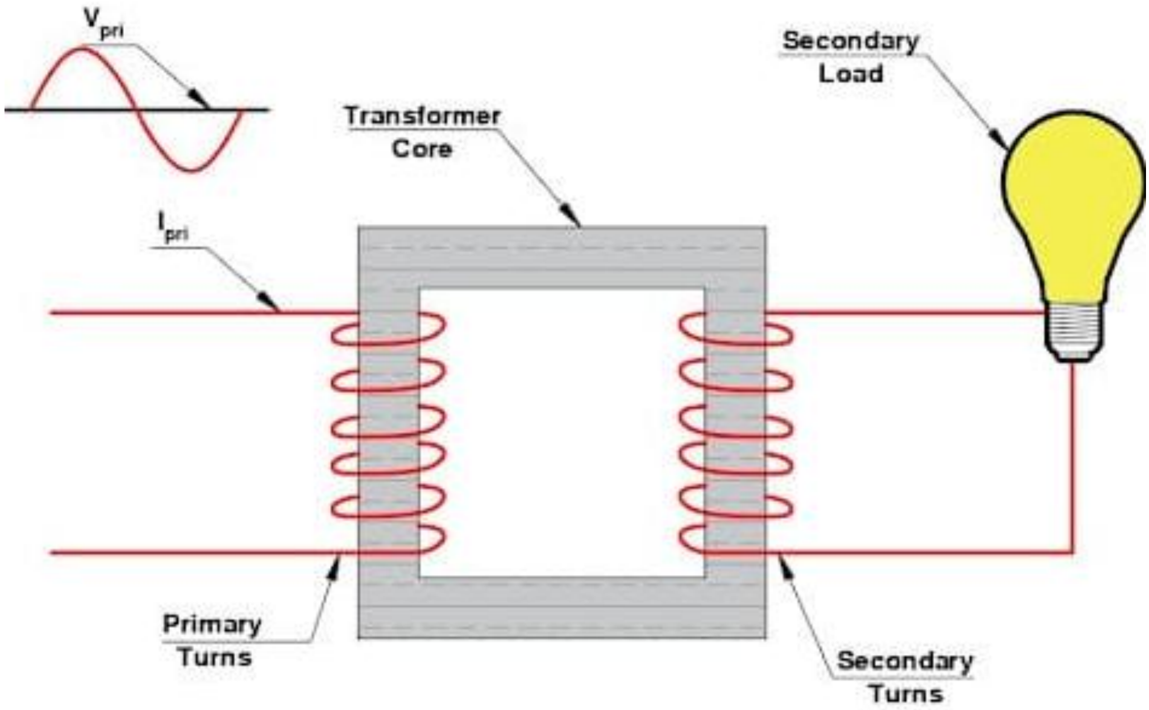


Figure 5.2 Customization of Isolation Transformers

Amorphous alloys and iron powder are superior core material substitutes for higher frequency applications. Toroidal transformers may also lessen stray field radiation and auditory noise. Metal bands may be added to toroidal isolation transformers to further reduce stray magnetic fields.

For equipment like patient monitoring systems that don't allow much space for interference, an isolation transformer may have additional insulation (Figure 5.3).

Figure 5.3 Customization of Isolation Transformers

Considerations when Choosing Isolation Transformers

Voltage: Pay close attention to this factor since transformers are used to modify the voltage of the main power source. Despite the fact that transformers may take a variety of voltages, the input voltage will depend on the main power source voltage. Based on the requirements, the output voltage may then be selected.

Number of phases: Determine if the need is one phase or three phases, and then choose an option in accordance. This will depend on the production demand. A home, a tiny dwelling, or an apartment complex shouldn't need anything more than single-phase electricity and single-phase transformers to transport current. In order to provide businesses and industries that use large loads and powerful equipment, a three-phase supply is necessary, therefore a three-phase transformer should be used.

Load requirement: This takes into consideration the necessity for the load. Consider the magnitude and kind of the load while doing this. This should ideally be considered in addition to the first factor.

Location: Before putting the product on the market, think about whether the transformer will be installed inside or outside, as well as if it will be placed next to any dangerous substances or other dangers. Make sure the transformer has the necessary physical characteristics to withstand any conditions.

Types of Isolation Transformers

The different types of isolation transformers include:

Transformator Ultra Isolation

Due to its distinctive shape, the extreme isolation transformer removes all types of electrical noise, but especially common mode noise. The ground on the secondary side is neutrally divided, and the primary and secondary are isolated, allowing for the construction of a separately derived source to combat current loops. High isolating materials and specific shielding methods are used to lower transverse mode noise and attenuate common mode noise.

For delicate, crucial equipment like computers and their peripherals, medical equipment, digital communication telemetry systems, CNC machines, and others, ultra isolation transformers are carefully designed. They stop loud equipment loads that are pumped into the power line from causing disturbances. For hyper isolation transformers, which are created with particular insulation between the primary and secondary, a high voltage between the windings is tested, defined, and labelled, often in the 1000-volt to 4000-volt range.

This transformer is specifically used by wireless stations and cutting-edge medical equipment. A feature is low coupling capacitance. An ultra-isolation transformer is a more complex transformer with effective shielding that is suited for power transformer application due to its high noise attenuation level. It is very effective and durable at different working voltages.

Constant Voltage Transformer

A Constant Voltage Transformer (CVT), a ferroresonant technology that delivers an output voltage that is not much effected by variations in input voltage, is a 1:1 transformer that is thrillingly high on its saturation curves. The constant voltage transformer, or CVT, uses a tank circuit made consisting of a high-voltage resonant winding and a capacitor to convert a fluctuating input into a virtually constant average output. The input winding typically functions at low flux linkage values.The output winding has built-in energy storage that works with the main capacitor to create a self-generated AC flux field that is subtly removed from the input winding. CVT is preferred over traditional stabilisers because it does not have relays, which might briefly interrupt the output voltage. A regulated output voltage offers CVT full spike protection (Figure 5.4).

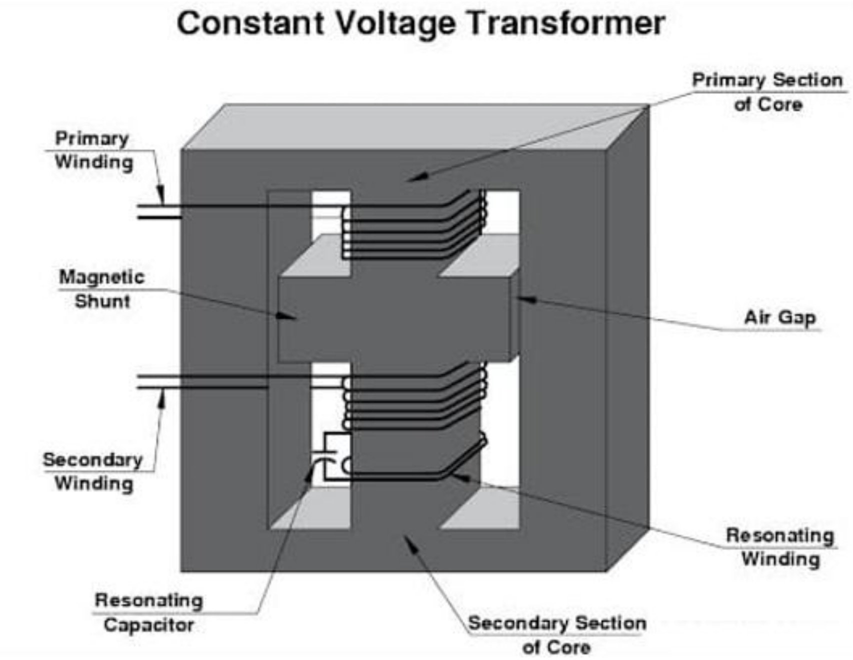


Figure 5.4 Constant voltage Transformers

Galvanic Isolation Transformer

The physical and electrical segregation of the input power circuit from the output power circuit is referred to as galvanic isolation in electrical equipment. Electrical isolation is accomplished with an isolation transformer. If the output power wire does not contact or connect to the input wiring, they are physically separated. Every personal computer already has galvanic separation between the input power and the computer logic. This is required by international safety groups to lower the danger of shock. Therefore, it is not essential to instal a second transformer.Most people believe that galvanic isolation may reduce noise on ground (or earth) line. All galvanic isolation transformers really only isolate the power wires, leaving the ground wire free to go through. Galvanic isolation is offered by several UPS systems. Contrary to popular belief, most online UPS systems do not provide galvanic isolation. Galvanic isolation, for instance, is not available in the online versions of Exide, Unison, and ON-LINE (Pheonixtec).

Isolation is hence a feature that may be implemented to any UPS and is not model-specific. The large decrease in common mode noise delivered to the computer is the real benefit of using an isolation transformer. To reduce common mode noise, noise filters may also be utilised, such as those found in the APC Smart-UPS line. Particularly at high frequencies where computers and networks operate, the filters may function just as well as the isolation transformer. The isolation transformer functions well at extremely low (audio) frequencies (Figure 5.5).

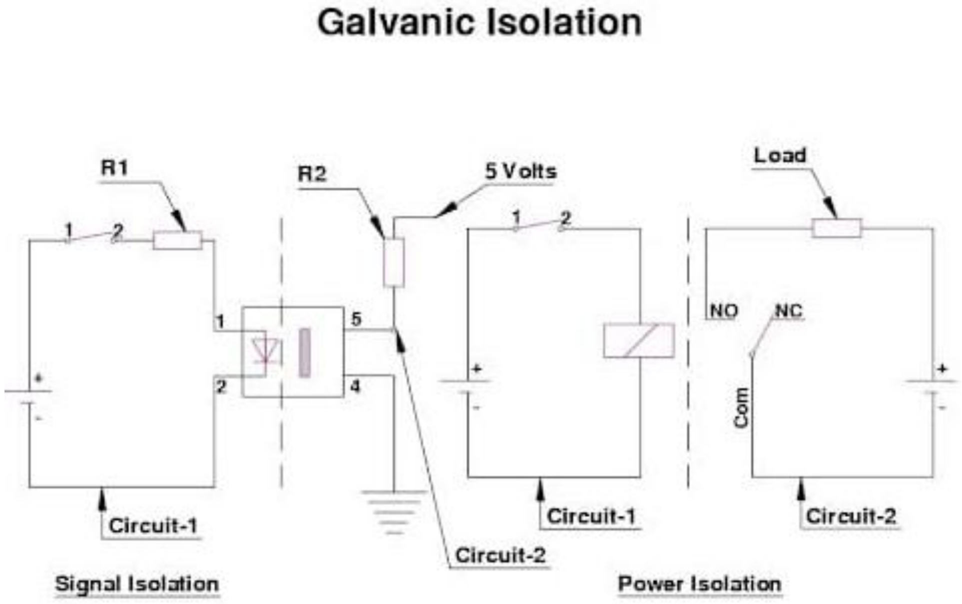


Figure 5.5Galvanic Isolation Transformers

Power line audio frequency noise has no effect on computers or computer peripherals. In computer applications, the isolation transformer is hence inferior to filters. The downside of the isolation transformer is the additional heat, which, if UPS batteries are close, shortens their lifespan. The weight of the UPS is greatly increased when an isolation transformer is used, which is another disadvantage.

Transformers for drive isolation

Drive isolation transformers provide electricity to drives with varied frequencies, both AC and DC. These transformers magnetically isolate the incoming line from the motor drive while providing a voltage change to match the required voltage for the SCR (Silicon Control Rectifier) Drive. Because of the mechanical strains, voltage distortions, and harmonics that

SCR-type drives create, strong mechanical and electrical design and testing are required. There are many various kinds of motor drives, but they all need rectifying incoming power to produce a DC level (Figure 5.6).

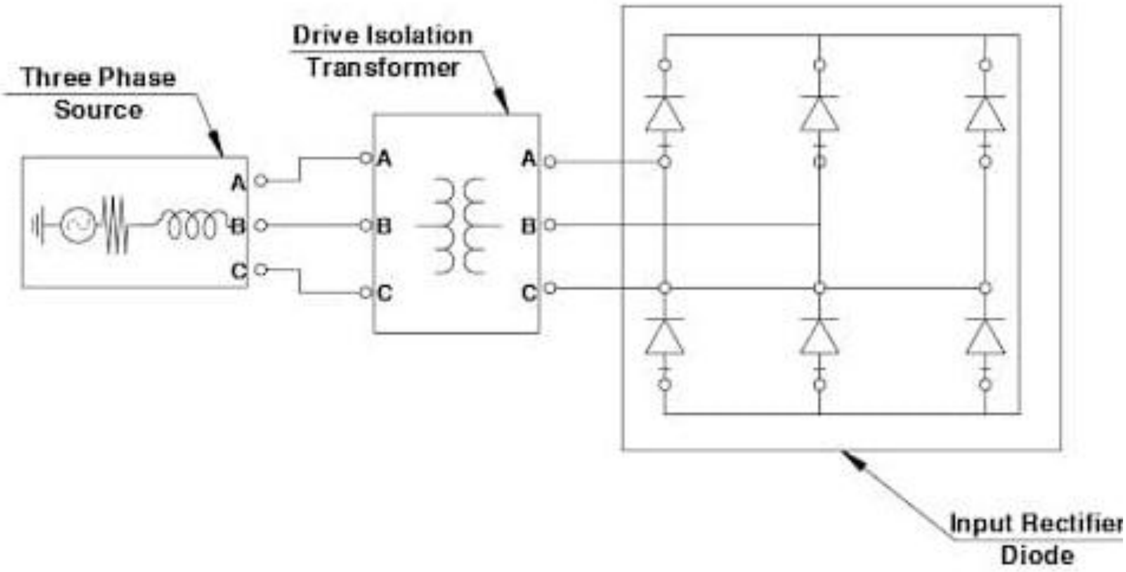


Figure 5.6 Transformers for drive isolation

The motor drive uses a three-phase rectifying bridge and an SCR to convert power from AC-DC-AC to AC-DC. The process of converting from AC to DC results in the creation of electrical noise, or harmonics. For a transformer used as an isolation drive element, harmonic currents (high-frequency currents) are particularly hazardous because at higher frequencies, they significantly increase heating and mechanical stress.

Drive isolation transformers are specifically designed to withstand the mechanical pressure, temperature, and voltage aberrations caused by motor drives. Common-mode voltages may result in motor bearing currents, line-to-ground voltage transients, and other system noise problems.

The transmission of common-mode noise will be stopped, considerably enhancing the system's dependability and safety, by grounding the secondary side. Transformers with a delta-wye-linked drive may create a ground reference on the secondary side. The motor drive system distorts the current on the line, and these high-frequency currents then return from the drive to the transformer winding. The extra watts must be taken into account when choosing a new transformer since these currents have the potential to dramatically increase the eddy-current losses in the windings. Eaton's drive isolation transformers are specifically designed to handle the high-frequency currents from the drive. Since the winding's high temperatures may reduce the transformer's lifetime or result in a catastrophic failure, drive isolation transformers include ThermoGuard protection incorporated into coils to notify the presence of high temperatures. ThermoGuards are a collection of "N.O." dry contacts.

Electrical Noises in Isolation Transformers: Their Causes and Effects

The sources and consequences of electrical sounds in isolation transformers will be covered in this chapter. Additionally, it will go over isolation transformer maintenance.Electrical sounds in isolation transformers have the following sources and effects:

Replacing electrical parts including capacitors, MCCBs, and ACBs, etc. Electrical noise intensity rises with switching current shift and system inductance.

Significant switching noises are also produced by inductive loads such as large motors, compressors, overhead cranes, elevators, presses, etc.Switching devices like inverters, converters, SMPS, or relays as well as switching equipment like thyristors, transistors, or relays all create electrical noise.Welding systems pollute earthing systems, modify waveforms by adding notches and high-frequency noises, and produce anomalies in power quality.

Lightning, static charge precipitation, and electrical discharges in the atmosphere are a few examples of the natural factors that produce various electrical sounds (Figure 5.6).

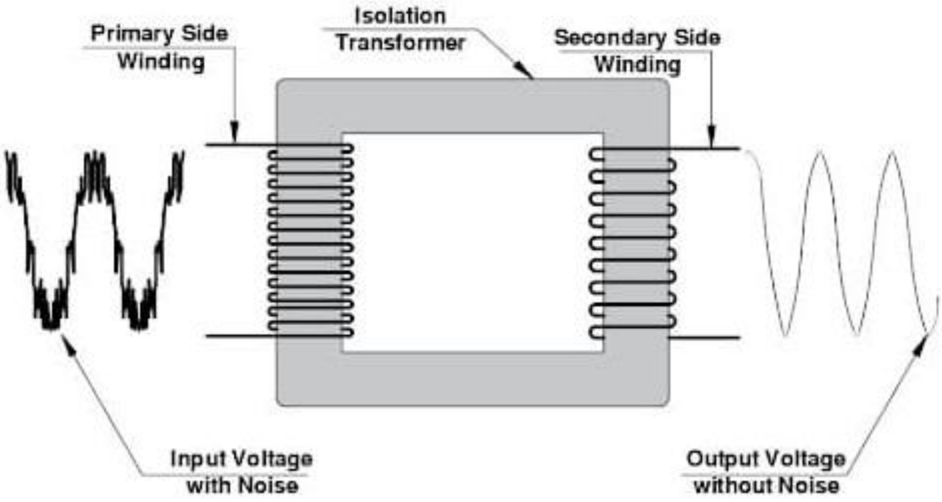


Figure 5.6 Electric noise elimination

Effects of Electrical Noises in Isolation Transformers

From 1 KHz to 100 MHz and above, there is a wide frequency range where electrical sounds may be seen. A magnitude of up to 6000 volts on a three-phase supply system was observed.In digital electronic equipment, high-frequency noise may lead to untraceable data errors, programme alterations, memory loss, unpredictable behaviour, etc.

Strong voltage spikes may cause thyristors or transistors, microprocessors, and other sensitive equipment to malfunction.Remote operation is possible for cranes, digital controls, and telecom equipment, however noise interference may occur.

Maintenance of Isolation Transformers

The most costly and important piece of machinery in an electrical substation is a power transformer. It is advisable to undertake a variety of preventive maintenance procedures in order to preserve the transformer's excellent performance and extended functioning life. One of the necessary regular maintenance operations for a power transformer is measurements and testing of the many different characteristics of the transformer.There are two types of maintenance on transformers. Regularly carry out the first set of tasks as part of preventive maintenance, and do the second group when necessary (i.e., as required). Other forms of maintenance on transformers, often known as emergency or breakdown maintenance, are only performed when required. However, doing regular maintenance correctly considerably reduces the need of performing such emergency repair.

The regular examination and repair of transformers is referred to as "condition maintenance." Therefore, by carrying out adequate condition maintenance, one may prevent emergency and breakdown repair. Technical staff members should thus concentrate mostly on condition maintenance. There is no equipment failure since all required maintenance has been carried out.

Maintenance performed daily on the isolation transformer

Transformer temperature, winding temperature, oil temperature, and load hours are all monitored daily during maintenance. This makes sure that the MOG (Magnetic Oil Gauge) values from both the main tank and the conservator tank are monitored. Monitoring the breather's silica's colour is another option. The transformer must be filled with oil if the MOG's oil level is insufficient, and the tank that houses the transformer must be checked for oil leaks. Do everything is required to halt an oil leak if one is found.

Isolation Transformer Maintenance on a Monthly Basis

It is essential to check the oil level in the oil cap behind the silica gel breather once a month. If it is found that the level within the cup has dropped below the acceptable level, transformer oil must be filled up. Silica gel breather breathing holes should also be inspected monthly and cleaned as necessary to ensure proper breathing action. It is important to manually monitor the oil level in each bushing linked to the oil gauge if the transformer has oil-filled bushings. This process has to be carried every each month. If required, add enough oil to completely fill the bushing. Oil filling will be carried out during a closure.

Transformation Isolator Periodic Base Maintenance

The cooling system's automated, remote, and manual functioning, including the oil pumps and air fans as well as their control circuit, has to be checked yearly. Check the physical condition of the pumps, fans, and control circuit if there is a problem. The transformer's bushings should be cleaned once a year using gentle cotton towels. While cleaning, the bushing should be checked for cracks.

The OLTC's oil condition has to be examined once a year. To do so, an oil sample must be taken from the diverter tank's drain valve and tested for moisture content and dielectric strength (BDV) (PPM). If the PPM for moisture is found to be greater than acceptable values and the BDV is low, the oil within the OLTC has to be changed or filtered.In addition, the inside of all marshalling boxes must be completely cleaned at least once a year. A annual inspection is required of all lights and space heaters, as well as a tightening of all terminal connections for the control and relay wire.

The appropriate cleaning product should be used to clean all of the relays, alarms, and control switches in the relay and control panel as well as the remote tap changer control panel. The efficiency of the Buchholz relay and pressure release mechanism must be checked annually. To check whether the corresponding relays in the remote panel are functioning properly, trip contacts and alarm contacts of the aforementioned devices are briefly connected by a short piece of wire.

Transformer insulation resistance and polarization index must be tested using a battery-operated megger with a 5 KV range. Annual clamp-on earth resistance meter measurements of the earth connection are required. Dissolved Gas Analysis, or DGA, of transformer oil should be carried out every year for 132 KV transformers, once every two years for those below 132 KV, and twice every two years for those over 132 KV transformers.

Applications and Benefits of Isolation Transformers

The uses and advantages of isolation transformers are covered in this chapter. These consist of:

Applications of Isolation Transformers

1. To create security-related isolation within a power source, powered circuit, or powered equipment
2. To change the electrical power flowing between two circuit lines that are not electrically connected, of the same or different voltage level
3. As pulse transformers, i.e., in computer network configuration applications
4. To protect against electrical shock in electrical circuits as electric lines
5. To eliminate electrical noise in electrical and electronic circuits and a very small number of sensitive equipment
6. To prevent ground-level loop interference in a circuit
7. To supply electricity to sensitive electronics, including computers, oscilloscopes, and medical equipment
8. To assist the function of electronic testing equipment, radars, levels, and communication circuits
9. To avoid damaging electrical sounds, spikes, etc., on computers, CNC machines, and telecommunication equipment • If the system's components' ground potentials differ from one another and they're subjected to the impacts of instability at high frequenciesIf the equipment's ground cannot be earthed • To protect many electronic devices from each other's electrical noise at a common busbar, such as CNC machines, drives, hardening devices, etc.
10. To avoid damage from internal noise interference due to NCTs' ability to operate in both directions
11. To safeguard against powerful lightning, impulse noise, bus short-circuits, and unintentional capacitor discharge

Benefits of Using Isolation Transformers

Reliable and Safe Equipment

Different types of electrical gadgets are well-protected from power problems by isolation transformers. Voltage swings and abrupt shocks can harm crucial equipment parts, interfering with the equipment's typical operation. In order to avoid such threats, isolation transformers disconnect the equipment from the power source, extending its safety and quality of life.

Because medical facilities like hospitals use electronic equipment for diagnoses, treatments, and other purposes, medical staff, nurses, and patients are particularly vulnerable to sudden equipment damage.

Using isolation transformers avoids such unwelcome problems caused by faulty equipment. They spare not only expensive appliances but also human lives.

Reduced Presence of Power Surges

Power-based appliances are severely damaged by power surges. Even while these voltage spikes only last a short time, the equipment can be seriously harmed. However, isolation transformers prevent such a catastrophe from happening. They prevent surges by galvanic isolation, which safeguards the machinery. There is typically no possibility of equipment damage from surges since isolation transformers isolate the DC power channels.

Reduced Noise Disruption

There are frequently noticeable noise disruptions when the signals from audio amplifiers reach the speakers' output circuit. Such audio issues are resolved with isolation transformers. As a result, they enable noise reduction and enhance the functionality of such electrical devices. Faraday shields, a specialized design element, are used in these transformers. These shields stop the electric field if there are any disruptions in the power flow. As a result, the equipment's electromagnetic noise will be minimized. Many industries can benefit from isolation transformers. In particular, dependable isolation transformers are essential for the efficient operation of telecommunication, CNC, remote controls, and other equipment.

Harmonics Correction

Electronic motors are used in a variety of industrial machinery types, and they cause harmonic voltage distortions. The equipment breaks down as a result of these harmonic changes. The best options for harmonics correction are isolation transformers. As a result, they are great protectors of industrial electric and electronic machinery.

Prevention of Earthing Failures

The ability to prevent earthing failures is a solid advantage of isolation transformers. There won't be a conductive connection between the ground and the secondary end of the transformer if these transformers are used. As previously stated, these transformers' Faraday shields increase efficiency.

Improved power quality

Isolation transformers lessen the possibility of current leakage, raising the standard of the power delivered to the machinery. As a result, isolation transformers indirectly improve equipment durability.

Disadvantages of Isolation Transformer

When the isolation transformer is used as a pulse transformer and operated at a low frequency, the secondary or output waveform produces distortion.The saturation property of the core is lessened when an isolation transformer is running at a DC pulse signal. Due to their unique construction, isolation transformers cost more than standard transformers

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CHAPTER 6

Classification to Electric Motor

P. Kishore Kumar, Associate Professor
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology,
JAIN (Deemed-to-be University), Karnataka – 562112
Email Id-k.kishore@jainuniversity.ac.in

Any member of the electric motor family of devices, which transform electrical energy into mechanical energy via electromagnetic phenomena. Most electric motors create their mechanical torque by the interaction of conductors carrying current in a direction that is at right angles to a magnetic field. There are many different types of electric motors, and each one differs in terms of the configuration of the conductors and magnetic field as well as the level of control that can be applied over the mechanical output torque, speed, and position. An electric motor is a device that converts electrical energy into mechanical energy (or electrical motor). The magnetic field of the majority of electric motors interacts with an electric current that is passing through a wire winding to power them. This contact generates a force in the form of torque that is delivered to the motor's shaft in accordance with Faraday's Law. Electric motors may be powered by Direct Current (DC) sources like batteries or rectifiers. Another option is to use sources of alternating current (AC), such as power grids, inverters, or electric generators. Motors make many of the contemporary technologies that we use every day feasible. Without the motor, we would still be in the time of Sir Thomas Edison, when the only things powered by electricity were lightbulbs. Electric motors are necessary for many things, including automobiles, trains, power tools, fans, air conditioners, household appliances, disc drives, and many more. There are small motors in some electronic clocks as well. Different motor types have been developed for a variety of uses. The basic principle that controls how an electrical motor works is Faraday's Law of Induction. This indicates that a force is generated when an alternating current interacts with a fluctuating magnetic field. This field of engineering has seen several advancements since the invention of motors, and its importance to modern engineers has increased.

Automobiles, rectifiers, and batteries all utilise direct current motors, whereas electrical generators, power grid stations, and inverters all use alternating current motors. Electric motors are used as a reverse source to recover the energy that generators lose. They are also used in disc drives and computers to provide cooling, which prevents equipment from eventually overheating and burning. Electric motors may be powered by either direct current (DC) sources like batteries or rectifiers or alternating current (AC) sources like the power grid, electrical generators, or inverters. Electric motors may be categorised based on factors like the kind of power source, the application, the construction, and the type of movement output. They may be single-phase, three-phase, two-phase, axial, brushless, or radial flux, and they can be cooled by liquid or by air. Standardized motors provide enough mechanical energy for use in the industrial sector. Examples of uses include blowers and pumps, industrial fans, power tools, household appliances, disc drives, and cars. There are small motors in electrical watches. In certain circumstances, such as regenerative braking in traction motors, electric motors may be operated in reverse as generators to recover energy that would otherwise be lost as heat and friction.

The operation of an electric motor

Electric motors may convert electrical energy into mechanical or kinetic energy, which allows them to be a commonplace feature of contemporary life. Eclectic motors are used in

EVs, fans, clocks, mixers, grinders, washing machines, and many more devices. Knowing the motor principles helps everyone use motorised devices more efficiently. The discussion of several common types of electric motors, such as synchronous motors, induction motors, and DC motors, follows. The magnetic field is the basis for how electric motors operate. A magnet or the windings around a magnetic core may generate the magnetic field. The theory begins with explaining the magnetic force of a current-carrying wire that is subjected to a magnetic field., the magnet creates a magnetic field between the N and S poles. From the N pole, the magnetic field lines enter the S pole. This magnetic field, which might resemble a DC magnetic field since it is steady and does not fluctuate (Figure 6.1).

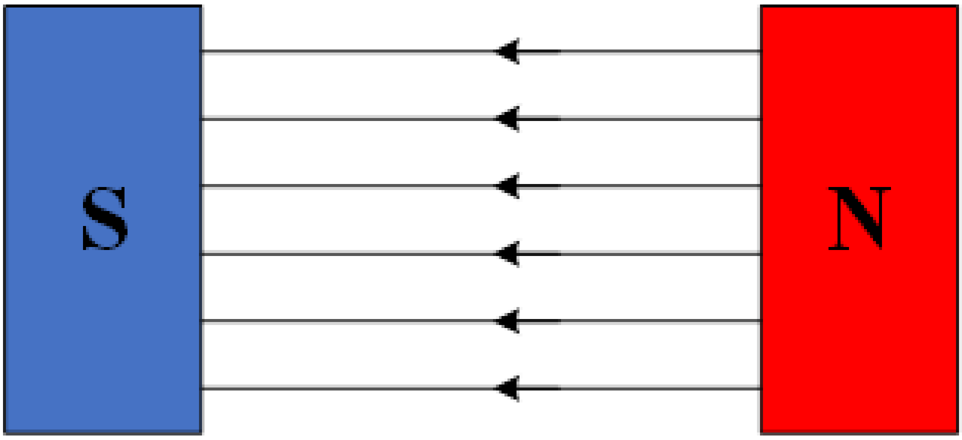


Figure 6.1 operation of an electric motor

A magnetic force is provided to a current-carrying wire when it encounters the magnetic field, which causes the wire to move. The degree of force is dependent on a few factors that are covered in this article. The amount of current flowing through the wire is the first factor that affects the magnetic force. Since the force is inversely proportional to the current when it is zero, there will be no force acting on the wire. As a result, the following equation may be written.

$$F \alpha I$$

Where,

I is the wire's current and F is magnetic force. The length of the wire that is exposed to the magnetic field is another factor. Additionally direct, the relationship between magnetic force and exposed wire length is as follows:

$$F \alpha l$$

Where,

L is the wire's length. The final variable is the strength of the magnetic field, which is directly related to the magnetic force as:

$$F \alpha B$$

When,

The magnetic field is perpendicular to the wire, these three factors define the maximum magnitude of magnetic force. Thus, any departure from the perpendicular position minimises the amount of applied force to the wire. Due to the angle between the magnetic field and the conductor's current, magnetic force is not at its highest level (Figure 6.2).

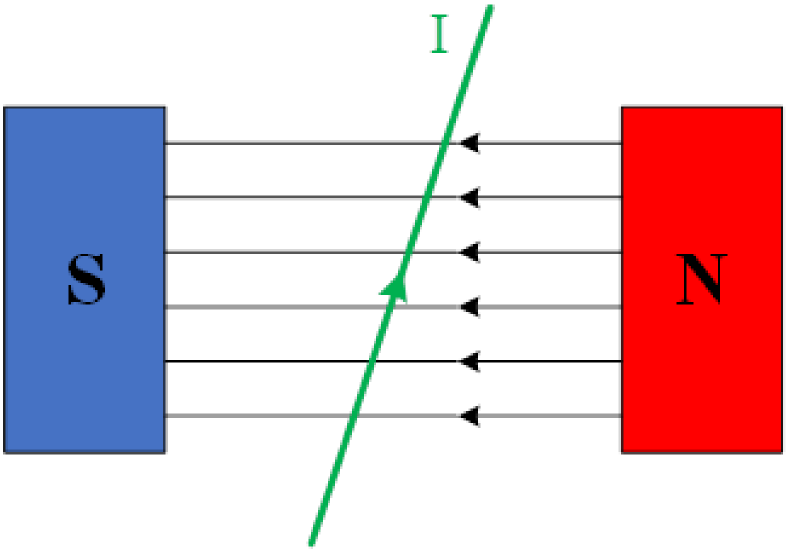


Figure 6.2 magnetic field is perpendicular to the wire

The given equation can be used to calculate the magnetic force taking into account all factors.

$$F=I.L.B.Sin\theta$$

Now, a loop between poles may be taken into account rather than a single conductor. Although the loop can take any form, it is assumed to be in a rectangle in for ease of understanding. In this case, a magnetic force and a current are present on either side of the loop. The left-hand rule may be used to determine the force direction (Figure 6.3).

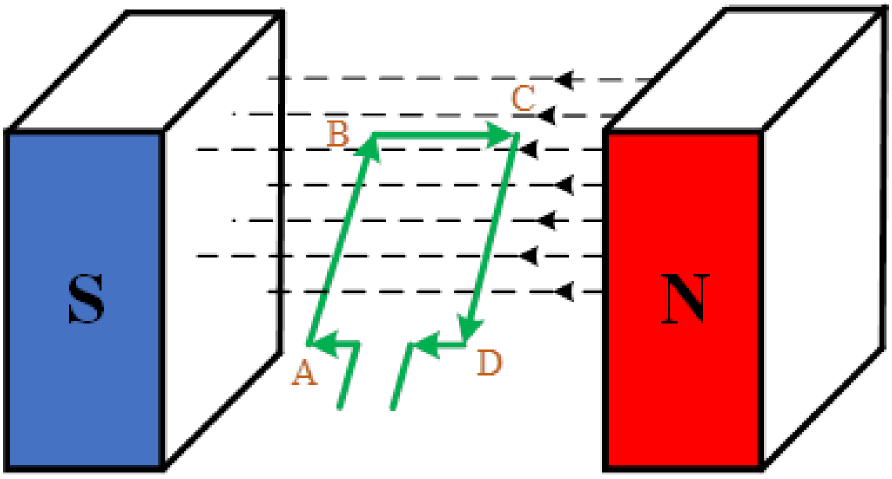


Figure 6.3 determine the force direction

In this rule, the forefinger represents the magnetic field, the middle finger represents the direction of the current, and the thumb is aligned with the magnetic force. All of these fingers are parallel to one another. Equation 4 states that when the carrying current is parallel to the magnetic field, there is no magnetic force. Therefore, there is no magnetic force in BC or AD. In this state, only AB and CD feel magnetic force. By applying the left-hand rule to AB and CD pathways, the magnetic force for the AB path would be upward, while for the CD path, the force direction would be downward. These two opposed forces spin the loop, but it cannot complete its revolution since the present orientation in the loop is constant. It implies that the loop is in a stable position when it is parallel to the magnetic field. In this condition, the upward and downward pressures balance each other, and the wire loop cannot move. To address this challenge, the present orientation in the loop must be respected in each half revolution to enable the wire loop to revolve. Additionally, the loop's inertia will enable it to keep rotating and past the stable position.

CHAPTER 7

Classification and Construction of D.C. Machines

Vivek Kumar Jain, Associate Professor,
Department of Electrical, Jaipur National University, Jaipur, India
Email Id- vivekkumar@jnujaipur.ac.in

DC generators and DC motors. Because they include both AC currents and AC voltages, the majority of DC machines are equal to AC machines. Because they convert AC power to DC voltage, DC machines only provide DC output. These machines are also known as commutating machines since the conversion that this mechanism does is known as the commutator.

The kind of machine most usually used for motors is DC. Torque control and simple speed are this machine's key advantages. The DC machine can only be used in railways, mills, and mines. Trolleys and subterranean subway carriages, for instance, both use DC motors. In the past, DC dynamos were used into the design of vehicles to charge their batteries. A DC machine is a tool for electromechanical energy modification.

The magnetic force created by an electric current flowing through a coil inside of a magnetic field causes the magnetic field to produce a torque, which turns the DC motor. There are two categories of DC machines: DC motors and DC generators.

DC Machine

A DC motor transforms DC electricity to mechanical power, while the primary purpose of a DC generator is to convert mechanical power to DC electrical power.

In industrial settings, the AC motor is widely utilised to convert electrical energy to mechanical energy. However, a DC motor may be used in situations where there is a need for excellent speed control and a wide range of speeds, such as in electric transaction systems.

Constructionof a DC Machine

The construction of the DC machine can be done using some of the essential parts like Yoke, Pole core & pole shoes, Pole coil & field coil, Armature core, Armature winding otherwise conductor, commutator, brushes & bearings. Below is a discussion of a few of the DC machine's components.

Describe a DC machine.

A DC machine is a tool for electromechanical energy modification. The magnetic force created by an electric current flowing through a coil inside of a magnetic field causes the magnetic field to produce a torque, which turns the DC motor. There are two categories of DC machines: DC motors and DC generators (Figure 7.1).

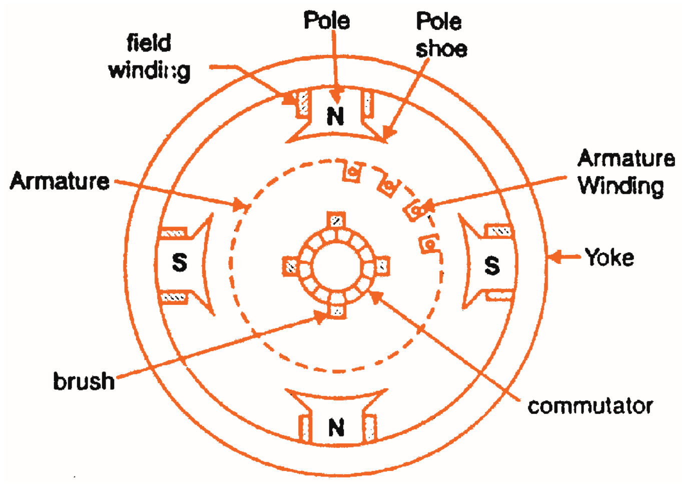


Figure 7.1 construction of DC machine

Yoke

The frame is another term for a yoke. The yoke's primary role in the machine is to provide mechanical support for the poles and shield the whole thing from moisture, dust, etc. Cast iron, cast steel, or rolled steel are the materials used to make the yoke.

Both poles and the Core

An electromagnet serves as the DC machine's pole, and the field winding is wound among the poles. The pole emits magnetic flux whenever the field winding is activated. Cast steel and cast iron, as well as pole core, are the materials utilised for this. To lessen the power loss caused by eddy currents, it might be constructed using annealed steel laminations.

Pole Shoe

The pole shoe is a substantial component of the DC machine that also serves to increase the pole's area. This area allows for the distribution of flux inside the air-gap as well as the passage of additional flux via the air space in the direction of the armature. Cast iron or cast steel is used to construct pole shoes. Annealed steel lamination is also used to lessen the loss of power caused by eddy currents.

String Windings

This has windings that are damaged near the pole core and is known as a field coil. When current is applied via a field winding, the poles electromagnetically provide the necessary flux. Copper is the primary component of field windings.

Armature Core

The edge of the armature core has a great number of slots. These holes hold the armature conductor. It offers a low-resistance pathway for the flux produced by field winding. Low-reluctance, permeability-enhancing materials like cast iron are employed in this core. Eddy current loss is reduced with the use of lamination.

Transformer Winding

The armature conductor may be connected to create the armature winding. When a primary mover turns an armature winding, both a magnetic flux and voltage are induced inside the winding. This winding is connected to a circuit outside. Conductive materials like copper are utilised to make this winding.

Commutator

In a DC machine, the commutator's primary job is to receive current from the armature conductor and then use brushes to send that current to the load, also gives a DC motor unidirectional torque. The commutator may be constructed using a sizable number of segments in hard drawn copper's edge shape. The thin mica layer shields the Segments in the commutator.

Brushes

The DC machine's brushes collect the current from the commutator and provide it to the external load. Brushes deteriorate with time, so check them periodically. Brushes are made of rectangular carbon or graphite, depending on the use.

Different Types of DC Machines

Separate and self-excitation are the two categories into which the excitation of the DC machine is divided. In a separate excitation type of dc machine, the field coils are activated with a separate DC source. In the self-excitation type of dc machine, the flow of current throughout the field-winding is supplied with the machine. The principal kinds of DC machines are classified into four types which include the following.

a) Individually energised DC machine

b) Shunt-wound/shunt machine.

c) Series wound/series machine.

d) Compound wound / compound machine.

Separately Excited

In Separately Excited DC Machine, a separate DC source is utilized for activating the field coils.

Shunt Wound

In Shunt wound DC Machines, the field coils are allied in parallel through the armature. As the shunt field gets the complete o/p voltage of a generator otherwise a motor supply voltage, it is normally made of a huge number of twists of fine wire with a small field current carrying.

Series Wound

In series-wound D.C. Machines, the field coils are allied in series through the armature. As series field winding gets the armature current, as well as the armature current is huge, due to this the series field winding includes few twists of wire of big cross-sectional region.

Compound Wound

A compound machine includes both the series as well as shunt fields. The two windings are carried-out with every machine pole. The series winding of the machine includes few twists of a huge cross-sectional region, as well as the shunt windings, include several fine wire twists.The connection of the compound machine can be done in two ways. If the shunt-field is allied in parallel by the armature only, then the machine can be named as the ‘short shunt compound machine’ & if the shunt-field is allied in parallel by both the armature as well as series field, then the machine is named as the ‘long shunt compound machine’.

EMF Equation of DC Machine

The DC machine e.m.f can be defined as when the armature in the dc machine rotates, the voltage can be generated within the coils. In a generator, the e.m.f of rotation can be called the generated emf, and Er=Eg. In the motor, the emf of rotation can be called as counter or back emf, and Er=Eb.

Let,

Φ is the useful flux for every pole within webers

P is the total number of poles

z is the total number of conductors within the armature

n is the rotation speed for an armature in the revolution for each second

A is the no. of parallel lane throughout the armature among the opposite polarity brushes.

Z/A is the no. of armature conductor within series for each parallel lane

As the flux for each pole is 'Φ', every conductor slashes a flux 'PΦ' within a single revolution.

The voltage produced for each conductor = flux slash for each revolution in WB / Time taken for a single revolution within seconds

As 'n' revolutions are completed within a single second and 1 revolution will be completed within a 1/n second. Thus the time for a single armature revolution is a 1/n sec.The standard value of produced voltage for each conductor p Φ/1/n = np Φ volts

The voltage produced (E) can be decided with the no.of armature conductors within series I any single lane among the brushes thus, the whole voltage produced E = standard voltage for each conductor x no. of conductors within series for each lane E = n.P.Φ x Z/A

The above equation is the e.m.f. the equation of the DC machine.

DC Machine Vs AC Machine (Table 7.1)

Table 7.1 the difference between the AC motor and the DC motor includes the following

AC Motor	**DC Motor**
AC motor is an electric device which is driven through an AC	DC motor is one kind of rotatory motor used to change the energy from DC to mechanical.
These are classified into two types like synchronous & induction motors.	These motors are available in two types like brushes & brushes motors.
The input supply of ac motor is alternating current	The input supply of dc motor is direct current

In this motor, brushes, and commutators are not present.	In this motor, carbon brushes and commutators are present.
Input supply phases of ac motors are both single and three-phase	Input supply phases of dc motors are single phase
The armature characteristics of ac motors are the armature is inactive whereas the magnetic field turns.	The armature characteristics of dc motors are, the armature turns whereas the magnetic field remains inactive.
It has three input terminals like RYB.	It has two input terminals like positive and negative
The AC motor speed control can be done by changing the frequency.	The DC motor speed control can be done by changing the current of the armature winding
The efficiency of the AC motor is less because of the loss in induction current & slip of motor.	The DC motor’s efficiency is high because there is no induction current as well as slip
It doesn’t require any maintenance	It requires maintenance
AC motors are used wherever high speed, as well as variable torque, is required.	DC motors are used wherever variable speed, as well as high torque, is required.
In practical, these are used in large industries	In practical, these are used in appliances

The following are some of the ways that an AC motor and a DC motor differ.

Production of a Magnetic Field

Ampere's Law states that:

$$\oint \vec{H} \cdot d\vec{l} = I_{enclosed}$$

Intensifying the magnetic field will initially result in a sharp increase in flux density. This suggests a high level of permeability. The rate of reduction of flux density with field intensity occurs at a certain point (usually between 1.0T and 1.5T in steels used in machines). The knee of the saturation curve is where this is located. The steel is considered to be saturated as the field intensity increases further, and bigger variations in field intensity have a lower impact on flux density changes.

As a consequence, electrical machines have a finite flux density. Later on, we'll find that dimensions and flux density are functions of force and torque. We are left with the truth that a greater torque necessitates a bigger machine because flux density is restricted. This is a significant overall finding.

It implies that smaller machines with a particular power rating have greater speeds (power is torque times speed). Additionally, it implies that in order to decrease the size of a machine for a given torque, the flux density must be raised (Figure 7.2).

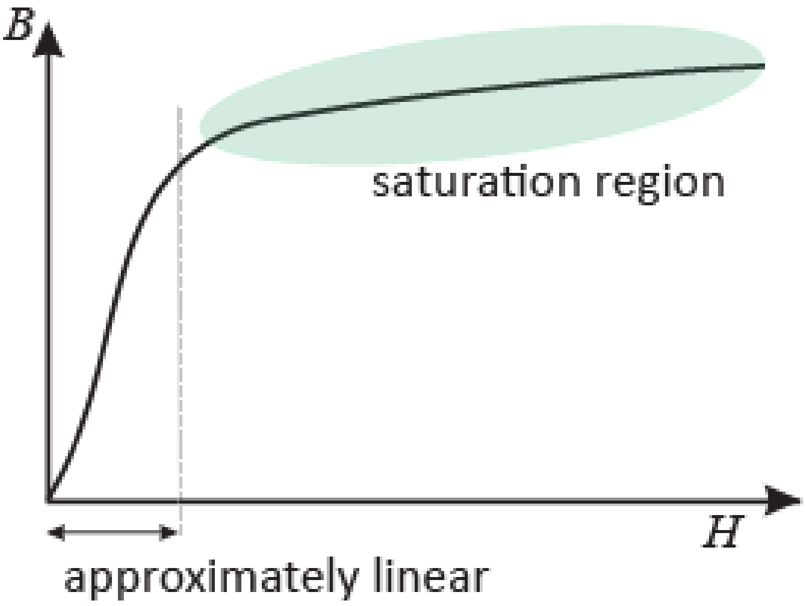


Figure 7.2 power is torque times speed

Transformer Action

Faraday's and Lenz' Laws state that

If the flux through a single turn of a wire fluctuates over time, an induced emf will occur across the turn and operate to induce a current that opposes the flux change.

A turn is created when a single wire is organised to make a closed loop. A "coil" is made up of many rounds of wire. Positive current may flow away from you in one side of the coil and towards you in the other half of the coil, which is how coils are often conceptualised. A "winding" is formed by connecting a number of coils.

The sum of the fluxes connecting each turn of the coil in a coil determines the overall flux travelling through the coil (linking the coil).

This is sometimes calculated as the quantity of turns times the flow connecting one turn. However, it is more accurate to consider a coil's total flux linkage, represented by the symbol. The units of flux linkage are Weber-turns. In this instance, the induced voltage is rewritten.

Motor Performance

A force is produced when current flows through a conductor in a magnetic field. Keep in mind that the force will be 0 if the current flows parallel to the direction of the magnetic flux.

When current flow is parallel to flux density, force is greatest.

Engine Activity

Moving a conductor through a magnetic field will cause a voltage to be induced in the conductor. In the equation above, v stands for linear velocity.

When the conductor, flux density, and motion are parallel to one another, the induced voltage is at its highest.

Different D.C. Machines

The magnetic flux in a d.c machine is produced by field coils carrying current. The production of magnetic flux in the device by circulating current in the field winding is called excitation.In a DC machine, there are two different forms of excitation.

Separate self-excitation from excitation. In self-excitation, the current flowing through the field winding is supplied by the machine itself, and in separate excitation, the field coils are energized by a separate D.C. Source.

The three main categories of D.C. machines are:

I. An independently energised DC machine
II. Shunt machine or shunt wound.
III. Series wound or series machine.
IV. Compound wound or compound machine

Separately excited D.C. machine:

When a separate D.C. source is used to energize the field coils it is called as separately excited D.C. machine. The diagram provides the connections showing the individually stimulated D.C. machines

Shunt wound D.C. Machine:

Shunt injury D.C. machines are those in which the armature and field coils are linked in parallel.

The shunt field is often constructed of a high number of turns of tiny wire carrying a little field current because it receives the whole output voltage of a generator or the supply voltage of a motor (Figure 7.3).

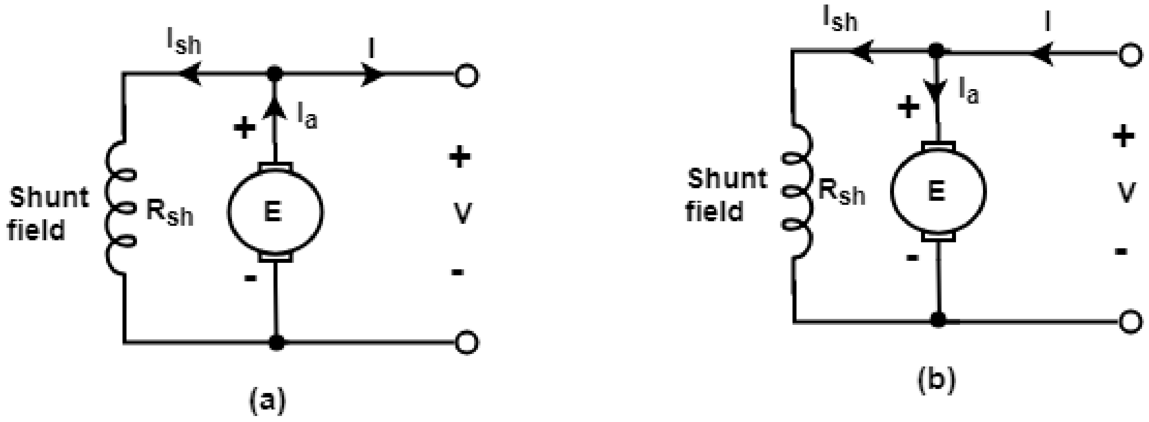
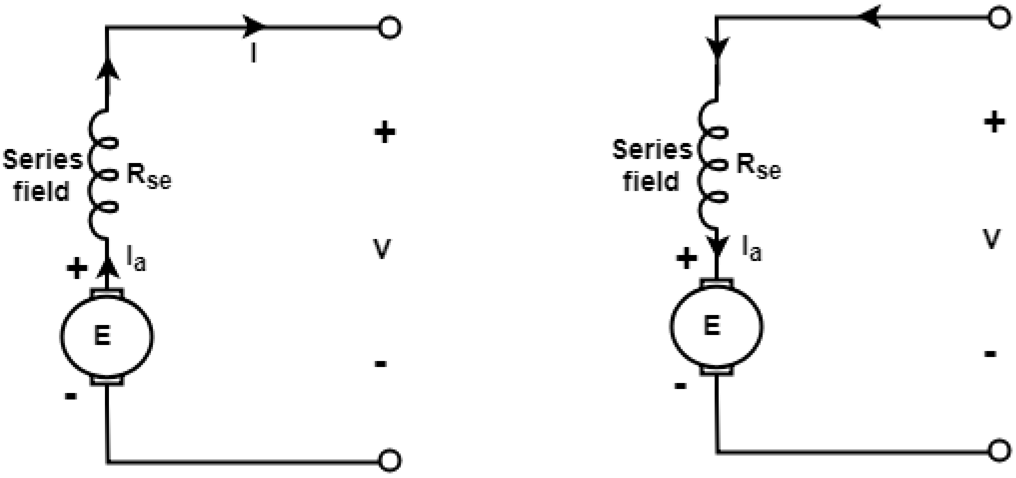


Figure 7.3 Shunt wound D.C. Machine

Series wound D.C. Machine:

Serieswound D.C. machines are those that have the armature and field coils linked in series.

The armature current is carried by the series field winding, which has a small number of turns of wire with a large cross-sectional area because of the high armature current (Figure 7.4).

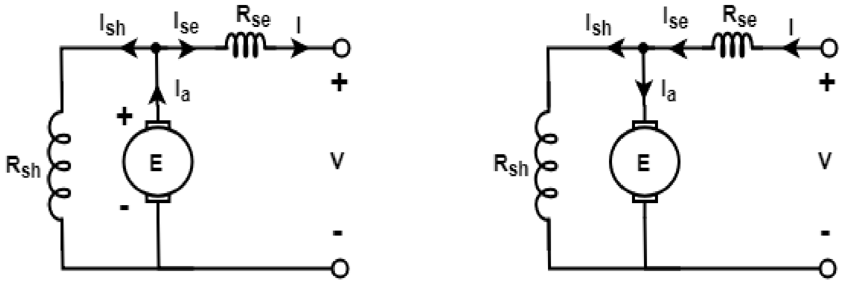


(a) (b)

Figure 7.4 Series wound D.C Machine

Compound wound D.C. machine:

A machine that has both shunt and series fields is referred to as a compound machine. The machine's poles each do two windings. The shunt windings feature numerous turns of thin wire whereas the series winding has few turns of high cross-sectional area.It may be linked in two different ways. If the shunt field is connected in parallel with the armature alone, the machine is called the short-shunt compound machine and if the shunt field in parallel with both the armature and series field, the machine is called the long-shunt compound machine (Figure 7.5).



(a) (b)

Figure 7.5Compound wound D.C Machine

Separate DC machines are excited:

The field winding is provided from a separate power source in independently excited dc devices. That indicates that the armature circuit and the field winding are electrically isolated. Due to their high cost and need for an external power source or circuitry, separately excited DC generators are not often employed.

They are used in research labs for precise Ward-Leonard system speed regulation of DC motors as well as a few other applications where self-excited DC generators fall short. In this form, permanent magnets may also be used to supply the stator field flux (such as in permanent magnet DC motors). Small toys, such a toy vehicle, often employ PMDC (permanent magnet DC) motors.

DC Machines that self-excite:

For a variety of performance qualities, field winding and armature winding are coupled in different ways in this kind (for example, field winding in series or parallel with the armature winding).The field winding is powered by the current they create in a self-excited form of DC generator. The residual magnetism at the poles causes a little quantity of flux to be present at all times. Thus, the residual magnetism is the sole factor at first responsible for current inducing in the armature conductors of a dc generator. As the induced current begins to flow through the field winding, the field flux steadily rises.

Self-excited machines may also be divided into:

Series wound DC machines are of this sort, with the armature winding and field winding coupled in series. As a result, the whole load current is carried by the field winding (armature current). Because of this, series winding is created using a small number of turns of thick wire and a very low resistance (about 0.5 Ohm).

Shunt wound DC machines: In these, the armature and field windings are linked in parallel. As a result, the field winding receives the entire voltage. A lot of turns are used to create shunt winding, and the resistance is maintained quite high (about 100 Ohm). It only uses a little amount of electricity, less than 5% of the rated armature current.

Compound wound dc machines - This category includes devices with two sets of field winding. The armature winding is linked to one in series and the other in parallel. Additionally, compound wound machines are categorised into (Figure 7.6):

Short shunt: Only the armature winding and field winding are linked in parallel.

Series field winding and armature winding are coupled in parallel with long shunt-field winding.

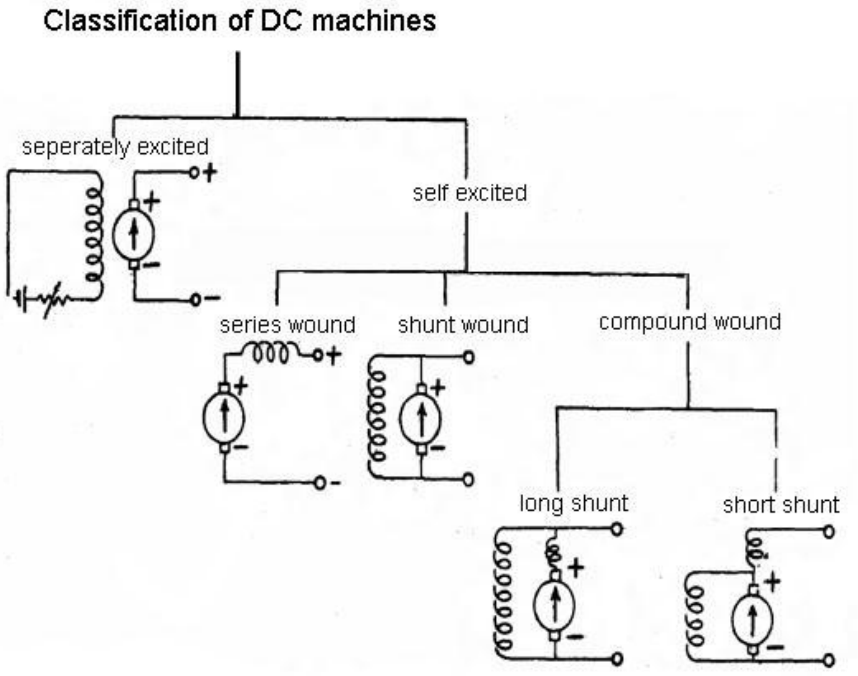


Figure 7.6Classification of D.C Machine

The DC machine's EMF and torque equation is as follows: The magnetic structure of a dc machine is such that, as long as the armature is not carrying any current, the flux density wave in the air-gap is flat-topped with quarter-wave symmetry. The flux density wave is shown in Section 7.6 to be deformed while the armature is carrying current (armature reaction effect destroys quarter-wave symmetry). The magnitudes of each of these are determined by the flux/pole independently of the form of the B-wave,

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CHAPTER 8

Equation for Dc Machine Torque and Armature Reaction in Dc Machines

Harsh Shrivastava, Assistant Professor,
Department of Electrical, Jaipur National University, Jaipur, India
Email Id-ershrivastava@jnujaipur.ac.in

Equation for DC Machine Torque:

Below figure depicts the conductor current distribution in the constructed armature for one pole-pair as well as the flux density wave in the air-gap (Figure 8.1).

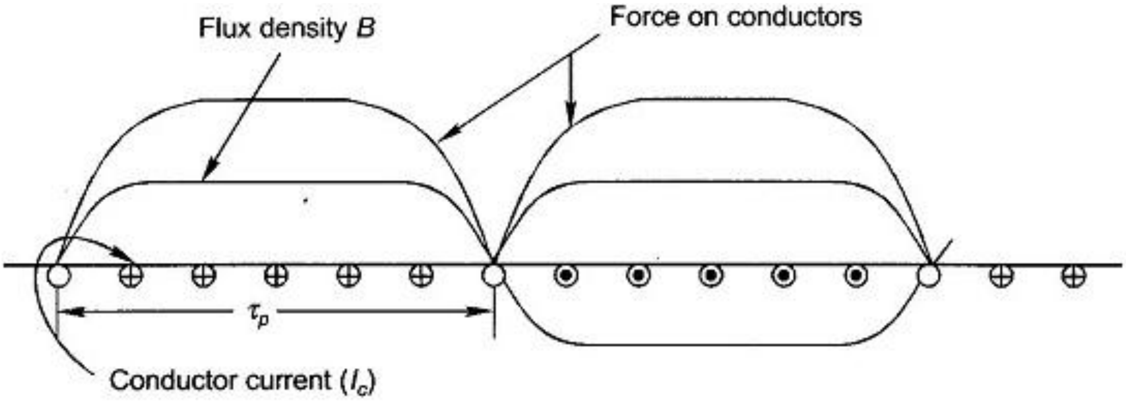


Figure 8.1 conductor current distribution

The force on conductors is unidirectional. Each conductor as it moves around with the armature experiences a force whose time variation is a replica of the B-wave. Therefore, the average conductor force

$$f_{c,\mathrm{av}} = B_{\mathrm{av}} l I_c$$

where B_{av} = average flux density over pole
l = active conductor length

Total force $F = Z f_{c,\mathrm{av}} = B_{\mathrm{av}} I_c l Z$

This force (and therefore torque) is constant (independent of time) because both the flux density wave and current distribution are fixed in space at all times. Now the torque developed

$$T = B_{\mathrm{av}} I_c l Z r$$

where r = mean air-gap radius

The flux/pole* can be expressed as

$$\Phi = B \quad \tau P l$$

where τP = pole-pitch $= \dfrac{2\pi r}{P}$

$$\therefore \qquad \Phi = B_{av}\left(\frac{2\pi r}{P}\right)l$$

or
$$B_{av} = \frac{\Phi P}{2\pi} \times \frac{1}{rl}$$

Substituting for B_{av} in Eq. (7.6),

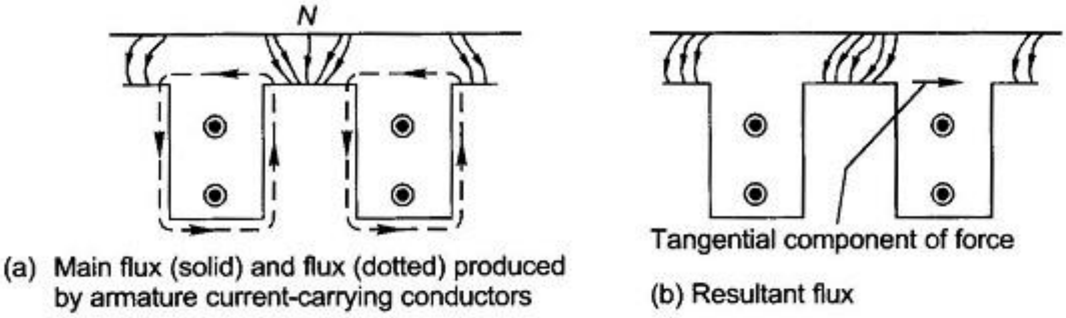
$$T = \frac{1}{2\pi}\Phi I_c ZP$$

$$= \frac{1}{2\pi}\Phi I_a Z\left(\frac{P}{A}\right) \quad \text{Nm}$$

$$= K_a \Phi I_a \quad \text{Nm}$$

Thus, it can be observed that for a given flux/pole and armature current, machine torque is uniform. Furthermore, it is unaffected by the B-form, wave's which is really changed when the armature mmf carries current.

In order to conveniently get the formula for armature torque, force applied to each conductor is used. However, in a real machine where conductors are inserted into armature slots, the method of torque creation is different. The interaction between the main flux and the flux created by current-carrying conductors inserted into armature slots results in the force. The primary flux travelling through the conductors and the force exerted on the conductor are minimal because of the significant resistance of the air-path of slots. The distortion of the flux lines travelling through the teeth, which is the principal source of force, acts on the armature's teeth as illustrated in below figure. The fact that conductors are only being pulled by a very small amount of force is fortunate. The insulation between conductors and slots would be crushed if all the effort were directed at the conductors (Figure 8.2).



(a) Main flux (solid) and flux (dotted) produced by armature current-carrying conductors

(b) Resultant flux

Figure 8.2main flux and resultant flux inn current carrying conductors

Power Balance:

Mechanical power

$$T\omega_m = K_a \Phi \omega_m I_a$$
$$= E_a I_a \qquad \text{W}$$

This is nothing but a statement of energy conservation, i.e. electrical and mechanical powers must balance in a machine.

$$T = \frac{1}{\omega_m} E_a I_a \text{ Nm}$$

Linear Magnetization:

If the magnetic circuit of the machine is assumed linear

$$\Phi = K_f I_f$$

where I_f = field current

K_f = field constant

Then $E_a = K_a K_f I_f \omega_m = K_e I_f n$ V

and $T = K_a K_f I_f I_a = K_t I_f I_a$ Nm

where $K_e = \frac{2\pi}{60} (K_a K_f)$

$K_t = K_a K_f$

The derivation of torque developed using magnetic field interaction is carried out after armature reaction ampere turns are determined.

Armature Reaction in DC Machines

In a DC machine, two kinds of magnetic fluxes are present; 'armature flux' and 'main field flux'. The effect of armature flux on the main field flux is called as armature reaction.

MNA and GNA

When the magnetic field lines are broken, EMF is generated in the armature conductors. Armature conductors travel parallel to the flux lines along an axis (or, you might say, a plane), so as long as they are on that plane, they do not cross the flux lines. The MNA (Magnetic Neutral Axis) is the axis that, when the armature conductors move parallel to the flux lines, produces no emf. Because the MNA is the axis along which current in the armature conductors is reversed, brushes are always positioned along this axis.GNA (Geometrical Neutral Axis) may be defined as the axis which is perpendicular to the stator field axis.

Armature Reaction

The effect of armature reaction is well illustrated in the Figure 8.3 below.

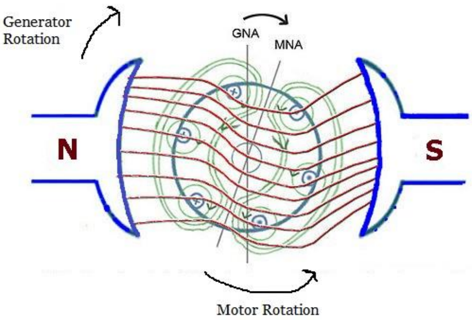


Figure 8.3Armature reaction

Take into account that only the field winding is powered and that the armature conductors are not carrying any current (as shown in the first figure of the above image). The magnetic flux lines at the field poles are symmetrical to the polar axis and uniform in this instance. The "Magnetic Neutral Axis" (M.N.A.) and the "Geometric Neutral Axis" are congruent (G.N.A.).

Armature flux lines caused by the armature current are seen in the second figure in the previous picture. Field poles lose their energy. Now, both fluxes flux resulting from the armature conductors and flux resulting from the field winding will be present simultaneously while a DC machine is operating. The primary field flux is disturbed because the armature flux superimposes over it (as shown in third figureof above image). In DC machines, this phenomenon is known as the armature response.

Armature Reaction's Negative Effects

The main flux is made weaker by armature response. A dc generators produced voltage decreases as the primary flux weakens.

Armature response shifts the location of M.N.A. by distorting the primary flow (M.N.A. is perpendicular to the flux lines of main field flux). Brushes should be set up on M.N.A. to prevent sparking at the surface of the brushes. Consequently, it is difficult to pinpoint the precise location of the MNA because to armature response.MNA will be moved in the direction of rotation for a loaded dc generator. On the other hand, MNA will be displaced away from the direction of rotation for a loaded dc motor.

Methods to Reduce Armature Reaction

For small machines (up to a few kilowatts), reducing the armature response is often not a priority. However, compensatory winding and interpoles are used in big DC machines to eliminate the negative consequences of armature response.Winding compensation: As of right now, we are aware that armature flux is what causes the response. The current flowing in the armature conductors causes armature flux to be created. The armature field will be negated if another winding is placed near to the armature winding and carries the same current as the armature current but in the opposite direction. The term "compensating winding" refers to this extra winding, which is mounted on the pole faces. Compensating winding and armature winding are linked in sequence so that current flows in the other direction.

Interpoles: The little auxiliary poles positioned in between the larger field poles are known as interpoles. The armature is linked in series with the winding on the interpoles. Each interpole is coiled such that it has the same magnetic polarity as the main pole in front of it. The flux along the quadrature axis is cancelled by interpoles.

The leading tip of the pole is the point where the armature conductors enter influence, and the trailing tip is the opposing tip in the opposite direction. For instance, if the motor turns anticlockwise in the image above, the lower tip for the North Pole would be the leading tip, and the higher tip for the South Pole would be the leading tip. The tips are switched if the motion is reversed (like with a generator). The magnetic neutral axis changes under load along the direction of rotation in a DC generator and in the opposite direction in a DC motor as a result of cross magnetization. If the brushes are left in their original placements, the generator's or motor's produced e.m.f. will decrease, causing significant sparking during commutation. This is due to the fact that only the coils on the brushes undergo commutation, and the commuting coil is affected by the alternative pole (changes its location from north to south pole or vice versa). As a result, the direction of the current quickly switches from I to -i or vice versa. This causes the coil to experience a very high reactance voltage (L di/dt), which escapes in the form of heat energy and sparking and damages the brushes and commutator section. The following techniques are used to lessen the aforementioned negative impacts and enhance the functioning of the machine:

Broom Shift

The brushes might be moved in a way that reduces the air gap flux, such as along the direction of rotation for generator action and against the direction of rotation for motor action. This will raise the speed of the motor and lower the induced voltage in the generator. Where Ia is the armature current, Z is the total number of conductors, P is the total number of poles, and is the angular shift of the carbon brushes, the demagnetizing mmf (magneto motive force) that is created is given by (in electrical Degrees).Brush shift is severely constrained, therefore the brushes must be moved to a new location if the load, the rotation's direction, or the mode of operation changes. Due to this, only extremely tiny machines may use brush shift. The brushes are likewise fixed in this location at a position that corresponds to the regular load and mode of operation. These drawbacks make this strategy less popular in general.

Pole to Pole

Almost all medium and big sized DC machines now utilise inter poles due to the brush shift's limitations. The inter polar axis has long, thin poles called inter poles. In the case of generator action, the succeeding pole is the one that will be rotated next, while in the case of motor action, the following pole is the one that will be rotated after the generator action. The inter pole's purpose is to balance the inter polar axis's armature response mmf. Inter poles are linked in series with the armature, thus as the armature's current direction changes, so does the inter pole's.

This is as a result of the armature reaction's mmf direction being in the interpolar axis. The reactance voltage (L di/dt) is totally neutralised by the commutation voltage, which is also provided for the coil that is undergoing commutation. As a result, sparking is prevented.Since inter polar windings are always maintained in series with the armature, they carry the armature current and function properly regardless of load, rotational direction, or mode of operation. To guarantee that they exclusively affect the coil that is undergoing commutation and that their impact does not extend to the other coils, inter poles are made smaller. To prevent saturation and enhance responsiveness, the base of the interpoles is made broader.

The issue with compensating winding commutation in DC machines is not the only one. When operating with significant loads, the cross magnetising armature response may result in very high flux densities at the leading pole tip and trailing pole tip of the generator and motor, respectively.Because this coil is physically near to the commutation zone (at the brushes), where the air temperature may already be high as a result of the commutation process, it may create an induced voltage high enough to trigger a flash over between the related neighbouring commutator segments.

This flash over might affect nearby commutator segments and eventually ignite a full-scale fire that spreads from brush to brush over the commutator surface. The voltage L di/dt that appears across the adjacent commutator segments of the machine may also increase to a value high enough to result in flash over between the adjacent commutator segments when the machine is exposed to rapidly changing loads. As the coil underneath it has the greatest inductance, this would begin at the pole's core. This might result in a fire similar to the one previously mentioned. This issue is more severe when the load is shifting from generating to motor activity, since the induced e.m.f. and voltage L di/dt will then support one another. The use of compensatory winding resolves the aforementioned issues.

The compensating winding is made up of parallel-to-the-shaft conductors implanted in the pole face that carry an armature current in the opposite direction as the armature conductors beneath that pole arc. The primary field has been fully compensated. Inductor in the armature circuit is also reduced, which enhances system responsiveness. No matter the load, rotational direction, or mode of operation, compensating winding performs adequately. Naturally, it aids in commutation since inter polar winding is freed of its responsibility to offset the armature mmf under the pole arc.

CHAPTER 9

Characteristics, Speed Control and Electric Braking of DC Generators

M. Sashilal Singh, Associate Professor,
Department of Electrical, Jaipur National University, Jaipur, India
Email Id- msashilal@jnujaipur.ac.in

Characteristics of DC Generators

The three qualities listed below are often taken into account while evaluating a DC generator:

1. Open Circuit Characteristic (O.C.C.)
2. Internal or Total Characteristic,
3. External Characteristic.

The following explains some features of DC generators.

O.C.C. (E0/If) Open Circuit Characteristic

Magnetic or no-load saturation characteristics are other names for open circuit characteristic. This characteristic displays the relationship between the field current (If) at a certain fixed speed and the produced emf (E0) with no load. The O.C.C. curve is essentially the same for all types of generators since it is just the magnetization curve. By running the generator with no load and maintaining a steady speed, the information for the O.C.C. curve may be collected. The terminal voltage is measured while the field current is steadily raised. The connection set up required to produce the O.C.C. curve is seen in the image below. The field winding is detached from the machine and linked across an external supply for shunt or series excited generators (Figure 9.1).

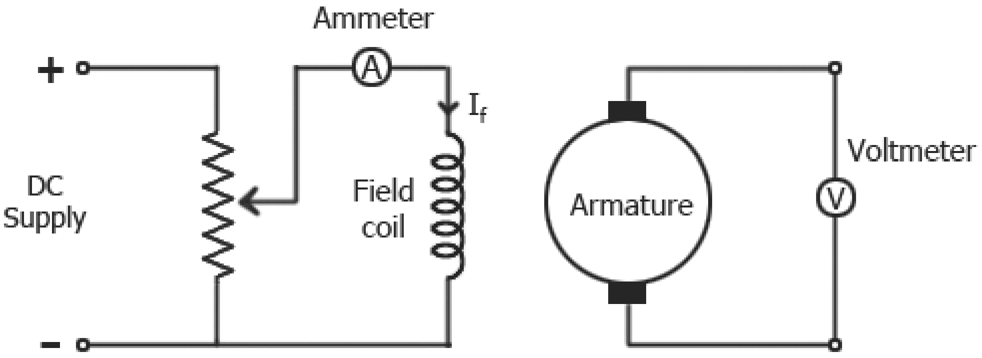


Figure 9.1 DC generators

We now know that Eg = k thanks to the dc generator's emf equation. Consequently, the produced emf need to directly relate to field flux (and hence, also directly proportional to the field current). Nevertheless, even when the field current is zero, some emf is still produced (represented by OA in the figure below). The fact that the field poles still contain some residual magnetism is what causes the first induced emf. The remaining magnetism causes the armature to experience a tiny initial emf. This originally generated emf helps the residual flux that already exists, increasing the total field flux. The induced emf inevitably rises as a result. O.C.C. travels in a straight path as a result. The poles, however, get saturated as the flux density rises, and the almost remains constant. When a result, even as we raise If more, continues to be constant, which also causes Eg to stay constant. The O.C.C. curve therefore resembles the B-H characteristic (Figure 9.2).

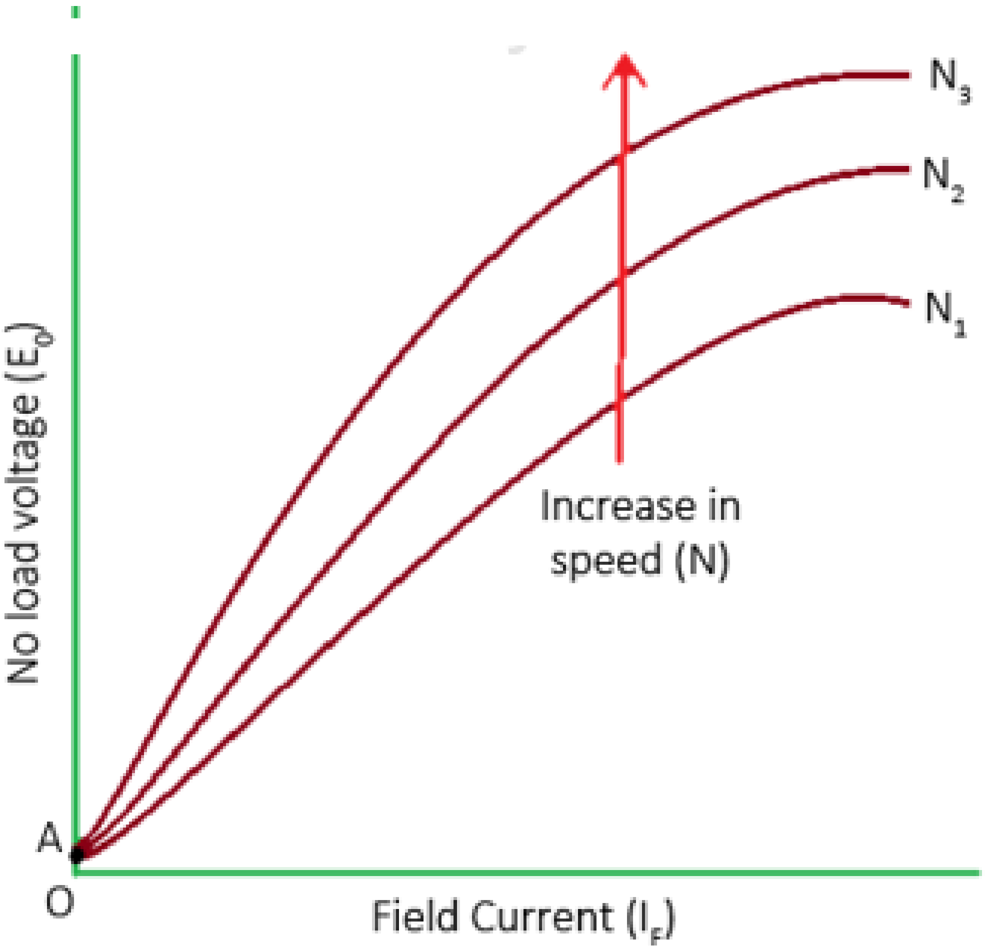


Figure 9.2 Open Circuit Characteristic

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

(E/Ia) Internal or Overall Characteristic

The relationship between the armature current and the on-load produced emf (Eg) is shown by an internal characteristic curve (Ia). Due to the armature response, the on-load produced emf Eg is always smaller than E0. Eg may be calculated by deducting the decrease in voltage caused by the armature reaction's demagnetizing impact from no-load voltage E0. Internal characteristic curve is thus located below O.C.C.

External Aspect (V/IL)

The relationship between the load current and terminal voltage (V) is shown via an external characteristic curve (IL). Due to voltage loss in the armature circuit, terminal voltage V is less than the produced emf Eg. External characteristic curve is hence below internal characteristic curve. Determining whether a generator is appropriate for a specific function depends heavily on its external qualities. The term "performance characteristic" or "load characteristic" are other names for this sort of feature.

For each kind of generator, the following characteristic curves, both internal and exterior, are shown:

Characteristics of Separately Excited DC Generator (Figure 9.3)

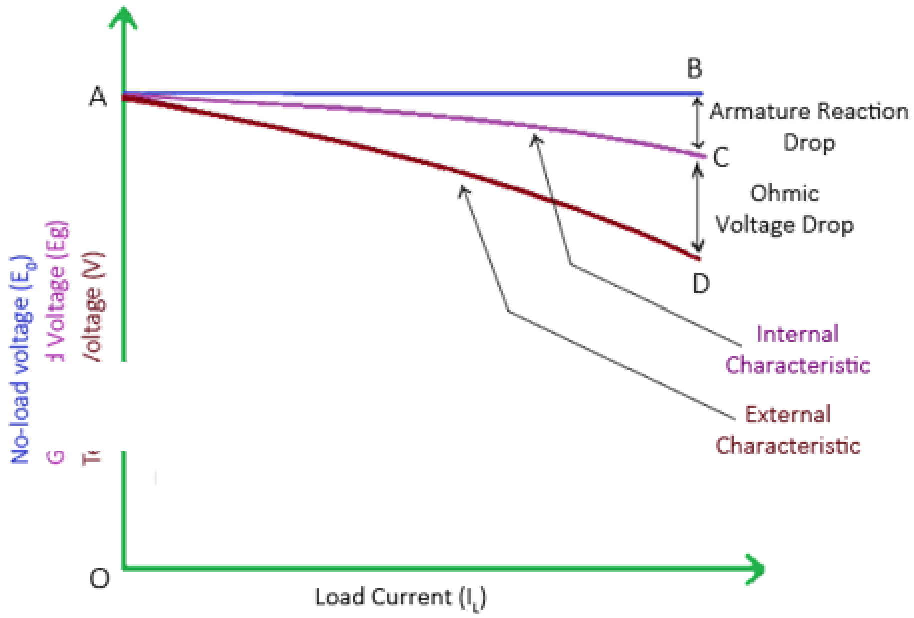


Figure 9.3 Characteristic of separately excited

The voltage will stay constant for whatever load current if there is no armature response or voltage drop. The no-load voltage vs. load current IL is therefore represented by the straight line AB in the previous picture. The on-load produced emf is lower than the no-load voltage because of the demagnetizing impact of the armature response. The curve AC shows the internal characteristic of the on-load produced emf Eg vs. load current IL (because Ia = IL for a separately stimulated dc generator). Additionally, the brushes and armature's ohmic loss cause the terminal voltage to be lower. The terminal voltage versus. Load current, or external characteristic, is shown by the curve AD.

Features of A DC Shunt Generator

A DC shunt generator is allowed to build up its voltage before any external load is applied in order to evaluate the internal and external load characteristics. A prime mover drives a shunt generator at its rated speed in order to increase voltage. Because of the remaining magnetism in the field poles, initial voltage is induced. The O.C.C. curve explains how the generator increases voltage. Once the generator has reached the desired voltage, a resistive load is progressively added, and measurements are obtained at regular intervals. The following figure illustrates the connection configuration (Figure 9.4).

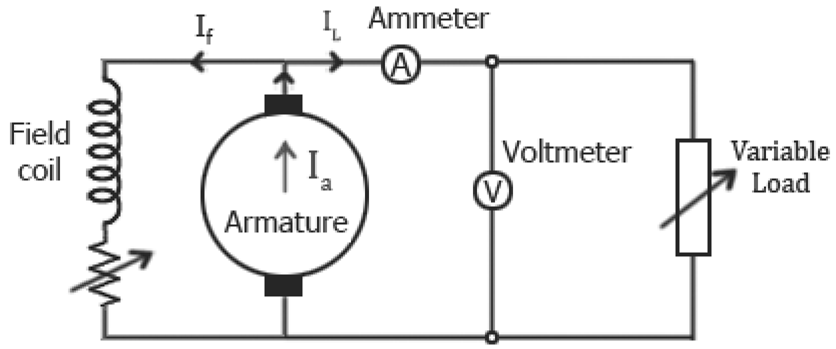


Figure 9.4DC Shunt Generator

Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a = I_L + I_f$. Hence, the internal characteristic can be easily transmitted to Eg vs. I_L by subtracting the correct value of I_f from I_a(Figure 9.5).

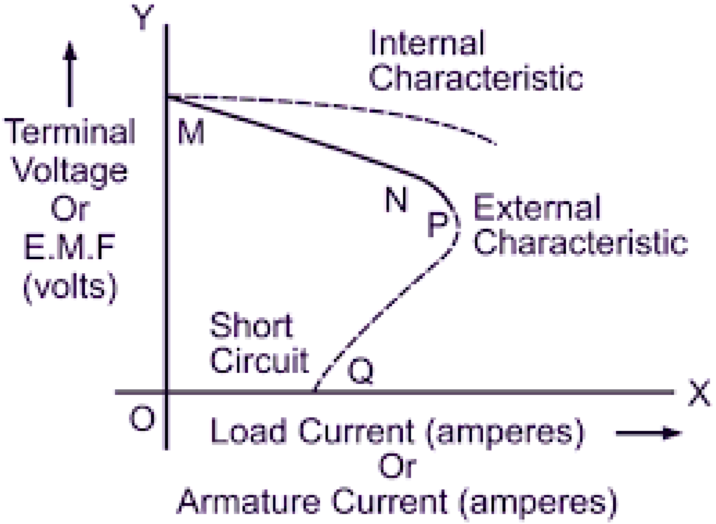


Figure 9.5 DC Shunt Generator characteristics

When the load resistance is reduced under typical operating conditions, the load current rises. However, terminal voltage likewise decreases as we continue to reduce the load resistance. Thus, the load resistance can be reduced only so much until the terminal voltage sharply drops as a result of excessive armature response at very high armature current and increasing I2R losses. Therefore, beyond this point, every additional reduction in load resistance leads to a reduction in load current. As a result, the exterior characteristic curve reverses, as seen by the dotted line in the previous image.

Characteristics of DC Series Generator (Figure 9.6)

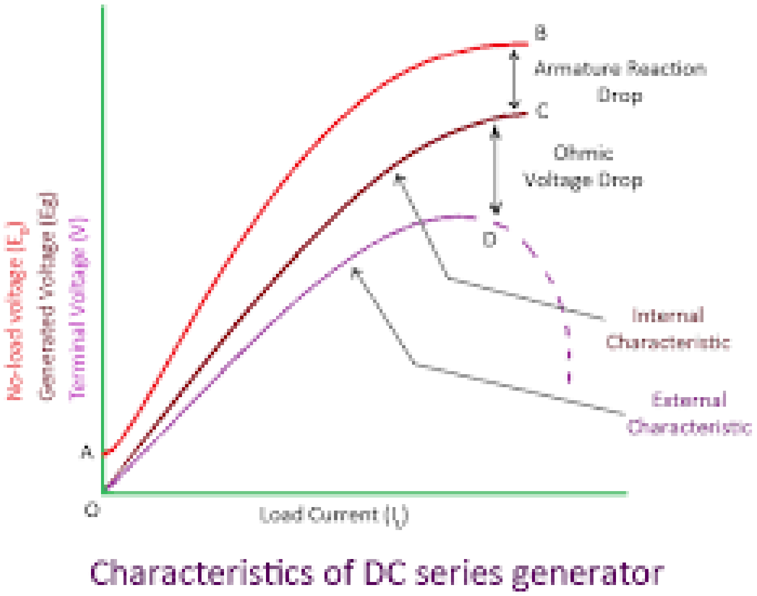


Figure 9.6DC Series Generator characteristics

In the previous illustration, curve AB is the same as the open circuit characteristic (O.C.C.) curve. This is so that the field winding in DC series generators may be linked in series with the armature and load. So, in this case, load current is comparable to field current (IL=If). The internal and exterior characteristics are represented by the curves OC and OD, respectively. The terminal voltage rises with the load current in a DC series generator. This is due to the fact that field current likewise rises when load current does. Beyond a certain point, however, the terminal voltage begins to decrease as the load increases. This is because the armature reaction's severe demagnetizing effects.

Characteristics of DC Compound Generator (Figure 9.7)

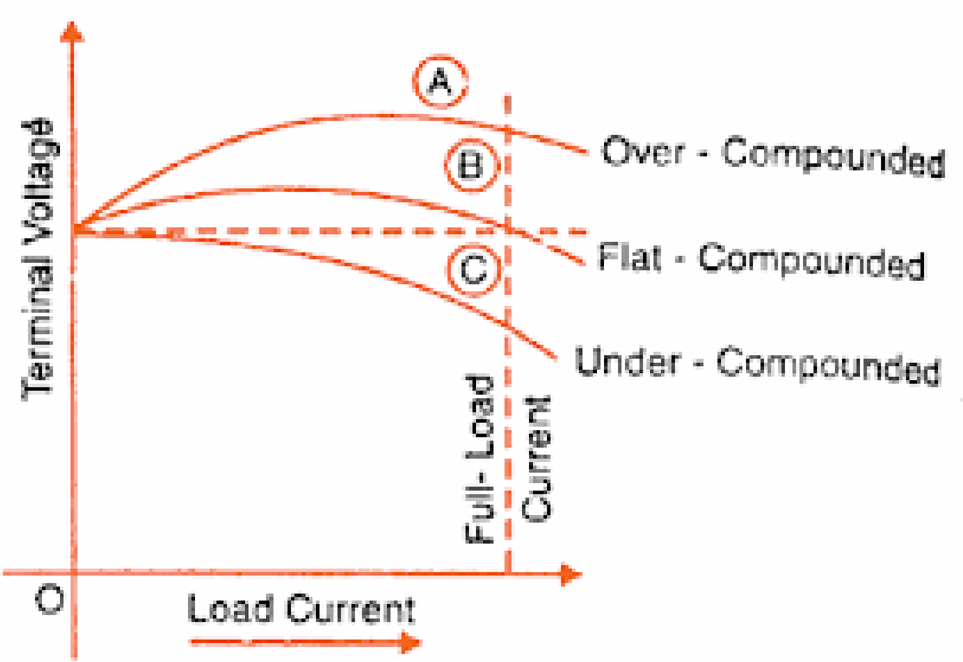


Figure 9.7DC Compound Generator characteristics

The exterior properties of DC compound generators are shown in the previous illustration. The generator is said to be over compounded if the series winding amp-turns are set up such that an increase in load current results in a rise in terminal voltage. The curve AB in the previous illustration depicts the external characteristic for an overcomplicated generator.

The generator is said to be flat compounded if the series winding amp-turns are tuned such that the terminal voltage stays constant even as the load current increases. The curve AC illustrates the exterior characteristic of a flat compound generator.

The generator is referred to as being under compounded if the series winding contains less turns than would be necessary to be flat compounded. The curve AD illustrates the exterior properties of an undercompound generator.

Controlling the speed of DC motors

The relationship given below gives the speed of a D.C. motor

$$N = \frac{V - I_a R_a}{k\varphi}$$

The aforementioned equation demonstrates how the speed is influenced by the supply voltage (V), the armature circuit resistance (Ra), and the field flux (), which is created by the field current. In reality, speed control is accomplished by varying these three elements. There are hence three common ways to regulate the speed of D.C. motors.

An armature circuit with variable resistance Rheostat control or armature resistance control is the name of this technique.

Changes in field flux

Field flux control is the term for this technique.

The applied voltage may change.

This process is further known as armature voltage control.

Armature resistance control (Rheostat Control), as shown in Figure 9.8:

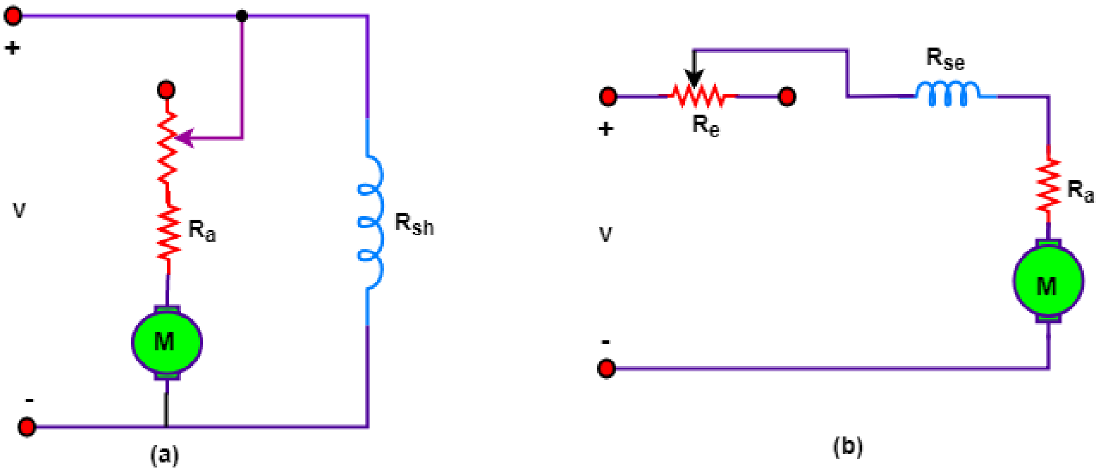


Figure 9.8 (a) Armature resistance control for speed control of a DC Shunt motor, (b) Armature resistance control for regulating the speed of a D.C. series motor.

This technique involves adding a variable series resistor Re to the armature circuit. The connecting technique for a shunt motor is shown in figure (a) above. In this case, the field is directly connected across the supply and therefore the flux Φ is not affected by variation of Re.

Re's voltage drops, which lowers the voltage that is supplied to the armature and lowers speed.

These are the disadvantages of this approach:

1. A lot of energy is lost in the external resistance Re.
2. This approach cannot be used to boost speed since control is restricted to giving speed below normal.
3. The speed decrease is not constant for a given amount of Re; instead, it fluctuates with the motor load.

Variation of field flux Φ (Field flux control):

Since the field current produces the flux, and if we control the field current then the speed can be controlled.

In the shunt motor, speed can be controlled by connecting a variable resistor Rc in series with the shunt field winding. In the diagram below resistor, Rc is called the shunt field regulator (Figure 9.9).

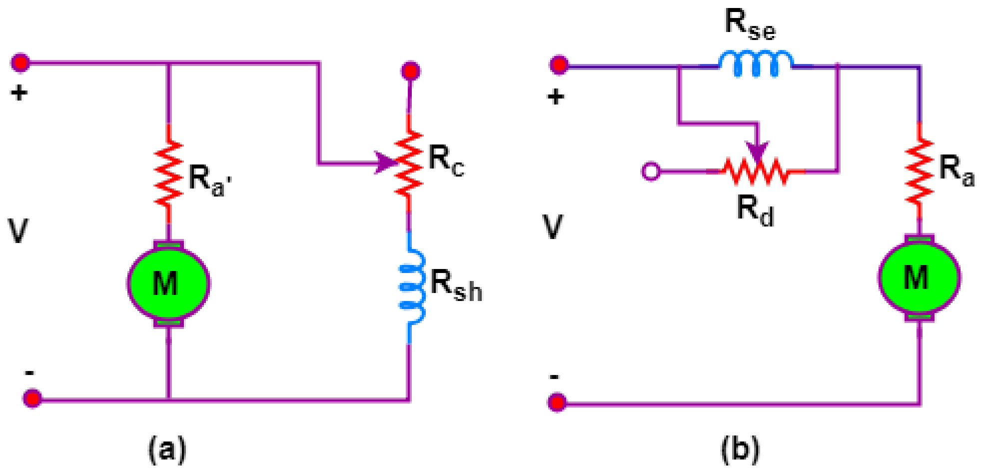


Figure 9.9 (a) Speed control of a D.C. shunt motor by variation of field flux. (b) The diverter in parallel with the series of D.C. Motor gives the shunt field current

$$I_{sh} = \frac{V}{R_{sh} + R_c}$$

Any of the one methods can vary the field current of the series motor:

A variable resistance R_d is connected in parallel with the series field winding. The resistor connected in parallel is called the diverter. A portion of the main current is diverted through R_d.

The second method uses a tapped field control.

Here the ampere-turns are varied by varying the number of field turns. This arrangement is used in electric traction (Figure 9.10).

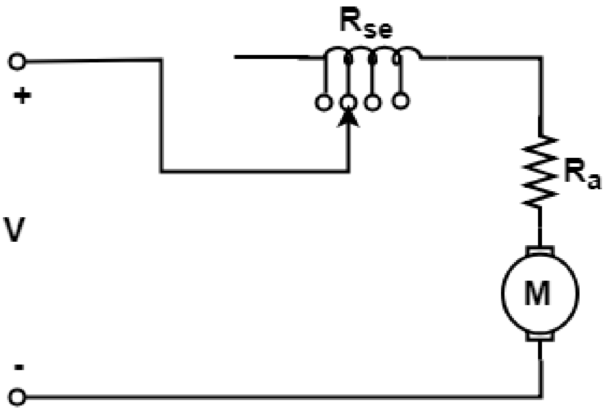


Figure 9.10 tapped field control

Tapped series field on D.C. motor

The advantages of field control are as follows:

This is an easy and convenient method.

The power loss in the shunt field is small because shunt field current I_{sh} is very small.

Armature Voltage control:

By altering the voltage delivered to the armature of the D.C. motors, we can adjust their speed. This armature voltage control theory underlies the Ward-Leonard method of speed control. In this system, G is an independently excited dc generator, and M is the primary dc motor whose speed has to be regulated. A three-phase driving motor, which might be either an asynchronous or induction motor, drives the generator G. The motor-generator (M-G) set is made up of an ac driving motor and a dc generator (Figure 9.11).

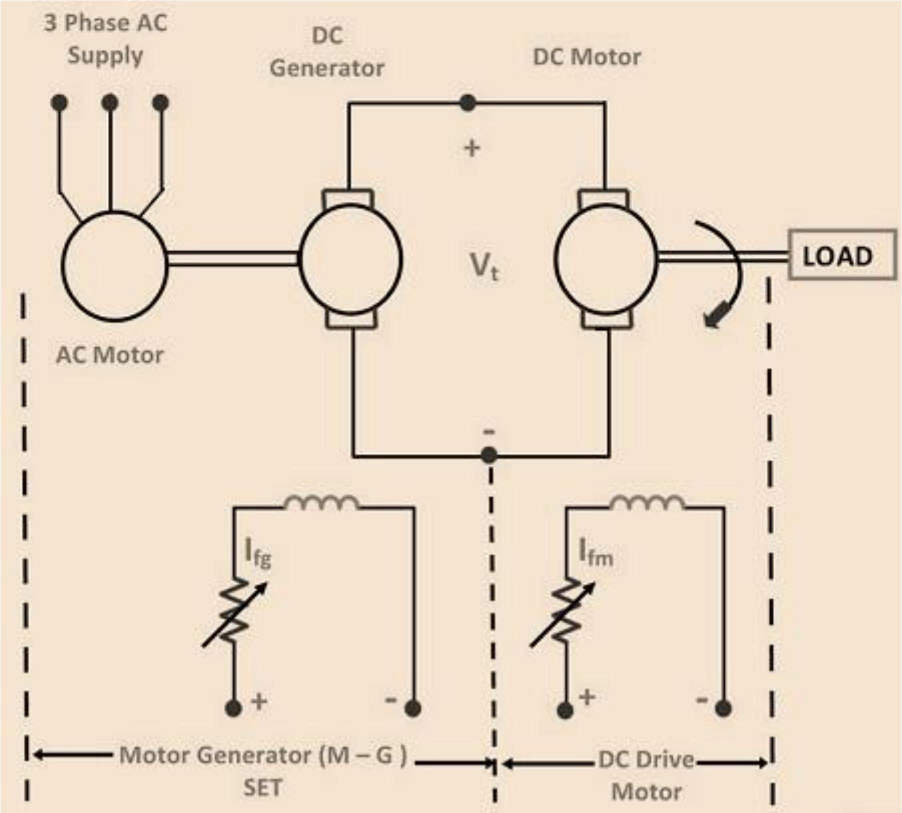


Figure 9.11 Armature Voltage control

Electric Braking Of DC Motors

Either mechanical braking or electrical braking may be used to swiftly stop a running motor. Mechanical break shoes are used to provide mechanical braking. Therefore, the surface and physical state of the brakes affect how smoothly mechanical braking occurs. Electric braking may be used to stop a motor smoothly.

Power braking

There are three different forms of electric braking that may be applied to a DC motor:

(1) Rheostatic or dynamic braking

(2) Plugging or reverse current braking

(3) Regenerative braking

In the case of DC shunt motors, the armature is separated from the supply and linked across by a rheostat (variable resistor). The supply is still linked to the field winding. Naturally, the armature is now propelled by inertia, and the machine begins to function as a generator. The linked rheostat will now receive current from the machine, and heat will dissipate at the rate of I_2R. By changing the resistance linked across the armature, braking effect may be adjusted.When using a DC series motor, the supply is cut off, the field connections are switched around, and a rheostat is wired in series.

To ensure that the current through the field winding flows in the same direction as previously, the field connections are switched around.

Plugging or Reverse Current Braking: In this technique, the connections to the armature are switched around, causing the motor to prefer to rotate anticlockwise. The armature terminals being reversed causes the applied voltage V and back emf Eb to start operating in the same direction, exceeding the total armature current.

A variable resistor is attached across the armature to restrict this armature current. This applies to both the series and shunt wound approaches.When compared to rheostatic braking, plugging provides more braking torque. Typically, this technique is used to operate elevators, machinery, printing presses, etc.

Regenerative braking is employed when the load on the motor has a high moment of inertia (e.g in electric trains). The armature current Ia and armature torque are visibly reversed when the supplied voltage to the motor is decreased to less than the back emf Eb. So, speed decreases.

Regeneration occurs when power is returned to the line because the produced emf is larger than the applied voltage (the machine is working as a DC generator). Speed continues to decrease, back emf Eb likewise decreases until it is lower than applied voltage, and the armature current's direction once again reverses to Eb.

Output Equations and Main Dimensions of DC Machine

Output equation relates the output and main dimensions of the machine. Actually it relates the power developed in the armature and main dimensions.

E : EMF induced or back EMF Ia : armature current

φ : Average value of flux / pole

Z : Total number of armature conductors N : Speed in rpm

P : Number of poles

A : number of armature paths or circuits D : Diameter of the armature

L : Length of the armature core

Power developed in the armature in kW = E Ia x 10-3

The term P φ represents the total flux and is called the magnetic loading. Magnetic loading/unit area of the armature surface is called the specific magnetic loading or average value of the flux density in the air gap Bav. That is,

Bav = Pφ /π DL Wb/m2 or tesla denoted by T

Therefore Pφ = Bav π DL

The term (Ia Z/A) represents the total ampere-conductors on the armature and is called the electric loading. Electric loading/unit length of armature periphery is called the specific electric loading q. That is,

$$q = \frac{I_a Z}{A \pi D} \text{ ampere - conductors / m}$$

Therefore $I_a Z/A = q \pi D$ .... (3)

Substitution of equations 2 and 3 in 1, leads to

$$\text{kW} = B_{av} \pi DL \times q \pi D \times \frac{N \times 10^{-3}}{60}$$

$$= 1.64 \times 10^{-4} B_{av} q D^2 L N$$

$$= C_0 D^2 L N$$

where C_0 is called the output coefficeint of the DC machine and is equal to $1.64 \text{ x } 10^{-4} B_{av} q$.

$$\text{Therefore } D^2L = \frac{\text{kW}}{1.64 \times 10^{-4} B_{av} q N} \text{ m}^3$$

Where C0 is called the output coefficeint of the DC machine and is equal to 1.64 x 10-4 Bq.

Therefore D2 L = (Kw/1.64 × 10-4 B q N) m3

The above equation is called the output equation. The D2L product represents the size of the machine or volume of iron used. In order that the maximum output is obtained /kg of iron used, D2L product must be as less as possible. For this, the values of q and Bav must be high.

Effect of higher value of q

Since armature current Ia and number of parallel paths A are constants and armature diameter D must be as less as possible or D must be a fixed minimum value, the number of armature conductors increases as q = Ia Z / A π D increases.

As q increases, number of conductors increases, resistance increases, I2R loss increases and therefore the temperature of the machine increases. Temperature is a limiting factor of any equipment or machine.

As q increases, number of conductors increases, conductors/slot increases, quantity of insulation in the slot increases, heat dissipation reduces, temperature increases, losses increases and efficiency of the machine reduces.

As q increases, number of conductors increases, armature ampere-turns per pole ATa / pole = (Ia Z / 2 A P) increases, flux produced by the armature increases, and therefore the effect of armature reaction increases. In order to overcome the effect of armature reaction, field MMF has to be increased. This calls for additional copper and increases the cost and size of the machine.

As q increases, number of conductors and turns increases, reactance voltage proportional to (turns)*2 increases. This leads to sparking commutation.

Effect of higher value of Bav

As Bav increases, core loss increases, efficiency reduces.

As Bav increases, degree of saturation increases, mmf required for the magnetic circuit increases. This calls for additional copper and increases the cost of the machine.

It is clear that there is no advantage gained by selecting higher values of q and Bav. If the values selected are less, then D2L will be large or the size of the machine will unnecessarily be high. Hence optimum value of q and Bav must be selected.

In general q lies between 15000 and 50000 ampere-conductors/m.

Lesser values are used in low capacity, low speed and high voltage machines. In general Bav lies between 0.45 and 0.75 T.

Armature Winding Of A DC Machine

A DC machine's armature is essentially wound using either the lap winding technique or the wave winding method. The conductor's end connections and commutator connections are the only distinction between these two. It is crucial to understand the following terminology in order to understand how armature winding is done:

Pole pitch is determined by the quantity of armature slots in each pole. For instance, the pole pitch is 36/4=9 if there are 36 conductors and 4 poles.

Coil pitch (Ys), also known as coil span, is the measurement of the distance between the two sides of a coil in terms of armature slots.

Front pitch (Yf): The distance between the first conductor of one coil and the second conductor of the subsequent coil, measured in terms of armature conductors. Alternately, it might be the separation between two coil sides that are attached to the same commutator section.

Back pitch (Yb): The back pitch of a coil is the amount by which it moves forward on the back of the armature. It is calculated using armature conductors.

Resultant pitch (Yr): The resultant pitch of the coi is the distance, in terms of armature conductor, between the commencement of one coil and the beginning of the following coil (Figure 9.12).

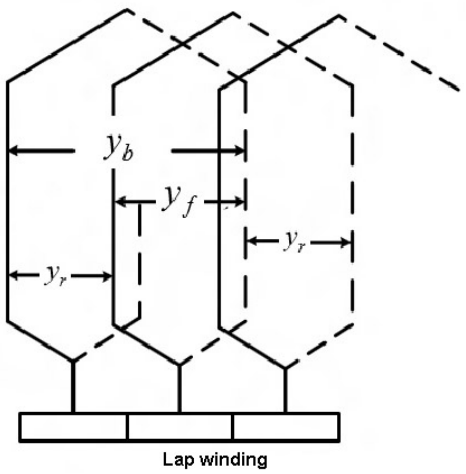


Figure 9.12 Lap winding

There are two ways to wind armatures: single layer or double layer. There are more parallel pathways because of the multiplexing, which might be simplex, duplex, or multiplex.

Both lap and wave winding

The next coils overlap each other during lap winding. The two ends of a coil are attached to neighbouring commutator segments in a simplex lap winding. Both progressive and retrogressive windings are possible. The coil is coiled in a progressive winding, which advances in that direction. Retrogressive is the alternative. The progressive simplex lap winding is seen in the Figure 9.13.

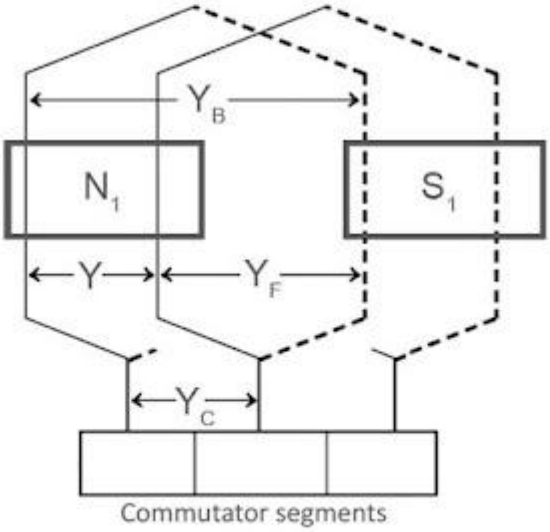


Figure 9.13 Commutator segments

In wave winding, a conductor under one pole is linked at the rear to a conductor under the next pole, which is of the opposite polarity, and occupies a nearly identical location. In other words, a series connection is made between all coils that convey emf in the same direction. The figure below illustrates a section of a simplex wave winding.

CHAPTER 10

Classification and Principle of Induction Machines

Harsh Shrivastava, Assistant Professor,
Department of Electrical, Jaipur National University, Jaipur, India
Email Id-ershrivastava@jnujaipur.ac.in

An electromechanical device known as an electrical motor transforms electrical energy into mechanical energy. The most popular motor for three-phase AC (Alternating Current) operation is an induction motor since it doesn't need an extra starting mechanism. Self-starting induction motors are the name given to these kinds of motors.

It's crucial to comprehend the design of a three-phase induction motor in order to fully comprehend its operating principle. The two main components of a three-phase induction motor are:

A rotor and stator

Three Phase Induction Motor Stator

The three phase induction motor's stator is made up of several slots that are used to build a three phase winding circuit that is connected to a three phase AC supply. When we turn on the three-phase AC supply source, we position the three-phase winding in the slots such that they create a single spinning magnetic field.

Rotor of three Phase Induction Motor

The three phase induction motor's rotor is made out of a cylindrical laminated core with parallel conductor-carrying slots. Heavy copper or aluminium bars that are short-circuited by the end rings and placed into each slot serve as the conductors. Due to the arrangement's ability to decrease magnetic humming noise and prevent the motor from stalling, the slots are not precisely formed parallel to the axis of the shaft but rather are slotted slightly misaligned.

Three Phase Induction Motor Operation

Making a rotating magnetic field

The motor's stator is made up of overlapping windings that are offset by an electrical angle of 120 degrees. The main winding or stator is connected to a three-phase AC supply, creating a rotating magnetic field that spins at synchronous speed.

Rotating

In accordance with Faraday's law, any circuit's induced emf is caused by the circuit's magnetic flux linkage's rate of change. As the rotor winding in an induction motor are either closed through an external resistance or directly shorted by end ring, and cut the stator rotating magnetic field, an emf is induced in the rotor copper bar and due to this emf a current flows through the rotor conductor.

Here, current generation is caused by the relative velocity between the spinning flux and the static rotor conductor; thus, in accordance with Lenz's law, the rotor will rotate in the same direction to lessen the relative velocity.As a result, it is clear from the three phase induction motor's operating principle that the rotor speed must not exceed the synchronous speed generated by the stator. Since there would be no relative speed if the speeds were equal, there would also be no current flowing and no induced emf in the rotor, which would prevent the generation of torque. As a result, the rotor is unable to attain synchronous speed. The slip is the differential between the rotor and stator speeds (synchronous speed). The benefit of an induction motor's rotating magnetic field is that the rotor does not need electrical connections.

Due to the lack of potential spark-generating commutators and brushes, the three phase induction motor provides the following advantages:

I. Self-starting
II. Less armature response and brush sparking
III. Solid in its structure.
IV. Economical.
V. Less work to keep up.

Rotating Magnetic Field in Three-Phase Induction Motor rotating magnetic field. To do so, let's first consider a single stator of an electric motor with three-phase windings spatially dispersed in the stator core at an angle of 120 degrees from one another.Although the vector sum of three currents in a balanced three-phase system is zero at any instant, but the resultant of the magnetic fields produced by the currents is not zero rather it will have a constant non-zero value rotating in space in respect to time.

The equations shown below may be used to describe the magnetic flux that is created by the current in each phase. As the flux is cophasial, this is a depiction of current that is analogous to a three-phase system.

With the current.

$$\phi_R = \phi_m \sin(\omega t)$$
$$\phi_Y = \phi_m \sin(\omega t - 120^o)$$
$$\phi_B = \phi_m \sin(\omega t - 240^o)$$

Where, φ_R, φ_Y and φ_B are the instantaneous flux of corresponding Red, Yellow and Blue phase winding, φ_m amplitude of the flux wave. The flux wave in the space can be represented as shown below.

Now, on the above graphical representation of flux waves, we will first consider the point 0. Here, the value of φ_R is

$$\phi_R = \phi_m \sin(0) = 0$$

The value of φ_Y is

$$\phi_Y = \phi_m \sin(0 - 120^o) = \phi_m \sin(-120^o) = -\frac{\sqrt{3}}{2}\phi_m$$

The value of φ_B is

$$\phi_B = \phi_m \sin(0 - 240^o) = \phi_m \sin(-240^o) = \frac{\sqrt{3}}{2}\phi_m$$

The resultant of these fluxes at that instant (φ_r) is $1.5\varphi_m$ which is shown in the figure below. Now, on the above graphical representation of flux waves, we will consider the point 1, where $\omega t = \pi / 6$ or 30^o.

Here, the value of φ_R is

$$\phi_R = \phi_m \sin(30^0) = \frac{1}{2}\phi_m$$

The value of φ_Y is

$$\phi_Y = \phi_m \sin(30^o - 120^o) = \phi_m \sin(-90^o) = -\phi_m$$

The value of φ_B is

$$\phi_B = \phi_m \sin(30^o - 240^o) = \phi_m \sin(-210^o) = \frac{1}{2}\phi_m$$

The resultant of these fluxes at that instant (φ_r) is $1.5\varphi_m$ which is shown in the figure below. Here it is clear thet the resultant flux vector is rotated 30^o further clockwise without changing its value.

Now, on the graphical representation of flux waves, we will consider the point 2, where $\omega t = \pi / 3$ or 60^o.

Here, the value of φ_R is

$$\phi_R = \phi_m \sin(60^o) = \frac{\sqrt{3}}{2}\phi_m$$

The value of φ_Y is

$$\phi_Y = \phi_m \sin(60^o - 120^0) = \phi_m \sin(-60^o) = -\frac{\sqrt{3}}{2}\phi_m$$

The value of φ_B is

$$\phi_B = \phi_m \sin(60^o - 240^0) = \phi_m \sin(-180) = 0$$

The resultant of these fluxes at that instant (φ_r) is $1.5\varphi_m$ which is shown in the figure below. Here it is clear thet the resultant flux vector is rotated 30° further clockwise without changing its value.Now, on the graphical representation of flux waves, we will consider the point 3, where $\omega t = \pi / 2$ or 90^o.

Here, the value of φ_R is

$$\phi_R = \phi_m \sin(90^o) = \phi_m$$

The value of φ_Y is

$$\phi_Y = \phi_m \sin(90^o - 120^o) = \phi_m \sin(-30^o) = -\frac{1}{2}\phi_m$$

The value of φ_B is

$$\phi_B = \phi_m \sin(90^o - 240^o) = \phi_m \sin(-150^o) = -\frac{1}{2}\phi_m$$

The resultant of these fluxes at that instant (φ_r) is $1.5\varphi_m$ which is shown in the figure below. Here it is clear that the resultant flux vector is rotated 30^o further clockwise without changing its value.In this way we can prove that the due to balanced supply applied to the three pfase stator winding a rotating or revolving magnetic fiels is established in thew space.

EMF Equation of Alternator

Lets,

P = No. of poles

Z = No. of conductors or Coil sides in series/phase i.e. Z = 2T…Where T is the number of coils or turns per phase (Note that one turn or coil has two ends or sides)

f = frequency of induced EMF in Hz

Φ = Flux per pole (Weber)

N = rotor speed (RPM)

K_d= Distribution factor = $\dfrac{\text{Sin } m\,\beta / 2}{m \text{ Sin } \beta / 2}$

Where Distribution factor = $K_d = \frac{e.m.f\ with\ distributed\ \ winding}{e.m.f\ with\ concentrated\ \ winding}$

K_c or K_P = Cos α/2

If induced EMF is assumed sinusoidal then,

K_f = Form factor = 1.11

In one revolution of the rotor i.e. in 60/N seconds, each conductor is cut by a flux of ΦP Webers.

$d\Phi = \Phi P$ and also $d\Phi$ = 60/N seconds

Then induced E.M.F per conductor (average) =

$$= \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60} \quad \ldots\ldots (i)$$

But we know that:

f = PN / 120 or N= 120f / P

Putting the value of N in Equation *(i)*, we get,

Average value of EMF per conductor

$$= \frac{\Phi P}{60} \times \frac{120 f}{P} = 2 f \Phi \text{ volt}$$

∴ (N= 120f/P)

If there are Z conductors in series per phase,

Then synchronous generator average E.M.F per phase = 2 f Φ Z Volts = 4 f ΦT *Volts* ….. (Z = 2T)

Also we know that;

Form Factor = RMS Value / Average Value

= RMS value = Form Factor x Average Value,

$V_{AV} = 1.11 \times 4 f \Phi T = 4.44 f \Phi T$ Volts.

(Note that is exactly the same equation as the EMF equation of the transformer)

And the actual available voltage of generator per phase

$V_{PH} = 4.44\ K_C\ K_D\ f\ \Phi T_{PH}$

$V = 4.44\ K_f K_C\ K_D\ f\ \Phi T$ Volts.

Where:

V = Actual generated Voltage per phase

K_C = Coil Span Factor or Pitch Factor

K_D = Distribution Factor

K_f = Form Factor

f = frequency

T = Number of coils or number of turns per phase

Note: If alternator or AC generator is star connected as usually the case, then the Line Voltage is √3 times the phase voltage as derived from the above equation.

Alternatively, let show the EMF equation of AC generator as follow.

EMF Equation of Synchronous Generator

This equation is used to calculate the induced EMF in an alternator. Let's derive the EMF equation for the alternator below.

Assume

P = No. Of poles

φ = flux per pole (Webers)

N = rotor speed (RPM)

As we know flux per pole is 'φ'. Therefore each conductor is cut by a flux of 'φP'. and The time taken by a pole to complete on revolution is '60/N' seconds.

So the average EMF per conductor becomes

Average EMF per conductor = φP/(60/N) = φNP/60

Where alternator speed, N is given by

f = PN/120 or N = 120f/P

Where 'f' is the frequency of induced EMF. Therefore the average EMF per conductor becomes

Average EMF per conductor = φNP/60 = (φP/60) x (120f/P)

Average EMF per conductor = 2fφ volts

Let Z = No. of conductors per phase, then the emf pretty phase becomes

EMF per phase = 2fφ x Z = 2fφZ

Let T = No. of turns (two conductors per turn), therefore Z = 2T and the equation becomes

EMF per phase = 2fφZ = 2fφ(2T) = 4fφT

Assume the induced EMF is sinusoidal, then its form factor

Form factor, kf = 1.11

Form factor = RMS value/ Average value

RMS value = form factor x Average value

RMS value per phase = 1.11 x 4fφT

V_{rms} per phase = $4.44\, f\varphi T$ volts

Now lets introduce ‘coil span factor k_c‘ and ‘distribution factor k_d‘ to get the actual induced EMF per phase.

Vrms per phase = $V_{ph} = 4.44\, k_c k_d f\varphi T$ volts

Or

$V_{ph} = 2.22\, k_c k_d f\varphi Z$ volts

This is the EMF equation of the alternator. Where

V_{ph} = Actual induced EMF per phase

K_c = Coil span factor

K_d = Distribution factor

f = Frequency

φ = Flux per pole (Weber)

Z = No. of conductors

T = No. of turns (Z=2T)

For star-connected alternator, the line voltage V_L is √3 times the phase voltage

$V_L = \sqrt{3}\, V_{ph}$

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Condition for Maximum Starting Torque

If supply voltage V is kept constant, then flux ϕ and E_2 both remains constant. Hence,

$$Tst = k_2 \frac{R_2}{R_2^2 + X_2^2}.$$

Hence, it can be proved that maximum starting torque is obtained when rotor resistance is equal to standstill rotor reactance. i.e. $R_2^2 + X_2^2 = 2R_2^2$.

Torque under Running Condition

$T \propto \phi\, I_r \cos\phi_2.$

Where, E_r = rotor emf per phase under running condition = sE_2. (s=slip)

I_r = rotor current per phase under running condition

Reactance per phase under running condition will be = sX_2

Therefore,

$$I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{(R_2^2 + (sX_2)^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

$$T = \frac{k\,\phi\,sE_2\,R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

As, $\phi \propto E_2$.

$$T = \frac{k_1\,sE_2^2\,R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi N_S}\,\frac{sE_2^2R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Maximum Torque under Running Condition

Torque under running condition is maximum at the value of slip (s) which makes rotor reactance per phase equal to rotor resistance per phase.

Equivalent Circuit of an Induction Motor

The Equivalent Circuit of an Induction motor enables the performance characteristics which are evaluated for steady-state conditions. An induction motor is based on the principle of induction of voltages and currents. The voltage and current are induced in the rotor circuit from the stator circuit for the operation. The equivalent circuit of an induction motor is similar to that of the transformer.

Stator Circuit Model

The stator circuit model of an induction motor consists of a stator phase winding resistance R_1, stator phase winding leakage reactance X_1 as shown in the circuit diagram below (Figurer 10.1):

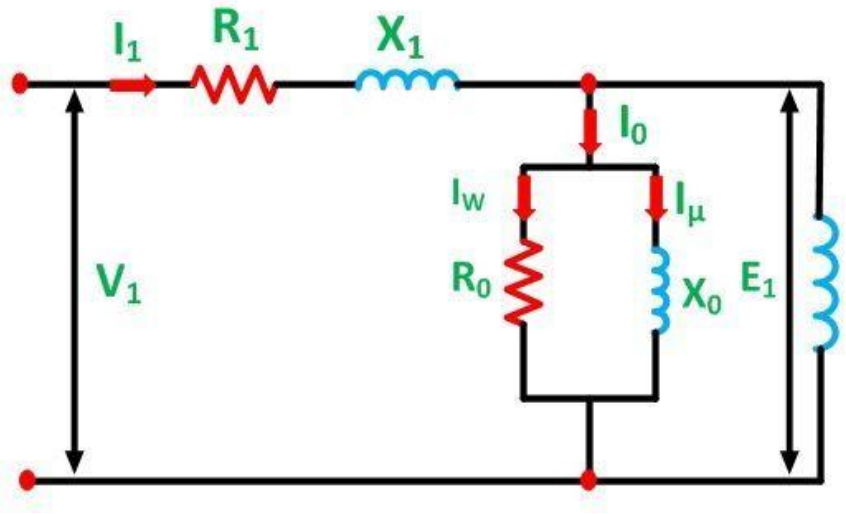


Figure 10.1 Stator Circuit Model

The no-load current I_0 is simulated by a pure inductive reactor X_0 taking the magnetizing component I_μ and a non-inductive resistor R_0 carrying the core loss current I_ω. Thus,

$$I_0 = I_\mu + I_\omega \ldots\ldots\ldots (1)$$

The total magnetizing current I_0 is considerably larger in the case of the induction motor as compared to that of a transformer. This is because of the higher reluctance caused by the air gap of the induction motor.

As we know that, in a transformer, the no-load current varies from 2 to 5% of the rated current, whereas in an induction motor the no-load current is about 25 to 40% of the rated current depending upon the size of the motor. The value of the magnetizing reactance X_0 is also very small in an induction motor.

Rotor Circuit Model

When a three phase supply is applied to the stator windings, a voltage is induced in the rotor windings of the machine. The greater will be the relative motion of the rotor and the stator magnetic fields, the greater will be the resulting rotor voltage. The largest relative motion occurs at the standstill condition.

This condition is also known as the locked rotor or blocked rotor condition. If the induced rotor voltage at this condition is E_{20} then the induced voltage at any slip is given by the equation shown below:

$$E_{2s} = sE_{20} \ldots\ldots\ldots (2)$$

The rotor resistance is constant and is independent of the slip. The reactance of the induction motor depends upon the inductance of the rotor and the frequency of the voltage and current in the rotor.

If L_2 is the inductance of the rotor, the rotor reactance is given by the equation shown below:

$$X_2 = 2\pi f_2 L_2$$

But, as we know,

$$f_2 = sf_1$$

Therefore,

$$X_2 = 2\pi\, sf_1L_2 = s\,(2\pi f_1 L_2) \quad \text{or}$$

$$X_2 = sX_{20} \ldots\ldots\ldots (3)$$

Where X_{20} is the standstill reactance of the rotor.

The rotor circuit is shown below Figure 10.2:

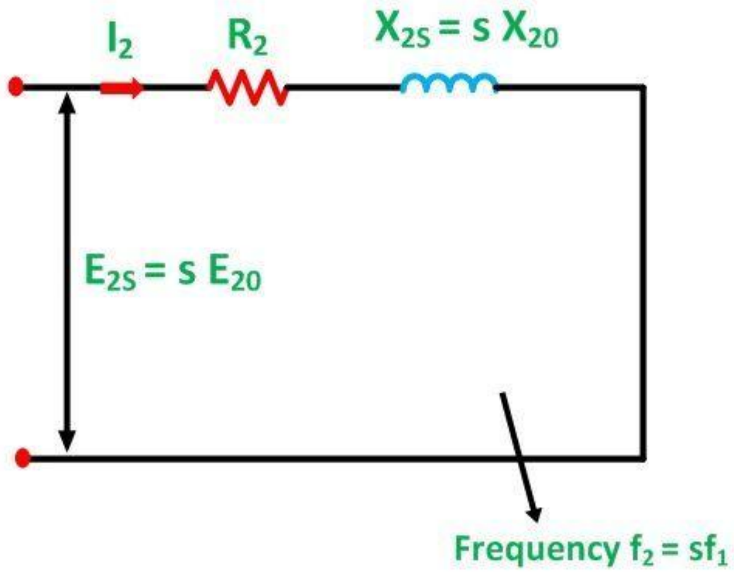


Figure 10.2 rotor circuit

The rotor impedance is given by the equation below:

$$Z_{2s} = R_2 + jX_{2s} \quad \text{or}$$

$$Z_{2s} = R_2 + jsX_{20} \ldots\ldots\ldots.(4)$$

The rotor current per phase is given by the equation shown below:

$$I_{2s} = \frac{E_{2s}}{Z_{2s}}$$

$$I_{2s} = \frac{sE_{20}}{R_2 + jsX_{20}} \ldots\ldots\ldots(5)$$

Here, I_2 is the slip frequency current produced by a slip frequency induced voltage sE_{20} acting in the rotor circuit having an impedance per phase of ($R_2 + jsX_{20}$).

Now, dividing the equation (5) by slip s we get the following equation:

$$I_{2s} = \frac{E_{20}}{\frac{R_2}{s} + jX_{20}} \ldots\ldots\ldots(6)$$

The R_2 is a constant resistance and a variable leakage reactance sX_{20}. Similarly, the rotor circuit shown below has a constant leakage reactance X_{20} and a variable resistance R_2/s.Equation (6) above explains the secondary circuit of an imaginary transformer, with a constant voltage ratio and with the same frequency of both sides. This imaginary stationary rotor carries the same current as of the actual rotating rotor. This makes it possible to transfer the secondary rotor impedance to the primary stator side.

Approximate Equivalent Circuit of an Induction Motor

The equivalent circuit is further simplified by shifting the shunt impedance branches R_0 and X_0 to the input terminals as shown in the circuit diagram below (Figure 10.3):

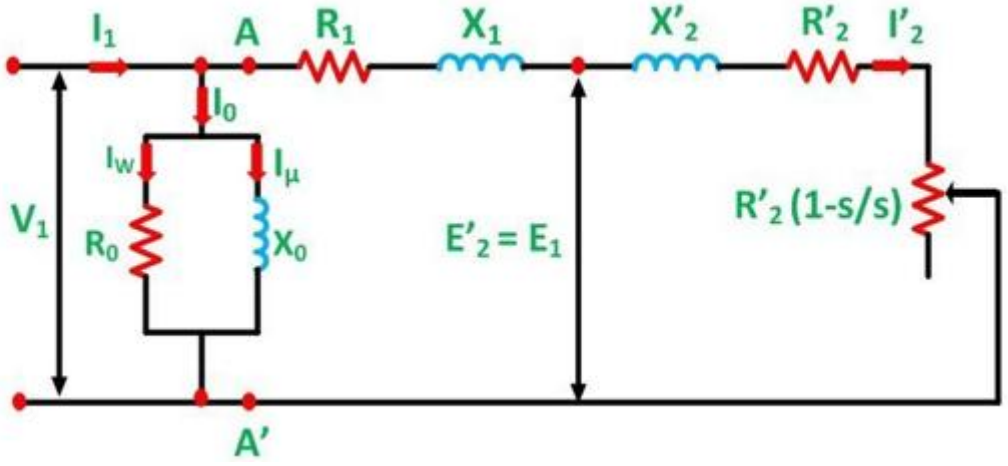


Figure 10.3 Equivalent Circuit of an Induction Motor

The approximate circuit is based on the assumption that $V_1 = E_1 = E'_2$. In the above circuit, the only component that depends on the slip is the resistance. All the other quantities are constant. The following equations can be written at any given slip s is as follows:

Impedance beyond AA' is given as:

$$Z_{AA}{}' = \left(R_1 + \frac{R'_2}{s}\right) + j(X_1 + X'_2) \ldots\ldots\ldots\ldots (7)$$

$$I'_2 = \frac{V_1}{Z_{AA}{}'} \ldots\ldots\ldots (8)$$

Putting the value of ZAA' from the equation (7) in equation (8) we get,

$$I'_2 = \frac{V_1}{\left(R_1 + \frac{R'_2}{s}\right) + j(X_1 + X'_2)} \ldots\ldots\ldots (9)$$

Therefore,

$$I'_2 = |I'_2| \frac{V_1}{\sqrt{\left(R_1 + \frac{R'_2}{s}\right)^2 + j(X_1 + X'_2)^2}} \ldots\ldots\ldots (10)$$

Hence,

$$I'_2 = I'_2\cos\varphi_2 - jI'_2\sin\varphi_2 \;\ldots\ldots..(11)$$

Where,

$$\tan\varphi_2 = \frac{X_1 + X'_2}{R_1 + \frac{R'_2}{s}} \;\ldots\ldots\ldots..(12) \quad \text{and}$$

$$\cos\varphi_2 = \frac{R_1 + (R'_2/s)}{|Z_{AA}'|} \;\ldots\ldots\ldots..(13)$$

No-load current I_0 is

$$I_0 = I_\mu + I_\omega$$

$$I_0 = \frac{V_1}{R_0} + \frac{V_1}{jX_0}$$

$$I_0 = V_1\left(\frac{1}{R_0} - j\,\frac{1}{X_0}\right)\ldots\ldots\ldots\ldots.(14)$$

The total stator current is given by the equation shown below:

$$I_1 = I'_2 + I_0$$

Total core losses are given by the equation shown below:

$$P_{h+e} = 3V_1I_0\cos\varphi_0 \ldots\ldots\ldots..(15)$$

$$\text{Stator input} = 3V_1I_1\cos\varphi_1$$

$$\text{Stator input} = 3V_1I'_2\cos\varphi_2 + P_{h+e}$$

$$\text{Stator input} = 3\,I'^2_2\left(R_1 + \frac{R'_2}{s}\right) + P_{h+e}$$

The air gap power per phase is given as:

$$P_g = V_1 I'_2 \cos\varphi_2 = I_2'^2 \frac{R'_2}{s} = \frac{V_1^2 (R'_2/s)}{\left(R_1 + \frac{R'_2}{s}\right)^2 + (X_1 + X'_2)^2}$$

The developed torque is given by the equation shown below:

$$T_d = \frac{P_g}{\omega_s} \quad \text{or}$$

$$T_d = \frac{V_1^2 (R'_2/s)}{\omega_S \left[\left(R_1 + \frac{R'_2}{s}\right)^2 + (X_1 + X'_2)^2\right]} \quad \ldots\ldots\ldots (16)$$

The above equation is the torque equation of an induction motor. The approximate equivalent circuit model is the standard for all performance calculations of an induction motor.

Torque Speed Characteristic of an Induction Motor

Torque Speed Characteristic is the curve plotted between the torque and the speed of the induction motor. We have already discussed the torque of the induction motor in the topic Torque Equation of an Induction motor. The equation of the torque is given as shown below:

$$T = \frac{k\, s\, R_2 E_{20}^2}{R_2^2 + (sX_{20})^2} \quad \ldots\ldots\ldots\ldots (1)$$

At the maximum torque, the speed of the rotor is expressed by the equation shown below:

$$N_M = N_S (1 - s_M) \quad \ldots\ldots\ldots (2)$$

The curve below shows the Torque Speed Characteristic (Figure 10.4):

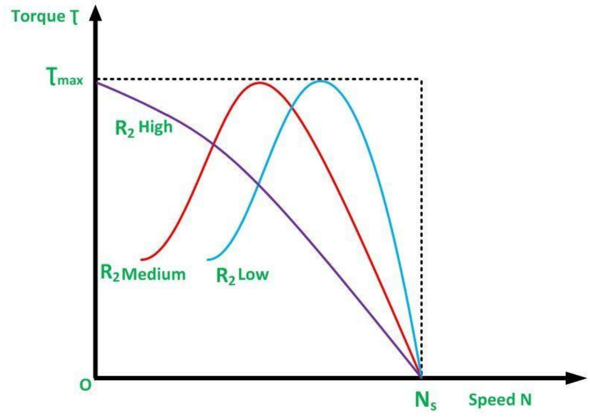


Figure 10.4 Torque Speed Characteristic

The maximum torque is independent of the rotor resistance. But the exact location of the maximum torque τ_{max} is dependent on it. The greater, the value of the R_2, the greater is the value of the slip at which maximum torque occurs. As the rotor resistance increases, the pullout speed of the motor decreases. In this condition, the maximum torque remains constant.

CHAPTER 11

Operating Principle of Induction Machines

Harsh Shrivastava, Assistant Professor,
Department of Electrical, Jaipur National University, Jaipur, India
Email Id-ershrivastava@jnujaipur.ac.in

Three Phase AC Induction Motor

An electric machine that rotates and is powered by a three-phase supply is called a three-phase AC induction motor. Asynchronous motor is another name for this three-phase motor. These AC motors come in two varieties: induction motors of the squirrel and slip-ring kinds. The creation of a spinning magnetic field is the foundation of the functioning of this motor.

Construction of a 3-phase induction motor

These three-phase motors have no electrical connections between their stator and rotor. To minimise hysteresis and eddy current losses, high-magnetic core materials are used in the construction of these stator and rotors (Figure 11.1).

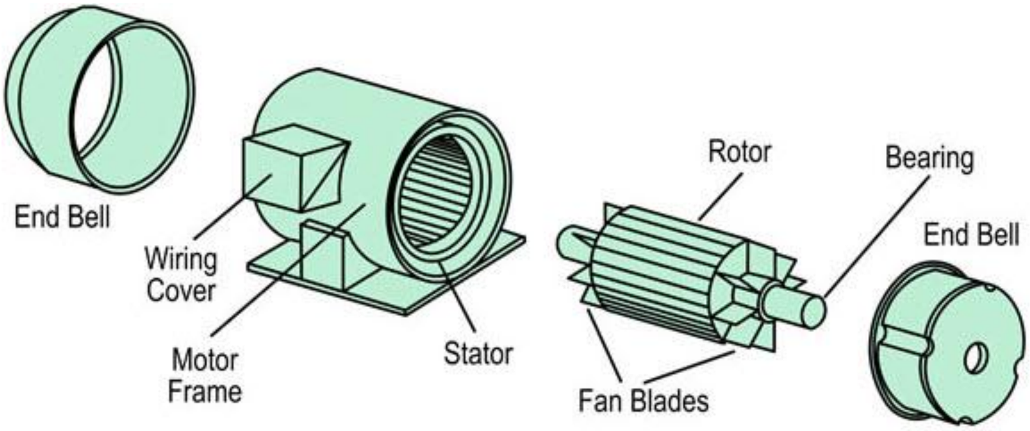


Figure 11.1 Three-phase induction motor

Three Phase Induction Motor Construction

Cast iron, aluminium, or rolled steel are all acceptable building materials for stator frames. The stator frame offers the laminated core, windings, and other ventilation components of the stator the essential mechanical security and support. Three-phase windings that are inserted into slotted laminations and overlapped at a phase shift of 120 degrees form the stator's wound core. The three windings' six ends are brought out and attached to the terminal box so that the three-phase main supply may excite the windings.

These windings are made of copper wire that has been varnish-insulated and put into laminations with insulation slots. This impregnated varnish maintains its rigidity at all operating temperatures. These windings exhibit strong insulation resistance as well as high resistance to moisture, alkaline fumes, oil and grease, among other things. These windings are coupled in either star or delta connections, depending on the voltage level.

Squirrel Cage Induction Motor

For the slip-ring and squirrel-cage induction motors, the rotor of the three-phase AC induction motor is different. The cylindrical slip-ring type rotor is made of thick aluminium or copper bars that are shorted at both ends. The induction motor's shaft is supported on two bearings at each end to provide friction-free rotation within the stator. It is made out of a stack of steel laminations with slots equally spaced around its circle, into which heavy, uninsulated aluminium or copper bars are inserted.

Three-phase windings are internal starred at one end of a slip-ring-type rotor, and the other ends are taken outside and linked to the slip rings installed on the rotor shaft. Additionally, these windings are coupled to the rheostat using carbon brushes in order to provide a strong beginning torque. Only during the initial phase is this external resistor or rheostat employed. The brushes are short-circuited once the motor reaches its typical speed, and the wound rotor then functions as a squirrel cage rotor.

Principle of Operation of 3-Phase Induction Motor (Figure 11.2)

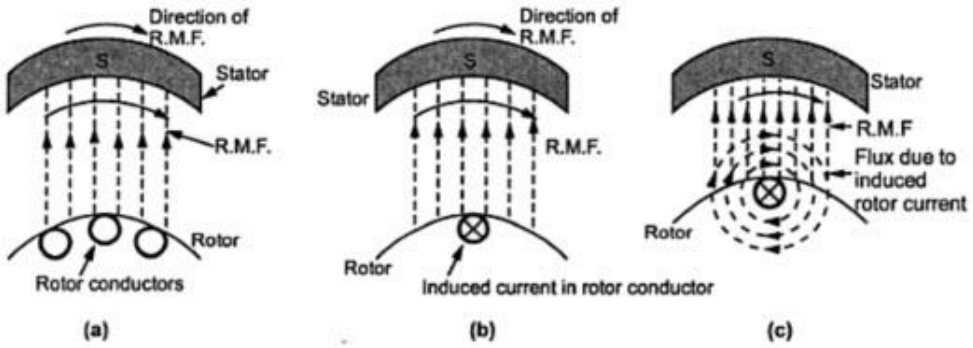


Figure 11.2 Operation of 3-Phase Induction Motor

Principle of Operation of 3-Phase Induction Motor

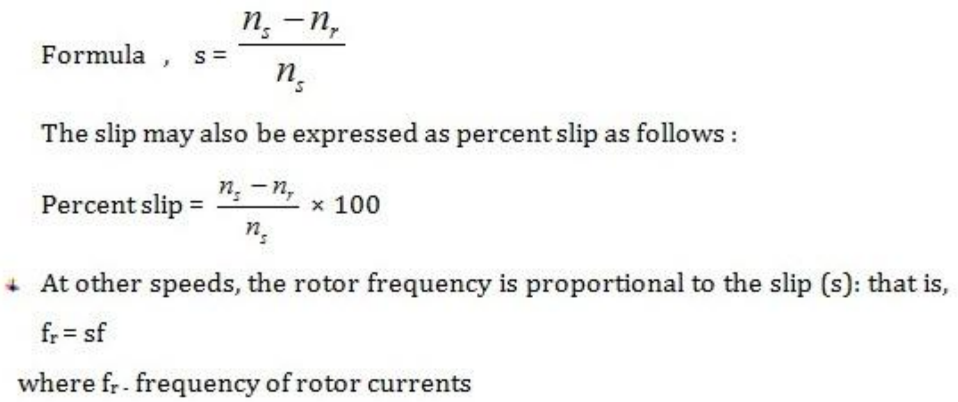
The three-phase stator winding creates a rotating magnetic field with 120 displacements at a constant magnitude that spins at synchronous speed when the motor is activated by a three-phase supply. According to Faraday's theories of electromagnetic induction, this shifting magnetic field cuts the rotor conductors and induces a current in them. The current begins to flow through these rotor conductors when they get shorted.

Because rotor conductors are positioned in the stator's magnetic field, the Lorenz force principle states that a mechanical force is exerted on the rotor conductor. Thus, the torque created by all the mechanical forces acting on the rotor conductors, or the total of those forces, tends to move the rotor in the same direction as the spinning magnetic field. Lenz's law, which states that induced currents in the rotor oppose the reason for their production—in this case, the spinning magnetic field can also be used to explain why this rotor conductor rotates.

As a consequence, the rotor begins to rotate in the same direction as the magnetic field of the stator. Because the magnetic fields of the rotor and stator rotate at different speeds, if the rotor speed is greater than the stator speed, no current will be induced in the rotor. Slip is the name given to this stator and the rotor field discrepancy. Due to the relative speed difference between the rotor and stator of a three-phase motor, this is how the term "asynchronous machine" is used.

As was already mentioned, the rotor rotates in a certain direction due to the relative speed of the stator field and rotor conductors. The difference between these two quantities, which relies on the load on the motor, must thus always be smaller than the stator field speed Ns in order to produce rotation.

The AC induction motor's slip, or speed difference, is expressed as



Formula , $s = \frac{n_s - n_r}{n_s}$

The slip may also be expressed as percent slip as follows :

Percent slip = $\frac{n_s - n_r}{n_s} \times 100$

- At other speeds, the rotor frequency is proportional to the slip (s): that is,

$f_r = sf$

where f_r - frequency of rotor currents

When the stator is stationary, Nr=0; so the slip becomes 1 or 100%.

When Nr is at synchronous speed, the slip becomes zero; so the motor never runs at synchronous speed.The slip in the 3 phase induction motor from no load to full load is about 0.1% to 3%; that's why the induction motors are called as constant-speed motors.A 3 phase induction motor derives its name from the fact that the rotor current is induced by the magnetic field, instead of electrical connections.The operating principle of a 3 phase induction motor is based on the production of a rotating magnetic field (r.m.f.).

Creation of a magnetic field that rotates

An induction motor's stator is made up of many overlapping windings that are spaced apart by an electrical angle of 120°. The main winding or stator creates a revolving magnetic field that spins at a synchronous speed when it is linked to a three phase AC source.The phase order of the supply lines and the order in which they are connected to the stator determine the motor's rotational direction. Therefore, switching the connections of any two main terminals to the supply will cause the rotation to go in the other direction.The stator of the motor rotates at a synchronous speed that is determined by the number of poles and the frequency of the supplied voltage. 2, 4, 6, or 8 poles are the most frequent configurations for motors. The following equation yields the synchronous speed, also known as the rotational speed of the field created by primary currents.Synchronous rotational speed is calculated as (120 x supply frequency) / the stator's number of poles.

GeneratingMagnetic Flux

The procedure starts with a revolving magnetic field within the stator. The rotors need to be carrying some current in order to generate a torque and revolve. This current originates from the conductors of the rotor in induction motors.

The rotor's conducting bars are cut by the stator's rotating magnetic field, which creates an electromotive force (e.m.f).An induction motor's rotor windings are either directly shorted or closed using an external resistance.

This results in current flowing in a direction that is counter to the direction of the rotating magnetic field in the stator, which causes the rotor to twist or experience torque.As a result, the rotor speed won't match the stator's r.m.fsynchronous.'s speed. If the speeds coincide, there would be no induced e.m.f. in the rotor, no current flowing, and no torque being produced. The slip is the differential between the rotor and stator speeds (synchronous speed).

The benefit of an induction motor's rotating magnetic field is that the rotor does not need electrical connections.Ultimately, a motor that is:

Self-starting

Because there are no spark-producing brushes, commutators, or slip rings, the device is explosion-proof. It is also sturdy in build, inexpensive, and simpler to maintain.

Two components make up a 3-phase induction motor: the Stator and the Rotor.Depending on the motor's power output, a little air gap between the rotor and stator may be anywhere from 0.5 mm to 4 mm.

Three-phase induction motor's stator

The stator is the motor's stationary component. It is made up of a hollow cylindrical core enclosed by a steel frame. To minimise eddy current and hysteresis losses, silicon steel is thinly laminated in the three phase induction motor's core.

On the inside edge of the laminated core, there are many slots that are evenly spaced apart, as indicated in the picture. To create a balanced 3-phase star or delta linked stator winding, the insulated conductors are inserted into these stator slots and connected in a suitable way.

The 3-phase stator windings are wound for a definite number of poles depending upon the requirement of speed, i.e., greater the number of poles, lesser is the speed of the motor and vice-versa.

When a balanced 3-phase supply is fed to the stator winding a rotating magnetic field (RMF) of constant magnitude is produced and this RMF induces currents in the rotor circuit by electromagnetic induction.

Rotor of Three Phase Induction Motor

The rotor of an induction motor is a hollow cylindrical laminated core, having slots on its outer periphery.

The rotor windings are placed in these rotor slots.

Depending upon the winding arrangement, the rotor of a 3-phase induction motor is of two types:

1. Squirrel Cage Type Rotor
2. Wound Type or Slip-Ring Type Rotor

3. Squirrel Cage Type Rotor

The squirrel cage rotor consists of a cylindrical laminated core having slots on its outer periphery which are nearly parallel to the shaft axis *or* skewed. An uninsulated copper or aluminium bar (rotor conductor) is placed in each slot.

At each end of the rotor, the rotor bar conductors are short-circuited by heavy end rings of the same material (see the Figure 11.3). This forms a permanently short circuited winding which is indestructible.

This entire arrangement resembles a cage which was once commonly used for keeping squirrels and hence the name.

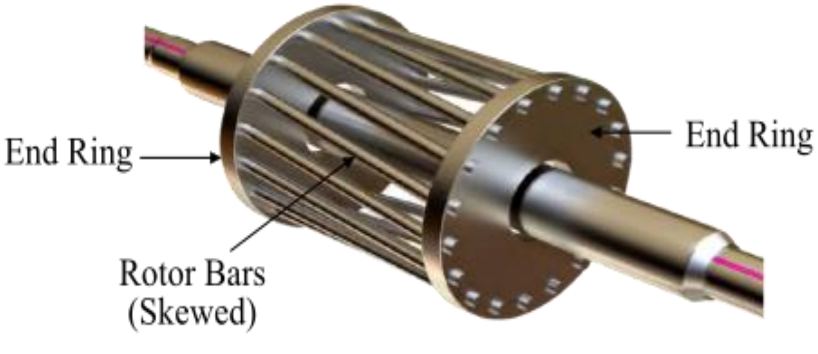


Figure 11.3 Squirrel Cage Type Rotor

Although this rotor is not electrically linked to the supply, the electromagnetic induction from the stator induces currents in it.Squirrel cage induction motors are those three-phase induction motors with a squirrel cage rotor. Due to its straightforward and durable structure, which enables it to function in even the most challenging environments, squirrel cage rotors are used in the majority of 3-phase induction motors in industries. However, it has the drawback of having a low beginning torque.

The following benefits are provided by skewing the conductors on squirrel cage rotors:

More consistent torque is created, noise is minimised during operation, and the rotor's inclination to cog or magnetically lock is lessened. The rotor and stator teeth locked with one another during cogging as a result of magnetic force.

Rotor with a wound or a slip ring

The cylindrical armature core of the slip ring rotor is laminated. On the outside perimeter, slots are supplied, and insulated conductors are inserted into the slots. Similar to the stator winding, a 3-phase double layer dispersed winding is created by connecting the conductors of the rotor. The windings on the rotor are joined in a star pattern (see the Figure 11.4).

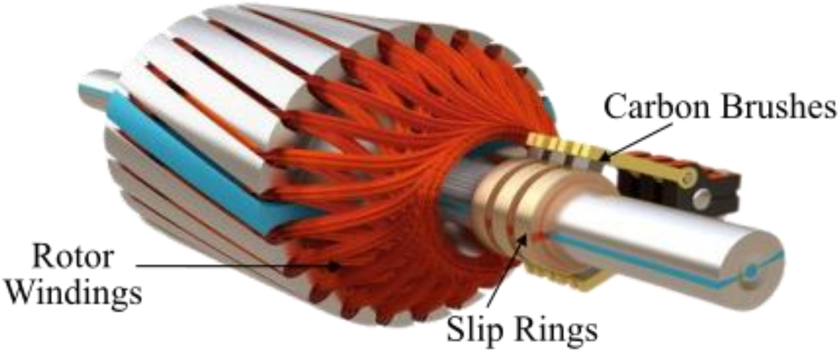


Figure 11.4 Rotor with a wound or a slip ring

Three insulated slip rings are attached to the open ends of the star circuit that are taken outside the rotor. The brushes rest on the slip rings, which are fixed to the rotor shaft. Three variable resistors that are also linked in a star shape are connected to the brushes. Here, a means of attaching external resistors to the rotor circuit is provided via slip rings and brushes. The following diagram displays the wound rotor's analogous circuit (Figure 11.5).

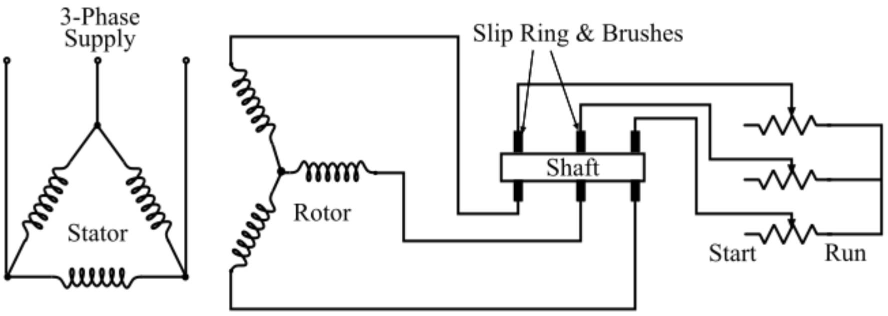


Figure 11.5 wound rotor's analogous circuit

To improve the beginning torque and decrease the starting current from the supply and to regulate the motor's speed, the external resistors allow the change of each rotor phase resistance.

Three-Phase Induction Motor Construction

The most popular electrical motor is the three phase induction motor. Due to their straightforward and durable design, cheap cost, favourable operating characteristics, lack of a commutator, and effective speed control, three phase induction motors provide over 80% of the mechanical power utilised by industries. In a three-phase induction motor, induction is used to transmit power from the stator to the rotor winding. Because it operates at a speed other than synchronous speed, the induction motor is sometimes referred to as a synchronous motor.

Construction of a 3-phase induction motor

A three-phase induction motor is made up of two primary components, the rotor and stator, much like any other kind of electrical motor induction motor:

Stator: The stator, as its name suggests, is an induction motor component that is stationary. The induction motor's stator is equipped with a stator winding, and a three-phase supply is applied.

Rotor: The rotor is an induction motor component that rotates. Through the shaft, the rotor is linked to the mechanical load.

The three phase induction motor's rotor is further divided into the following categories:

A phase wound rotor, wound rotor, or slip ring rotor.

The following categories of three phase induction motor exist depending on the rotor construction style:

An induction motor with a squirrel cage

An induction motor with a slip ring, a wound motor, or a phase wound motor.

Both types of three-phase induction motors have identical stator architecture, which is briefly covered below. If you're planning to disassemble a motor yourself, please make sure you're using the right electrical tools.

A three-phase induction motor's additional components include: 1. A shaft for transferring torque to the load. Steel makes up this shaft.

Bearings for the spinning shaft's support.

The generation of heat during an electrical motor's spinning is one of its issues. For cooling, we need a fan to solve this issue.

To accept an electrical connection from outside you need a terminal box.

The rotor and stator are separated by a very tiny distance that typically ranges from 0.4 mm to 4 mm. A space like this is known as an air gap.

By studying our electrical engineering course, you may find out more about induction motors.

Three-phase induction motor's stator

a) The three-phase induction motor's stator is made up of these three components:

b) The three components of a stator are its frame, core, and winding.

c) Inverter Frame

It is the three phase induction motor's exterior. Supporting the stator core and the field winding is its primary duty. All of the induction motor's internal components are protected and given mechanical strength by this covering, which also serves as a covering. Steel is either die-cast or manufactured to make up the frame. Given that the air gap length of a three phase induction motor is so tiny, the frame should be sturdy and stiff. Otherwise, there will be an imbalanced magnetic pull since the rotor won't stay concentric with the stator.

Inverter Core

The stator core's primary job is to transport the alternating flux. The stator core is laminated to lessen the eddy current loss. These laminated structural kinds are constructed from stamping that is between 0.4 and 0.5 mm thick. To create the stator core, which is subsequently contained in the stator frame, all of the stamps are combined and stamped. Due to the silicon steel used in the stamping, the motor's hysteresis loss is reduced.

Field winding or Stator Winding

The three-phase induction motor features three phase windings in the slots around the stator core. We feed this three-phase winding with a three-phase ac supply. Depending on the sort of beginning technique we choose, the three stages of the winding are linked either in a star or a delta pattern. The squirrel cage motor's stator is coupled in a delta fashion since we often start them using a star-delta stater. The slip ring three-phase induction motor is started by adding resistances, allowing the stator winding to be linked in either a star or a delta configuration. A spinning magnetic field is created when the winding on the stator of a three phase induction motor, also known as the field winding, is stimulated by a three phase ac supply.

Three-phase induction motor types

Three-phase induction motor with squirrel cage

The squirrel cage three-phase induction motor's rotor is cylindrical and has slots all around it. The slots are slightly skewed rather than parallel to one another (the skewing is not shown in the squirrel cage rotor picture, though), which avoids magnetic locking of the stator and rotor teeth and enhances the smoothness and quietness of the motor's operation. Bars made of copper, brass, or aluminium make up the squirrel cage's rotor (copper bras rotor is shown in the figure beside). Rotor conductors are these aluminium, brass, or copper bars that are inserted into the rotor's slots. The end rings, which are made of copper or aluminium, permanently short the rotor conductors. The term "squirrel cage induction motor" refers to this full closed circuit, which resembles a cage and is anchored to the end ring to give mechanical strength. The winding of the squirrel cage rotor is balanced. The rotor resistance is relatively low since end rings permanently short the bars, and it is impossible to introduce external resistance at this point. The design of squirrel cage three-phase induction motors is highly straightforward and durable since slip rings and brushes are not required, making them a commonly used three-phase induction motor. The ability to use any number of pole pairs is a benefit of these motors. The below diagram shows a squirrel cage induction rotor having aluminum bars short circuit by aluminum end rings.

1. Squirrel Cage Induction Rotor Benefits
2. Its construction is very simple and durable.
3. These motors need less maintenance since they don't have brushes or a slide ring.
4. Squirrel Cage Induction Rotor Applications
5. Lathes, drilling machines, fans, blowers, printing machines, etc. all employ squirrel cage induction motors.

Slip Ring Motor

The rotor of this particular kind of three-phase induction motor is coiled for the same number of poles as the stator, but it has fewer slots and a smaller number of turns per phase of a heavier conductor. Similar to the stator winding, the rotor also has star or delta winding.Numerous slots make up the rotor, and the rotor winding is inserted into these spaces. A star connection is created by joining the three end terminals. The three phase slip ring induction motor, as its name suggests, comprises of slip rings coupled on the same shaft as the rotor.

These slip rings are inextricably linked to the three ends of the three-phase windings. The three phase induction motor's starting torque may be increased and speed can be controlled by simply connecting the external resistance via the brushes and slip rings. Current is transferred to and from the rotor winding through the brushes. Additional connections are made between these brushes and three-phase star-connected resistances. Below is a slide ring three phase induction motor's electrical diagram (Figure 11.5).

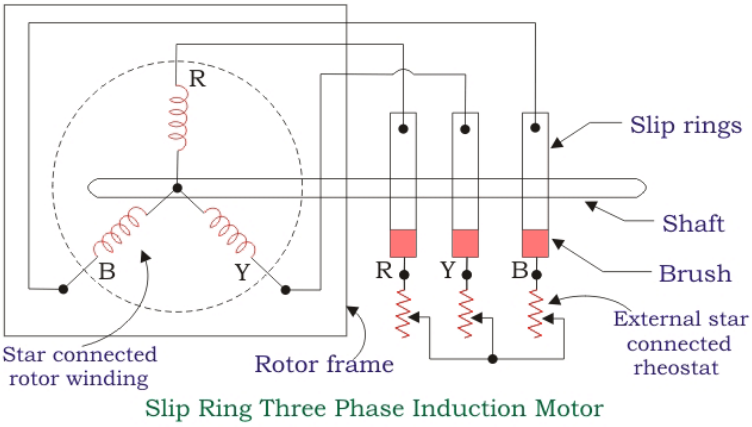


Figure 11.5 Slip ring three phase induction motor

The resistance is first linked to the rotor circuit and is progressively disconnected as the rotor gains speed. The slip rings are shorted while the motor is operating by attaching a metal collar that joins every slip ring together and also removes the brushes. This lessens the brushes' wear and tear. Slip rings and brushes make the rotor assembly a little more difficult, which reduces its utilisation compared to squirrel cage induction motors.

Slip Ring Induction Motor Benefits

It starts quickly and uses little current.

The ability to increase resistance to regulate speed

Slip ring induction motor applications

Types of Induction Motor

Single-phase and three-phase induction motors are the two categories into which induction motors fall. A 1-phase induction motor connects to a single-phase AC power source, as suggested by its name, but a 3-phase induction motor may be linked to a three-phase AC power source.

These induction motor types are divided once further into many subgroups. Three-phase is divided into two varieties whereas single-phase is divided into four types.

Single-phase Induction Motor

A single-phase induction motor cannot start on its own. The primary winding of a motor that is coupled to a single-phase power source is carrying an alternating current. It seems sense that the engine that costs the least and requires the least repair will be used the most often. Since they don't start on their own, they may be classified into many sorts depending on how they begin. They are capacitor, dual phase, and shaded pole motors. Again, there are three types of capacitor motors: permanent, capacitor start, and capacitor run. Below is a picture of a permanent capacitor motor.

The start winding of these motors may contain a centrifugal switch or a series capacitor. Because of the main winding impedance, when the supply voltage is applied, the current in the main winding trails the supply voltage. And depending on the impedance of the starting mechanism, the current in the start winding follows or follows after the supply voltage.The phase difference created by the angle between the two windings is enough to create a rotating magnitude field that generates a beginning torque. A centrifugal switch on the motor shaft opens and disconnects the beginning winding when the motor achieves 70% to 80% of synchronous speed.

Single-Phase Induction Motor Types

Four different kinds of single-phase induction motors are categorised, including Split Phase, Capacitor Start, Capacitor Start & Capacitor Run, and Shaded Pole Induction Motor.

Phase Split Induction Motor

Resistance Start Motor is another term for a split-phase induction motor. This kind of motor has a stator and a rotor with a single cage, and the stator has two windings a beginning winding and a main winding. These two windings are shifted in space by 90 degrees. While the main winding has a very low resistance and a strong inductive reactance, the beginning winding has less inductive reactance and a higher resistance.This kind of motor is more affordable and suitable for simply starting loads when the beginning frequency may be limited. Because of its lower starting torque, this motor cannot be used for drives that need more than 1 KW. Washing machines, floor polishers, AC fans, mixer grinders, blowers, centrifugal pumps, drilling & lathe machines are just a few of the uses for split-phase inductor motors.

Induction motor with capacitor start

A 1-phase motor having a stator and rotor with a single cage is known as a capacitor start induction motor. This motor's stator primarily consists of two windings, a primary winding and an auxiliary winding. Starting winding is another term for an auxiliary winding. These two windings may be arranged individually at 90 degrees in space for building a motor.

Capacitor start induction motors are employed in applications where frequent starts, such as larger inertia loads, are required.

This kind of motor is used to power compressors, pumps, machinery, and conveyors. It is also used in refrigerators & AC compressors.

Induction motor with capacitor start and run

The operating theory of a capacitor-run induction motor is the same as that of a capacitor-start induction motor. We are aware that a single-phase induction motor cannot start on its own since the magnetic field it produces is not rotational in nature. Induction motors thus need phase difference to produce a rotating magnetic field. Resistance is required in a split-phase induction motor to produce phase difference. The capacitor, however, will cause a phase difference in these motors.

It is true that the voltage is controlled by the current that flows through the capacitor. Two windings, such as the main and the beginning, are present in capacitor start and capacitor start capacitor run type motors.

Due to a link in the capacitor's beginning winding, the current it supplies bends the applied voltage in a certain direction. These two motors are employed mostly in grinders, conveyors, compressors, air conditioners, etc. because of their strong starting torque.

Induction motor with a shaded pole

This is a self-starting, single-phase induction motor that allows one of its poles to be shaded using a copper ring, commonly known as a shaded ring. This ring in the motor serves as a secondary winding's primary purpose.

This kind of motor can only turn in one direction, and it is not feasible to move the motor in backward. This motor has very large power losses, a poor power factor, and potentially very low induced starting torque. Due to its tiny size and low power ratings, this motor has a low efficiency. Due to its cheap cost & ease of starting, shaded pole induction motors are used in tiny devices like fans & relays.

Hairdryers, exhaust fans, table fans, air conditioners, cooling fans, refrigerators, record players, projectors, tape recorders, and photocopying equipment all utilise this motor. These motors are also used to start 1-phase synchronous timing motors and electronic clocks.

Applications

The single phase induction motor has several uses in both industrial and home settings and is often employed in low-power applications. And a few of them are listed below: pumps, compressors, and miniature fans

Mixers, toys, fast-cleaning vacuums, electric shavers, and drilling equipment

Motor, Three-Phase Induction

These motors start themselves without the need of a centrifugal switch, a capacitor, or any other starting mechanism. In commercial and industrial settings, three-phase AC induction motors are often employed.

These come in two varieties: slip ring and squirrel cage motors. Due to their robust structure and simple design, squirrel cage motors are often employed. External resistors are necessary for slip ring motors to have a high starting torque.

Industrial and household appliances employ induction motors because they are very inexpensive, have a robust design that requires little maintenance, and just need power to run the stator.

Phase induction motor types

The stator and the rotor are two crucial parts of a three-phase induction motor. The stator serves as the motor's fixed component while the rotor rotates. The load is attached to the shaft of this motor. Over the stator, three-phase armature winding is possible. Once this winding is supplied with balanced 3-phase current, the air gap may provide a consistent amplitude rotational magnetic field.

The load current is carried by this armature winding, which is coupled to the three-phase power source. Based on how it is built, this sort of motor is divided into two categories, including Wound Rotor & Squirrel Cage Rotor

Induction motor with a squirrel cage

The building of a squirrel cage induction motor is quite straightforward. The rotor of this motor has several slots on the exterior perimeter and a cylindrical core that may be laminated. These slots are twisted at certain angles and are not similar.

These grooves help prevent magnetic locking between the rotor's and stator's teeth so that smooth operation and minimal humming noise may be accomplished. In lieu of the rotor winding, these motors use bar-shaped rotors that are made of copper, brass, or aluminium.

In this kind of motor, the rotor's winding consists of an aluminium bar that is fastened into partially closed rotor slots alongside uninsulated copper. These conductors are short-circuited at both ends of the motor via an end ring made of a related substance. This kind of induction motor is referred to as a squirrel cage induction motor since the rotor it uses is comparable to a squirrel cage.

A Slip Ring or Wound Rotor Induction Motor

The wound rotor motor is another name for the slip-ring induction motor. This motor has a laminated cylindrical core in the rotor. There are various gaps around the outside, much like the squirrel cage. One inserts the rotor winding into the slots.

The insulated windings in the wound rotor are coiled on top of the rotor in a manner similar to that of the stator. In the STAR paradigm, the winding of this rotor may be linked and dispersed equally.

Through the slide ring, the three terminals of this STAR connection may be removed. This explains why this motor is referred to as a slide ring induction motor.

Three-Phase Induction Motor Self Start due to:

Three single-phase wires with a 120° phase difference make up a 3-phase motor. Therefore, the rotating magnetic field also has a phase difference, and the rotor will revolve as a result.

For instance, if we think of phases a, b, and c as three, the rotor will move toward phase a once phase a becomes magnetic. The rotor will get magnetised when phase "b" becomes magnetized in the following second phase, and phase "c" will follow. The rotor will continue to revolve in this manner.

Single-Phase Induction Motor Start

A single phase supply causes a one-phase induction motor to produce a pulsing magnetic field rather than a rotating one. A conductor's current supply creates a flux that may be divided into two halves, each of which rotates at a constant speed in the opposite direction.As a result, the net flux, the current flowing in the induced conductors of the rotor, and the torque all become zero. A single-phase induction motor is not self-starting as a consequence.This motor may be briefly changed into a 2-phase motor during beginning in order to solve this problem and make it self-starting. As a result, in addition to the primary winding like the beginning winding, the one-phase motor's stator is provided. These windings are thus spread out along the 1-phase supply.It is possible to design the windings such that there is a significant phase difference between the currents in the two stator windings. This motor functions as a two-phase motor as a result. The two currents provide a spinning flux that enables the single-phase motor to start on its own.

Advantages

The following diagram illustrates the benefits that the induction motor has as a result of its design and the method that electric power is delivered. And let's quickly review them.

Advantages of Induction Motor

Low Cost: In comparison to synchronous and DC motors, induction machines are considerably inexpensive. The induction motor's understated design is to blame for this. Because AC line power can be connected quickly, these motors are widely chosen for fixed speed applications in industrial, commercial, and residential settings.

Low Maintenance Cost: Unlike synchronous and dc motors, induction motors need no maintenance. An induction motor's construction is fairly straightforward, and since maintenance is likewise straightforward, it has a minimal maintenance cost.

Operation is made easy by the absence of an electrical connection that supplies power to the rotor; instead, current is generated by the movement of the transformer performed on the rotor owing to the low resistance of the spinning coils. Self-starting motors include induction motors. As a consequence, less work may be required for upkeep.

Speed Fluctuation: The induction motor's speed variation is almost constant. When transitioning from no load to rated load, the speed normally only changes by a few percent.

Strong Starting Torque: The induction motor's high starting torque makes it beneficial for tasks where the load is applied before the motor starts. In contrast to synchronous motors, 3-phase induction motors will have self-starting torque. Single-phase induction motors, on the other hand, lack self-starting torque and need some auxiliaries to turn.

Durability: An induction motor's durability is another key benefit. It is hence the best machine for a variety of tasks. As a consequence, the motor lasts for many years without needing any repairs or maintenance.

Due to all these benefits, induction motors are used in many industrial, household, and other applications.

Disadvantages

The following are some drawbacks of induction motors.

When there is a light load, the power factor is quite low and a lot of current is used. As a result, there may be significant copper loss, which lowers efficiency under light load conditions.

The starting torque of the squirrel cage induction motor is not small.

Because of its invariable speed, this motor cannot be used in applications requiring uneven speed.

It is difficult to manage the motor speed.

This motor has a strong inrush current at startup, which initially results in a drop in voltage.

Applications

The following are some examples of uses for various induction motor types.

Hoists, lifts, cranes, and large capacity exhaust fans

Operating lathe machines; crushing equipment; factories that extract oil; textiles, etc.

Magnetic Field Rotating in an Induction Motor

The stator winding in the space between the stator and the rotor creates a revolving magnetic field that causes the induction motor to revolve. The stator contains a three-phase stationary winding that may be coupled either in a delta or star pattern.

Line currents IR, IY, and IB begin to flow whenever the stator windings are linked to the AC supply. The phase difference between these line currents is 120 degrees with regard to one another. Each line current creates a sinusoidal flux in the air gap. The frequency of these fluxes is the same as the frequency of the line currents, and they also share a phase difference of 120 degrees with one another.

Let the flux produced by the line currents I_R, I_B, I_Y be φ_R, φ_B, φ_Y respectively (Figure 11.6).

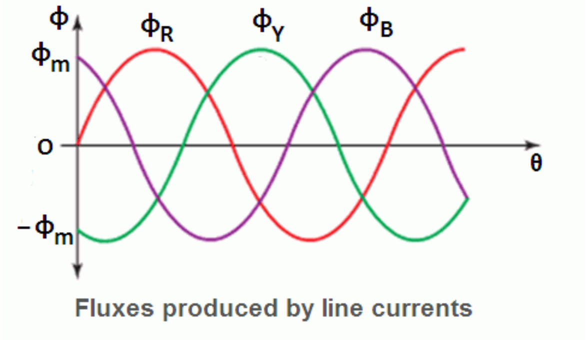


Figure 11.6 flux produce by line currents

Mathematically, they are represented as follows:

$\varphi_R = \varphi_m \sin \omega t = \varphi_m \sin \theta$
$\varphi_B = \varphi_m \sin (\omega t - 120^o) = \varphi_m \sin (\theta - 120^o)$
$\varphi_Y = \varphi_m \sin (\omega t - 240^o) = \varphi_m \sin (\theta - 240^o)$

The effective or total flux (ϕ_T) in the air gap is equal to the phasor sum of the three components of fluxes ϕ_R, ϕ_Y and, ϕ_B.

Therefore, $\phi_T = \phi_R + \phi_Y + \phi_B$

Prove that RMF in Induction Motor is Rotating

To prove that this RMF is rotating we will:

Step 1: We will find the values of total flux ϕ_T for different values of θ such as 0, 60, 120 , 180 ….. 360^o.

Step 2: For every value of θ in step 1, we will draw the phasor diagrams.

By observing these phasor digrams you can understand easily that ϕ_T keep shifting its position from 90^o to 30^o to -30^o to -90^o and so on. In other words ϕ_T rotates in the clock wise direction.

We will use the phasor ϕ_R as the reference phasor i.e. all the angles are drawn with respect to this phasor.

ϕ_T at $\theta = 0^o$

EMF Equation of Synchronous Generator or Alternator

Let,

Z = number of conductors in series per phase.

Z = 2T, where T is the number of coils or turns per phase. One turn has two coil sides or conductor as shown in the below diagram.

P = Number of poles.

f = frequency of induced emf in Hertz

Φ = flux per pole in webers.

K_p = pitch factor, K_d = distribution factor,

K_f = Form factor

N = Speed of the rotor in rpm(revolutions per minute)

N/60 = Speed of the rotor in revolutions per second.

Time taken by the rotor to complete one revolution,

dt = 1/(N/60)= 60/N second

Single turn coil

In one revolution of the rotor, the total flux Φ cut the by each conductor in the stator poles, dΦ = ΦP weber

By faraday's law of electromagnetic induction, the emf induced is proportional to rate of change of flux.

We know, the frequency of induced emf

Submitting the value of N in the induced emf equation, We get

If there are Z conductors in series per phase,

RMS value of emf per phase = Form factor x Average value of induced emf = 1.11 x 4 Φ f T

RMS value of emf per phase = 4.44 Φ f T volts

The obtained above equation is the actual value of the induced emf for full pitched coil or concentrated coil. However, the voltage equation gets modified because of the winding factors.

Actual induced emf per phase = 4.44 K_p K_d Φ f T volts = 4 K_f K_p K_d Φ f T volt

The relationship between the torque created and the motor's rotational speed is what is referred to as the torque-speed characteristics of a three-phase induction motor. It provides details on how the motor torque varies with changes in speed.Although the speed of a three-phase induction system affects its torque, their connection cannot be described by a straightforward equation. As a result, we represent their connection using the torque-speed curve (Figure 11.7).

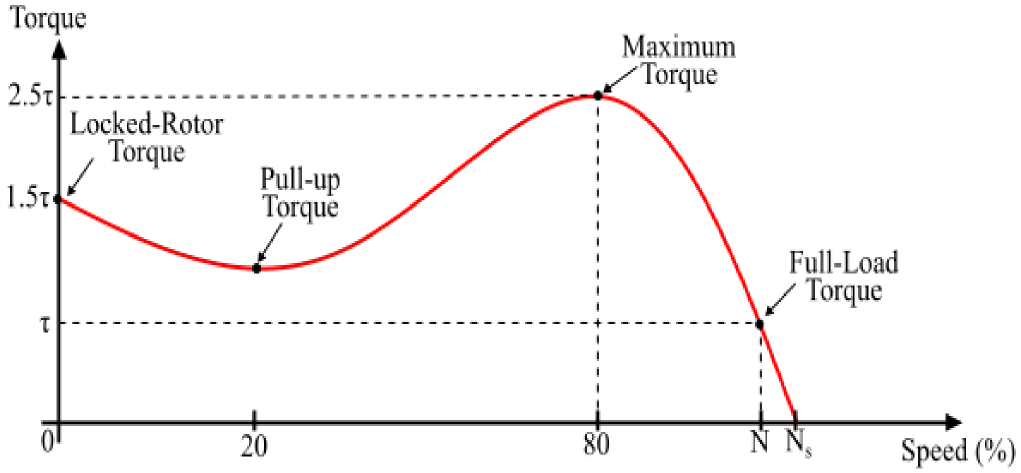


Figure 11.7 torque-speed curve

Refer the torque-speed curve, it reveals the following facts:

If the maximum torque (also referred to as breakdown torque) is 2.5 times the full-load torque, the locked rotor torque or beginning torque is 1.5 times the full-load torque.The motor's full load speed is N. The motor speed will decrease as the mechanical load on the shaft rises until the electromagnetic torque (also known as motor torque) is once again equal to the load torque. The motor will operate at a constant speed that is lower than the previous speed as soon as the two torques are equal. However, the will abruptly halt if the torque reaches the breakdown torque (2.5).

A three-phase induction motor's torque-speed characteristics are a straight line between the no-load and full-load operating positions. The rotor circuit resistance determines the slope of the curve line; hence, the steeper the slope of the curve, the greater the rotor circuit resistance.

While big motors (more than 1000 kW rating) create their maximum torque at a speed around 98% of synchronous speed, tiny three-phase induction motors (below 10 kW rating) do so at a speed about 80% of synchronous speed.

Speed Control Methods of Induction Motor

An induction motor is practically a constant speed motor, that means, for the entire loading range, change in speed of the motor is quite small. Speed of a DC shunt motor can be varied very easily with good efficiency, but in case of Induction motors, speed reduction is accompanied by a corresponding loss of efficiency and poor power factor. As induction motors are widely being used, their speed control may be required in many applications. Different speed control methods of induction motor are explained below.

Induction Motor Speed Control from Stator Side

By Changing the Applied Voltage:

From the torque equation of induction motor,

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (s X_2)^2)}} = \frac{3}{2\pi N_s} \frac{s E_2^2 R_2}{\sqrt{(R_2^2 + (s X_2)^2)}}$$

Rotor resistance R_2 is constant and if slip s is small then $(sX_2)^2$ is so small that it can be neglected. Therefore, $T \propto sE_2^2$ where E_2 is rotor induced emf and $E_2 \propto V$ Thus, $T \propto sV^2$, which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases. This method is the easiest and cheapest, still rarely used, because

Large change in supply voltage is required for relatively small change in speed.

Large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

By Changing the Applied Frequency

Synchronous speed of the rotating magnetic field of an induction motor is given by,

$$Ns = \frac{120\,f}{P} \quad \text{(RPM)}$$

Where, f = frequency of the supply and P = number of stator poles. Hence, the synchronous speed changes with change in supply frequency. Actual speed of an induction motor is given as N = Ns (1 - s). However, this method is not widely used. It may be used where, the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance.

And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

Constant V/F Control of Induction Motor

This is the most popular method for controlling the speed of an induction motor. As in above method, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux will tend to saturate.

This will cause excessive stator current and distortion of the stator flux wave. Therefore, the stator voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant.

The magnitude of the stator flux is proportional to the ratio of the stator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, by keeping V/F constant, the developed torque remains approximately constant.

This method gives higher run-time efficiency. Therefore, majority of AC speed drives employ constant V/F method (or variable voltage, variable frequency method) for the speed control.

Along with wide range of speed control, this method also offers 'soft start' capability.

Changing the Number of Stator Poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles.

Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots.

For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.

For supply frequency of 50 Hz

i) Synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM
ii) Synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

Speed Control from Rotor Side:

Rotor Rheostat Control

This method is similar to that of armature rheostat control of DC shunt motor. But this method is only applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cage motors is not possible.

Cascade Operation

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following Figure 11.8.

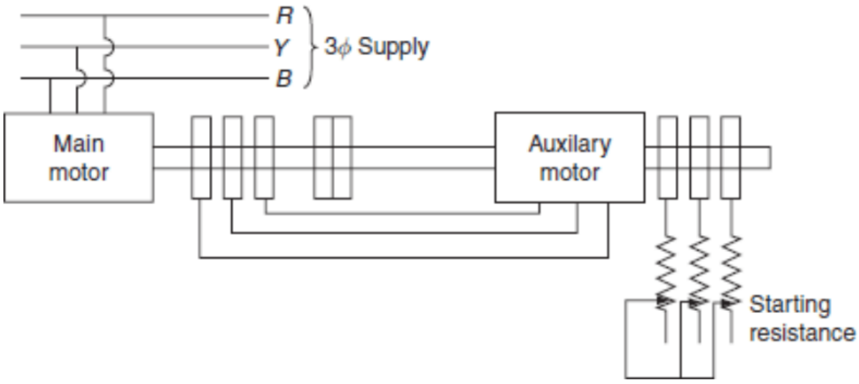


Figure 11.8 Cascade Operation

Motor A is called the main motor and motor B is called the auxiliary motor.
Let, N_{s1} = frequency of motor A
N_{s2} = frequency of motor B
P_1 = number of poles stator of motor A
P_2 = number of stator poles of motor B
N = speed of the set and same for both motors
f = frequency of the supply

Now, slip of motor A, $S_1 = (N_{s1} - N) / N_{s1}$.
frequency of the rotor induced emf in motor A, $f_1 = S_1 f$
Now, auxiliary motor B is supplied with the rotor induce emf

therefore, $N_{s2} = (120f_1) / P_2 = (120S_1f) / P_2$.

now putting the value of $S_1 = (N_{s1} - N) / N_{s1}$

$$N_{s2} = \frac{120f(N_{s1} - N)}{P_2 N_{S1}}$$

At no load, speed of the auxiliary rotor is almost same as its synchronous speed.

i.e. $N = N_{s2}$. from the above equations, it can be obtained that

$$N = \frac{120f}{P_1 + P_2}$$

With this method, four different speeds can be obtained
when only motor A works, corresponding speed = .Ns1 = 120f / P_1
when only motor B works, corresponding speed = Ns2 = 120f / P_2
if commulative cascading is done, speed of the set = N = 120f / ($P_1 + P_2$)
if differential cascading is done, speed of the set = N = 120f (P1 - P2)

By Injecting EMF in Rotor Circuit

EMF Injection in the Rotor Circuit

By injecting a voltage into the rotor circuit, an induction motor's speed is regulated using this technique. It is essential that the voltage's (emf's) frequency match that of the slip frequency. However, the phase of the injected emf is not constrained. Rotor resistance will rise if we inject emf that is in phase opposite to the rotor-induced emf. Rotor resistance will diminish if we inject emf that is in phase with the rotor-induced emf. Thus, speed may be managed by adjusting the injected emf's phase. The key benefit of this technology is that it allows for both above- and below-normal speed control. There are several ways to inject the emf, including the Kramer system and the Scherbius system.

Single Phase Induction Motor

For home, commercial, and to some degree industrial usage, we employ the single-phase power system more often than the three-phase system. Because a single-phase system is more cost-effective than a three-phase system because most homes, businesses, and offices have modest power needs that a single phase system can readily provide.The single phase motors have a straightforward design, are inexpensive, dependable, and are simple to fix and maintain. The single phase motor is used in vacuum cleaners, fans, washing machines, centrifugal pumps, blowers, etc. because of all these benefits.

The single phase AC motors may also be divided into:

Single phase asynchronous or induction motors.

Synchronous motors in one phase.

Motors for commutators.

The basics, a description, and the operation of a single phase induction motor are provided in this article.

Single-phase induction motor construction

The rotor and stator are the two major components of an asynchronous motor, much like any other electrical motor.

Stator: An induction motor's stator is a stationary component, as its name suggests. The stator of a single phase induction motor receives a single phase AC supply.

Rotor: An induction motor's rotor is a spinning component. The shaft is connected to the mechanical load via the rotor. The single-phase induction motor uses a squirrel cage rotor as its rotor.

The single phase induction motor is built very similarly to the three phase squirrel cage induction motor. However, compared to a three phase induction motor, a single phase induction motor's stator contains two windings as opposed to one three phase winding.

Single-phase induction motor's stator

Laminated stamping is present on the stator of the single-phase induction motor to reduce eddy current losses there. On its stamping, slots are given for the stator or main winding. To minimise hysteresis losses, silicon steel is used to make stampings. The magnetic field is created and the motor spins at a speed only a little bit slower than the synchronous speed Ns when we attach a single phase AC supply to the stator winding. Where f is the supply voltage frequency and P is the number of poles on the motor, synchronised speed Ns is calculated.

Except for two differences in the single phase induction motor's winding, the stator of a three phase induction motor is built similarly to a single phase induction motor.

The concentric coils used in single-phase induction motors are the norm. With the aid of concentric coils, we may quickly change the number of turns per coil. The distribution of the mmf is almost sinusoidal.

Asynchronous motors, with the exception of shaded pole motors, have two stator windings, referred to as the main winding and the auxiliary winding. These two windings are arranged in quadrature with respect to one another.

Single-phase induction motor's rotor

The single-phase induction motor's rotor is built similarly to the three-phase induction motor with a squirrel cage. The cylindrical rotor features slots all around its edge. The slots are slightly skewed rather than parallel to one another in order to avoid magnetic locking of the teeth on the stator and rotor and to improve the smoothness and quietness of the induction motor's operation (i.e. less noisy).Bars made of brass, copper, or aluminium make up the squirrel cage rotor. These copper or aluminium bars are known as rotor conductors and are inserted into the rotor's slots on the outside. The rotor conductors known as the end rings are permanently shorted by the copper or aluminium rings.

The term "squirrel cage induction motor" refers to the full closed circuit that results from the bracing of the rotor conductors to the end ring for mechanical support. The electrical resistance of the rotor is exceptionally low since end rings permanently short the bars, making it impossible to introduce external resistance. The single phase induction motor's design is very simple and durable since brushes and slide rings are not used.

The Single Phase Induction Motor's Operation

Alternating current begins to flow through the stator or main winding of a single phase induction motor when we attach a single phase AC supply to it. The primary flux is an alternating flux created by this alternating current. The rotor conductors are severed as a result of this primary flux's linkage to the conductors.The rotor induces emf in accordance with Faraday's law of electromagnetic induction. The current begins to flow in the rotor after the rotor circuit is closed. The rotor current is the name of this flow. The flux created by this rotor current is known as the rotor flux. The induction motor earned its name because it operates on the induction principle, which causes this flux to be created. There are now two fluxes: the main flow and the rotor flux. The needed torque, which the motor needs to spin, is produced by these two fluxes.

Single Phase Induction Motor not Self Start

The double field revolving theory states that we may divide every alternating quantity into two halves. Each component rotates in the opposite direction from the other and has a magnitude that is equal to half the maximum magnitude of the alternating quantity. For instance, a flux may be separated into its two components.

$$\frac{\phi_m}{2} \; and \; -\frac{\phi_m}{2}$$

Each of these parts rotates in the opposite direction; for example, if one m/2 is revolving clockwise, the other m/2 rotates anticlockwise.The stator winding of a single phase induction motor creates its flux of magnitude, m, when we add a single phase AC supply to it. The double field revolving theory states that this alternating flux, m, may be split into two components, each of size m/2. These parts will all revolve at the same synchronous speed, Ns, but in the opposite direction.Let's refer to these two flux components as the advancing flux component (f) and the backward flux component (b). The sum of these two flux components at any given instant provides the value of the instantaneous stator flux at that specific moment.

$$i.e.\phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \; or \; \phi_r = \phi_f + \phi_b$$

The forward and backward components of flux are now precisely opposite one another at the initial state. Additionally, the magnitude of each of these flow components is the same. As a result, they cancel one another, leaving the rotor in the starting state with zero net torque. Therefore, single phase induction motors cannot start themselves.

Making Single Phase Induction a Self-Starting Motor: Techniques

Due to the alternating nature of the stator flux generated and the fact that its two components cancel out at startup, it is clear from the discussion above that single-phase induction motors are not self-starting. As a result, there is no net torque. Making the stator flux rotational, as opposed to the alternating kind, which spins only in one direction, will solve this issue. The induction motor will thereafter start on its own.

We now need two alternating fluxes with a phase difference between them in order to create this rotating magnetic field. A resultant flux is created when these two fluxes interact with one another. This resulting flux spins in space in just one direction and has a rotational character.

We can get rid of the extra flux once the motor starts up. Only the main flux will have any further effect on the motor. There are primarily four types of single phase induction motor, namely: 1. Split phase induction motor; 2. Capacitor start inductor motor; 3. Capacitor start capacitor run induction motor; and 4. Shaded pole induction motor, depending on the techniques used to make asynchronous motors into Self Starting Motors.

A single value or permanently divided capacitor motor.

Three-phase and single-phase induction motor comparison

- Compared to three phase induction motors, single phase induction motors are easy to build, dependable, and cost-effective for lower power ratings.
- Compared to three phase induction motors, single phase induction motors have a lower electrical power factor.
- Single-phase induction motors for the same size provide around 50% of the power of three-phase induction motors.
- Asynchronous motors and single phase induction motors have low starting torque.
- Single phase induction motors' efficiency is lower than three phase induction motors'.
- For modest ratings, single phase induction motors are straightforward, strong, dependable, and less expensive. They come in ratings of up to 1 KW.
- Methods for Starting a Single Phase Induction Motor

- Because the single-phase induction motor cannot start on its own, it requires an additional method or piece of machinery. Because mechanical techniques are problematic, the motor is temporarily started as a two-phase motor.
- In general, single-phase induction motors are categorized based on the auxiliary device used to start the motor. They are categorized based on the initial approaches.

The various starting methods of a Single Phase Induction motor are as follows:

Separate Phase Motor

Two value capacitor motor or a capacitor start capacitor run motor

Single value capacitor motor or Permanent Split Capacitor (PSC)

Motor with Shaded Poles.

In their own articles, each of these beginning strategies is thoroughly explored. These beginning strategies rely on the two alternating fields that are phase- and spatially dispersed.

The combination of the two separate fields creates the spinning field. The cage rotor responds with this spinning field to provide the beginning torque. The field winding creates one field, while the beginning winding or auxiliary winding creates the other.

Single phase induction motor fundamentals

It takes some effort for the single-phase induction motor to start. For the motor to start, we need a starter. The primary winding of the motor conducts alternating current when it is coupled to a single-phase A.C power source. Single phase induction motors may be divided into several categories based on how they start.

Split phase induction motors and shaded pole induction motors are two examples of single phase induction motors.

Single-phase induction motor benefits

Utilizing single-phase motors provides a number of benefits. Compared to other motor types, single-phase induction motors are less costly to make. These motors are built using simple materials. Single-phase motors may also endure for many years, and the majority of their failures are often due to improper application rather than a manufacturing flaw in the motor itself. Single-phase induction motors seldom need repairs and need very minimal maintenance.

CHAPTER 12

Classification of Synchronous Machines

Harsh Shrivastava, Assistant Professor,
Department of Electrical, Jaipur National University, Jaipur, India
Email Id-ershrivastava@jnujaipur.ac.in

Synchronous machines are made up of both synchronous generators and motors. There are various benefits of an AC system over a DC one. As a result, the production, transmission, and distribution of electric power are all done via the AC system. The device that transforms mechanical energy into alternating current (AC) electricity is known as a synchronised generator or alternator.

Synchronous motors, on the other hand, are used to run the same machine as a motor.An AC machine known as a synchronous machine relies on the preservation of the following connection to function well.

$$N_s = \frac{120f}{P} \dots\dots\dots (1) \quad \text{or}$$

$$f = \frac{PN_s}{120}$$

Where,

- N_s is the synchronous speed in revolution per minute (r.p.m)
- f is the supply frequency
- P is the number of poles of the machine.

A synchronous machine always upholds the relationship shown above when linked to an electric power supply, as indicated in equation (1).The machine will not produce enough torque to continue rotating if the synchronous machine acting as a motor is unable to sustain the average speed (Ns).

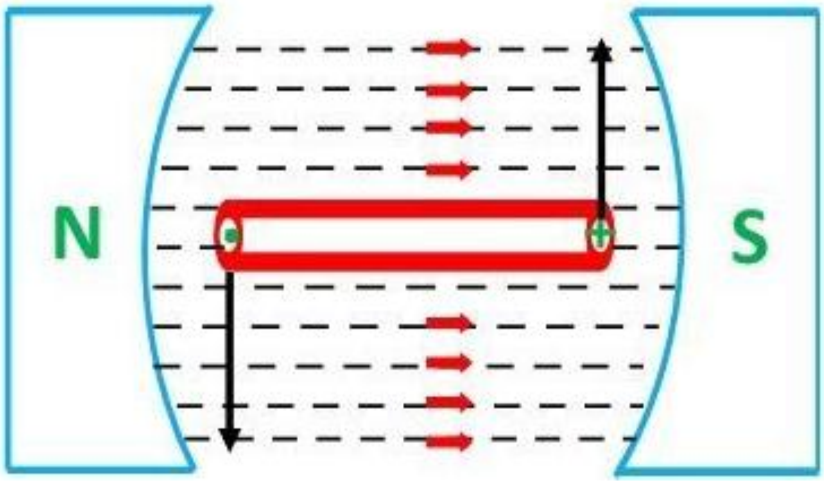
As a result, the machine will halt. It is then claimed that the motor has been pulled out of step.When a synchronous machine is used as a generator, it must operate at a constant speed known as Synchronous speed in order to produce electricity at a certain frequency. Since every equipment or appliance is built to function at this frequency. The frequency value in certain nations is 50 hertz.

Basic Synchronous Machine Principles

An electromechanical transducer that changes mechanical energy into electrical energy or vice versa is all that a synchronous machine is. The Law of Electromagnetic Induction and the Law of Interaction are the underlying phenomena or laws that enable these transformations.

Electromagnetic Induction Law

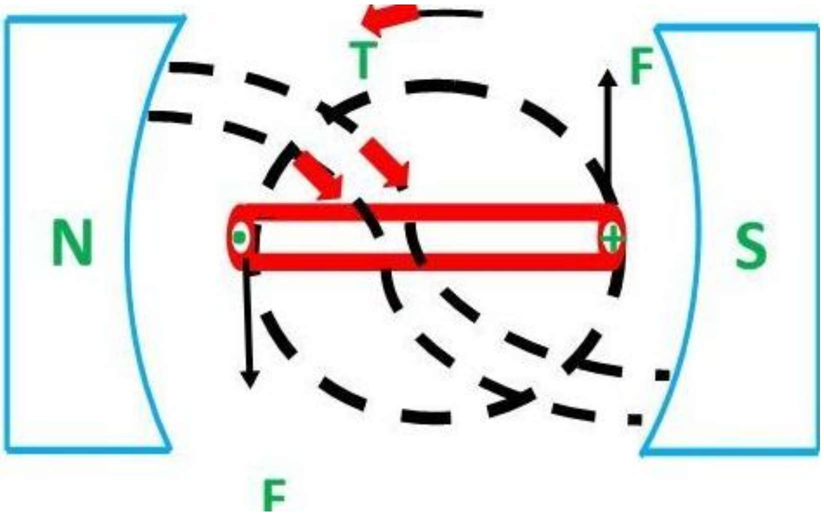
Faraday's First Law of Electromagnetic Induction is another name for this rule. According to this rule, emf is generated anytime a conductor crosses the magnetic field, as seen below Figure 12.1:



Figuer 12.1 emf is generated by conductor crosses the magnetic field

Law of Interaction

This rule refers to the creation of force or torque, i.e., anytime a current-carrying conductor is put in the magnetic field, force is imposed on the conductor creating torque by the interaction between the magnetic field created by the current-carrying conductor and the main field. The graphic is seen below Figure 12.2:



Figuer 12.2Law of Interaction

Three-Phase Synchronous Machine

The machinery utilized in home appliances, such as the tiny machinery used in fans, air conditioners, refrigerators, and air coolers. The following are the reasons why big AC machines are three-phase type synchronous machines.Three-phase electricity is transferred and distributed more economically than single-phase power. Three-phase machines have over 1.5 times the output of single-phase machines for the same size of the frame.

Three-phase motors may start themselves

Single-phase motors have pulsing torque, but three-phase motors provide an absolute uniform continuous torque.As opposed to a big synchronous machine, which has the field winding on the rotor and the armature winding on the stator, a tiny synchronous machine has the field winding on the stator and the armature winding on the rotor.

Building a Synchronous Machine

The stator and the rotor are the two primary components used in the construction of a synchronous machine, such as an alternator or motor. The machine's stator is its stationary component. The armature winding, which is where the voltage is produced, is carried by it. The stator serves as the machine's output. The machine's spinning component is called the rotor. The primary field flux is created by the rotor.

The following list includes the Synchronous Machine's key components:

a. Stator
b. Rotor
c. Miscellaneous

Construction of Stators

Stator is the name of the machine's stationary component. It has a number of components, including the stator frame, stator core, stator windings, and cooling system. They are thoroughly discussed here.

Frame

It serves as a protective shell for the machine's internal components and is composed of cast iron.

Core

Silicon steel is used to make the stator core. It is constructed from many separate stamps that are isolated from one another. Its purpose is to accommodate the stator winding and offer a simple route for the magnetic lines of force.

Inductor Winding

On the inner edge of the stator core, slots are carved into which 3 phase or 1 phase windings are inserted. Copper that has been enamelled is used for winding. Star connections link the winding. Each phase's winding is split over a number of slots. An essentially sinusoidal spatial distribution of EMF is created when current flows in a dispersed winding.

Construction of rotors

Rotor refers to the component of the machine that rotates. The salient pole type and the cylindrical rotor type are the two different forms of rotor construction.

Rotor Salient Pole

Projecting is what the word salient signifies. As a result, a salient pole rotor consists of poles that extend from the rotor core's surface. A standard six-pole salient pole rotor is seen from the end. below in the Figure 12.3:

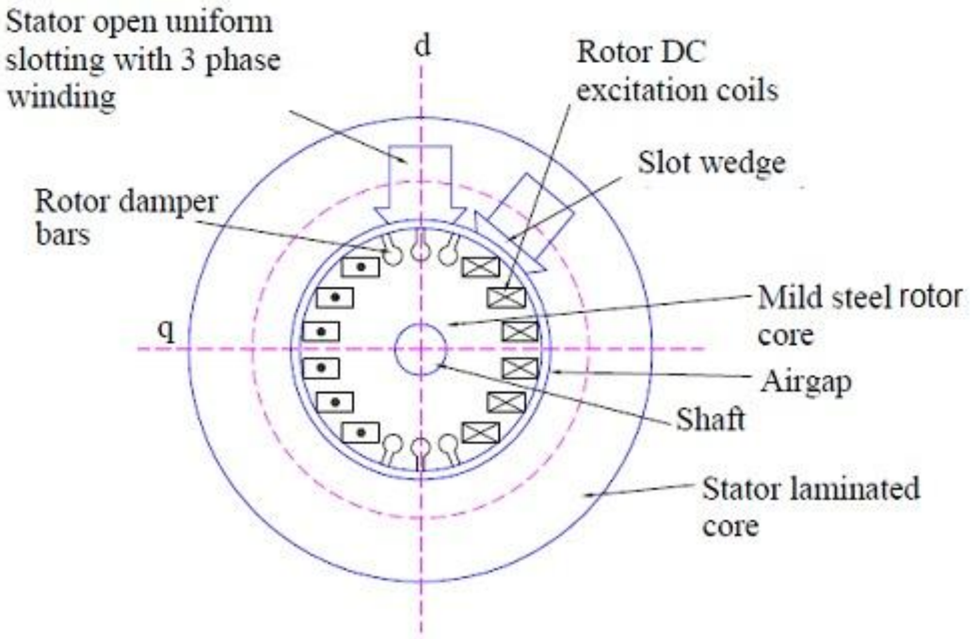


Figure 12.3 six-pole salient pole rotor

The rotor is composed of steel laminations to prevent eddy current losses since it is exposed to fluctuating magnetic fields. Laminations are stacked to the necessary length before being joined to form poles with equal diameters. The air gap of a salient pole synchronous machine is not uniform. Under the centres of the poles, the air gap is at its smallest, and between the poles, it is at its largest.They feature a lot of poles and are designed for medium and low speeds. The diameter of a salient pole generator is big. The salient pole rotor consists of the following crucial components:

Spider:

To provide a simple channel for magnetic flux, it is formed of cast iron. The pole core and pole shoe are keyed to it at the outer surface, and it is keyed to the shaft.

The pole's core and shoe are composed of steel sheet laminate. The pole shoe evenly disperses the magnetic field across the whole perimeter to create a sinusoidal wave, while the pole core offers the least resistance route for the magnetic field.

It is coiled using either field winding or exciting winding, then set around the pole core. It receives a DC supply by slide rings. The requisite magnetic field is created when direct current passes through the field winding.

Copper bars are put into holes at the very edge of the device and short-circuited at both ends by rings to produce the damper winding.

Cylindrical or Non-Salivating Pole Rotor

There are no projected poles in this kind of rotor; instead, the poles are created by the current passing through the excited winding. Solid forgings of high-grade nickel chrome-molybdenum steel are used to create cylindrical rotors. It has a large axial length and a relatively tiny diameter.They are beneficial in fast machinery. Two or four poles may be found on the rotor of an alternator with a cylindrical rotor. The mechanical strength of such a design is increased, and it enables more precise dynamic balancing. The machine's consistent air gap and smooth rotor reduce windage losses and noise levels during operation (Figure 12.4).

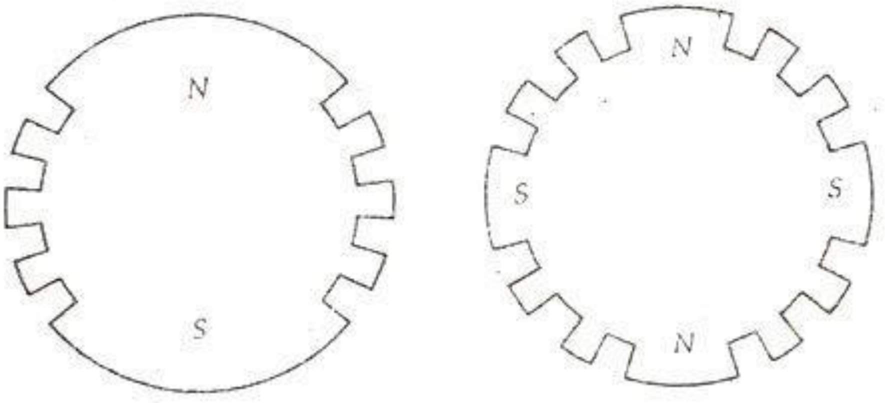


Figure 12.4 The 2 pole and 4 pole cylindrical rotors' end views

Steam or gas turbines are used to power them. Turbo-alternators and turbo generators are terms used to describe cylindrical synchronous rotor synchronous generators. The machines may be purchased in ratings ranging from 10 MVA to more than 1500 MVA. The super thermal power plant in India uses the largest size with a 500 MVA rating.

The following components are found in non-salient pole-type rotors. These are what they are:

Rotating core

The silicon steel stampings that make up the rotor core. The shaft receives it. Slots are carved out along the perimeter, where exciting coils are positioned.

Rotor winding, also known as an exciting winding, is a winding that is attached to a rotor and through which current is sent in order to produce poles that meet the specifications.

Slip Rings: The rotor windings are supplied with DC power via slip rings.

Diverse Components

The supplemental components are listed below:

Brushes: Made of carbon, brushes are designed to slide across slip rings. The brushes get a DC supply. The thrilling windings are reached once the current passes from the brushes to the slip rings.

Bearings: To lessen friction, bearings are placed between the shaft and the outer stationary body. High carbon steel was used to make them.

Shaft: Mild steel was used to make the shaft. The machine receives or receives mechanical power via the shaft.

Synchronous machine types

Synchronous machines are divided into two categories based on the configuration of the armature and field windings: Types of rotating apparatus include rotating fields.

In a rotating armature type, the armature winding is located in the rotor, and the slip ring and carbon brush assembly provide the current or emf to the load. Only tiny rating machines may use this kind of synchronous machine.

The rotor of a rotating field type synchronous machine is wound using field winding. By assembling a slip ring and carbon brush, a DC supply is provided to the field winding. Using stationary terminals located on the stator, electrical power is delivered to the load. This kind is more well-known and often used in big synchronous machines.

Synchronous generators are divided into the following categories based on the kind of primary mover:

Hydro-generators: A hydro-generator is a generator that is powered by a hydro-turbine. These operate at a slower speed of about 1000 rpm or less and are essentially salient pole types.

Turbo-generators: These generators turn the thermal energy of steam into electrical energy and are powered by steam turbines. These rotate at a greater speed and have cylindrical poles. Typically, the frequency of the grid controls the rotor's speed. The two pole generator's rotor rotates at 3000 rpm if the grid frequency is 50 Hz (Ns = 12050 / 2 = 3000).

Generators using an internal combustion (IC) engine: These generators have a speed of less than 1500 rpm.

An alternator's armature winding might be either a closed type or an open type. In the alternator's armature winding, closed winding creates a star connection.

Armature winding has several characteristics with other processes

Two sides of any coil should be beneath two neighboring poles, which is the first and most crucial characteristic of an armature winding. Therefore, coil span equals pole pitch.

There are two types of winding: single layer and double layer.

Because the winding is configured in various armature slots, sinusoidal emf must be produced.

Types of Alternator Armature Winding

Different armature winding types are used in alternators. There are two types of armature windings: single phase and poly phase.

- Distributed and concentrated winding.
- Winding that is partially and fully coiled.
- Winding in a single and double layer.
- Concentric or spiral winding, laps, and waves
- Coil winding using full pitches and fractional pitches.

Additionally to this, the alternator's armature winding may either be integral slot winding or fractional slot winding.

Winding a single phase armature

There are two types of single phase armature winding: concentrated and dispersed.

Concentrated Armature Winding

Where the number of slots on the armature equals the number of poles in the machine, the focused winding is used. Although not quite sinusoidal, the alternator's armature winding produces the highest output voltage.In below figure, the simplest single-phase winding is shown. In this case, the number of poles equals the sum of the slots and coil sides. One coil side is in a slot under one pole in this instance, while the second coil side is in other slots beneath the subsequent pole. The induced emf in one coil side is multiplied by the emf in the neighbouring coil side (Figure 12.5).

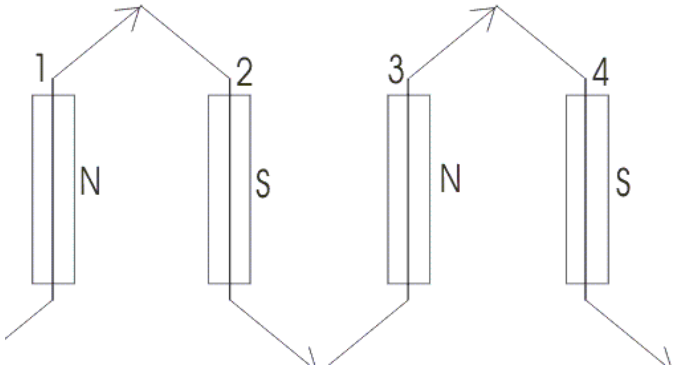


Figure 12.5 Concentrated Armature Winding

Skeleton wave winding is the name for this configuration of an alternator's armature winding. According to above, the coil side under the N-pole is linked to the coil side under the S-pole at the rear, the coil side under the front, and so on.

Induced emf on coil side 1 is directed upward, whereas induction on coil side 2 is directed downward. Again, since coil side 3 is below the N-pole, the emf will be in the upward direction. The sum of the emf on all coil sides is hence the total emf. Although fairly simple, this kind of armature winding is seldom utilised since it demands a lot of room for the end connections of each coil side or conductor. By utilising multi turns coil, we can somewhat solve this issue. To get a greater emf, we employ a multi-turn half-coiled winding. We refer to this winding as Half coiled or Hemi-tropic winding since the coils only encircle one-half of the armature. The term "whole coiled winding" refers to the winding of an armature where all of the coils are distributed over the whole perimeter.

Distributed Armature Winding of Alternator

Conductors are inserted into a number of slots beneath a single pole in order to produce a smooth sinusoidal emf wave. Distributed winding is the term for this armature winding. Although the alternator's spread armature winding lowers emf, it is nevertheless highly useful for the reasons listed below.

- It also lowers harmonic emf, which enhances waveform.
- It lessens the response of the armature.
- Even conductor distribution aids in improved cooling.
- The conductors are dispersed throughout the slots on the armature perimeter, completely using the core.

Winding of the Alternator's Lap

The alternator below has a full pitched lap winding with 4 poles, 12 slots, and 12 conductors (one conductor per slot).

The number of conductors per pole determines the back pitch of the winding, which is 3; the front pitch is determined by subtracting the back pitch from 3. As indicated in figure - 4 below, the winding is finished for each pair of the poles before being joined in series.

Alternator Wave Winding

Figure-e below depicts the wave winding of the same device, which has four poles, 12 slots, and 12 conductors. The front pitch and rear pitch are both equal to one conductor per pole in this case.

Spiral or Concentric Winding

Figure-f below illustrates this winding for the same equipment, a four pole, twelve slot, twelve conductor alternator. The coils in this winding have various pitches. The inner coil has a pitch of 1, the middle coil has a pitch of 3, and the outside coil has a pitch of 5.

Alternator's Poly Phase Armature Winding

For better comprehension, let's go over a few words connected to poly phase armature winding of alternator first.

Group Coil

It is the result of a spinning machine's number of phases and poles.

Coil group equals the product of the number of poles and phases.

Integrated Winding

The winding is referred to as balanced winding if there are an equal number of coils of various phases beneath each pole face. Coil group should be an even number in a balanced winding.

Incorrect Winding

Unbalanced winding is a winding where the number of coils per coil group is not a full number. In this scenario, the number of coils on each pole face varies by phase and is uneven. Two single-phase windings are positioned on the armature of a two-phase alternator at a distance of 90 electrical degrees from one another.

Three single-phase windings are positioned on the armature of a three-phase alternator at an electrical angle of 60 degrees from one another.A Skelton two-slot per pole, two-phase, four-pole winding is shown in the diagram below. 180/2 divided by 90 equals the electrical phase difference between neighbouring slots.

The beginning points of the first and second phase windings of a two-phase alternator are points a and b. The two-phase alternator's first and second phase winning points are a' and b', respectively. A Skelton three-slot per pole, three-phase, four-pole winding is shown in the diagram below. The neighbouring slots' electrical phase difference is 180/3 = 60 degrees (electrical) Red, Yellow, and Blue phases of the three-phase winding have beginning positions a, b, and c, respectively, and concluding points a', b, and c' (Figure 12.6).

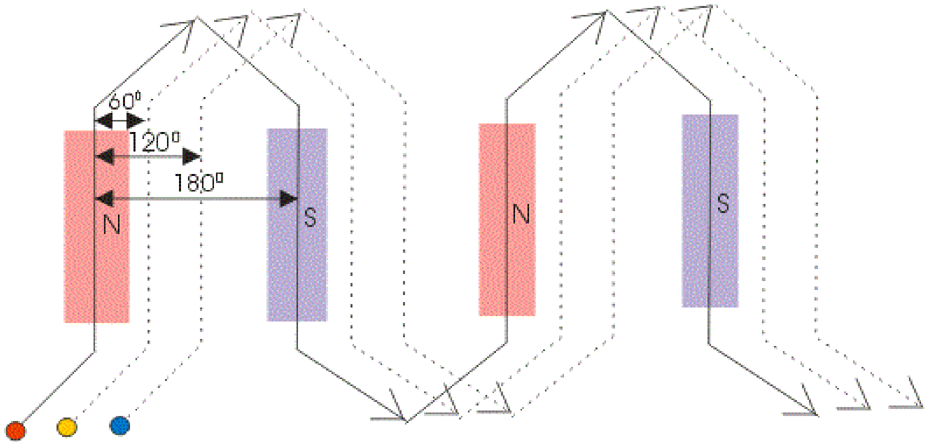


Figure 12.6Concentrated Armature Winding

A red phase winding can begin at slot number one and conclude at slot number ten. Then, the yellow or second winding begins in slot number two and concludes in slot number eleven. The third or blue phase winding begins at slot number three and concludes at slot number twelve. Red phase and yellow phase, yellow phase and blue phase, and blue phase and red phase windings, respectively, have generated emf phase differences of 60 degrees, 60 degrees, and 240 degrees (electrical respectively). Since the phase difference between the red, yellow, and blue phases of a three-phase system is 120 degrees (electrical). By revering the yellow phase (second winding) winding as seen in the above image, this may be accomplished.

The diagram below shows a distributed winding with 4 poles, 24 slots, a single layer, and three phases. Slots per pole and phase, number. The phase difference between emfs induced in the conductors, of two adjacent slots is

Hence,

Slots No: 1, 2, 7, 8, 13, 14, 19, and 20 for R phase
Slots No: 5, 6, 11, 12, 17, 18, 23 and 24 for Y phase

3, 4, 9, 10, 15, 16, 21, and 22 slots for the B phase

Three phase full pitched two layer lap winding is seen in the image below. Each winding is 120 electrical degrees apart from the two windings next to it. There are 12 slots per pole and phase in this winding. The pitch of each depends on the fact that the winding is a fully tuned coil. With 12 slots, the coil. Given that one pole has 180 electrical space degrees, the slots are spaced at a pitch of 180/12, or 15°.

We reduce the coil span in a fractional pitch winding to fewer than 180 electrical space degrees. In the illustration above, a coil's pitch has been changed from 12 slots to 10 slots such that its spread is no longer equal to the pole pitch.The coil span comes in two varieties. The first is a complete pitched coil, which has two sides that are 180 degrees apart electrically. When a coil is fully pitched, one side will be under the N pole, while the other side will be under the S pole. The 180-degree difference between the induced emfs on the coil's two opposing sides (electrical). As a consequence, the coil's emf is just the arithmetic sum of these two emfs.

The second is a short-pitched coil, in which the electrical angle between two opposing sides of a coil is less than 180 degrees. The phase difference between the emf of the two coil sides in this instance is likewise less than 180 degrees (electrical). As a consequence, the resulting emf of the coil is the vector sum of two emfs rather than just the basic arithmetic addition of the two emfs.

As a consequence, the resulting emf of a coil with a short pitch is always lower than that of a coil with a full pitch. But even so, we should utilise short-pitch coils wherever possible since they remove harmonics from waveforms.

Slot Winding with Integral and Fractional Slots

When there are an even number of slots per pole per phase, the winding is called an integer slot winding; however, when there are an odd number of slots per pole per phase, the winding is called a fractional slot winding.

Only with a double-layered winding is fractional slot winding practical. Because phase groups under multiple poles must be linked in series before a unit is generated and broadening respects the pattern to provide the second unit that may be joined in parallel with the first, it restricts the number of parallel circuits that are possible.

Synchronous Motor:

A straightforward Equivalent Circuit of Synchronous Motor may be created by assuming the linearity of the magnetic circuit. Given that air-gap is the machine's magnetic circuits predominate component, this assertion is supported.

The synchronous reactance accounts for both the leakage flux and the flux generated by the passage of balanced 3-phase currents in the stator. The flux created by the rotor field is accounted for by the excitation emf, Ef (dc excited). The dc field current (If), also known as the excitation current, may regulate the excitation emf's magnitude. If the machine's load is altered, Ef, the machine's open-circuit voltage, manifests at the machine's terminals. Ef is also known as voltage behind synchronous impedance or reactance with reference to Fig. 8.10(c) (as Ra can be neglected).It is important to keep in mind that the synchronous impedance model of the synchronous machine is only applicable to cylindrical-rotor machines, is based on the linearity assumption, and will hold for the unsaturated zone of machine operation.

Synchronous Impedance Range:

The synchronous reactance of synchronous machines has a limited range of values as expressed in the pu system. According to empirical data, the armature resistance (Ra) is typically in the range of 0.01 pu, which means that at the rated armature current, the voltage drop in the armature resistance is equivalent to 1% of the rated voltage. The synchronous reactance (Xs = Xar + Xl) is in the order of 1.0 to 2 pu, whereas the leakage reactance value varies from 0.1 to 0.2 pu. Consequently, it is clear that the armature resistance of a synchronous machine is so low that it may be disregarded for all practical reasons other than when computing losses, temperature increase, and efficiency. It should be noted that Ra must be minimal to reduce the I2R loss and keep the machine's temperature from rising, and Xs must be big to cap the amount of current that may flow in a fault (short-circuit) scenario. However, due to the availability of quick-acting circuit breakers to separate a machine from the faulty line, it is currently standard practise to design Equivalent Circuit of Synchronous Motor with a middle range of values for synchronous reactance.

Here, we'll go through the simplest method for creating a phasor diagram for a synchronous motor as well as some of its benefits. Let's write the numerous notations for each quantity in one location before drawing the phasor diagram. Here, Ef will stand in for the excitation voltage and Vt for the terminal voltage.

Ia stands for the armature current, for the angle between the terminal voltage and the current, for the angle between the excitation voltage and the current, for the angle between the excitation voltage and the terminal voltage, and for the angle between the excitation voltage and the armature per phase resistance.In order to create the phasor diagram for the synchronous motor, we will use Vt as the reference phasor. Two crucial things that are listed below need be understood in order to construct the phasor diagram:

We are aware that if a machine is designed to function as an asynchronous motor, the armature current will flow in a phase opposite to the excitation emf.The phasor terminal voltage is always behind the phasor excitation emf.

Drawing a phasor diagram for a synchronous motor just requires the aforementioned two points. Below is the synchronous motor's phasor diagram (Figure 12.7).

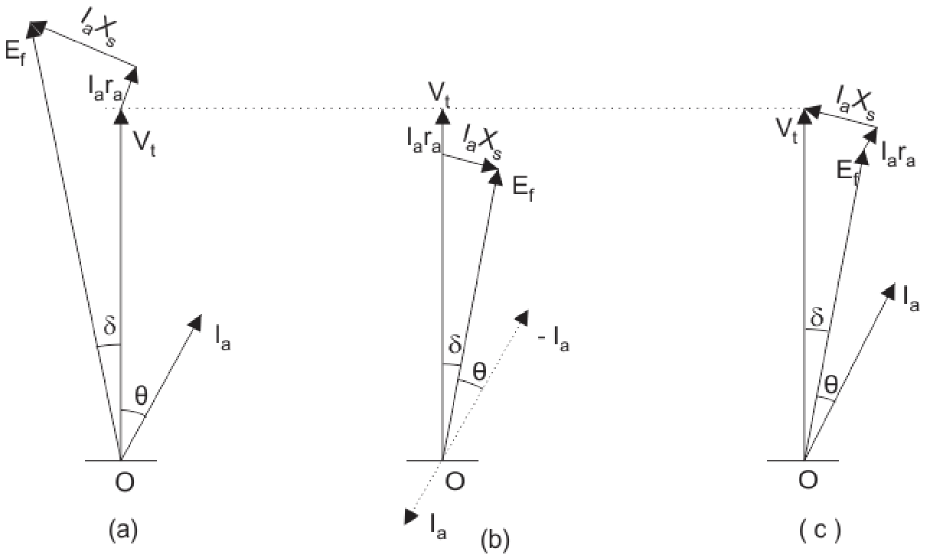


Figure 12.7phasor diagram for a synchronous motor

The direction of the armature current in the phasor one is in phase opposition to that of the excitation emf.In the phasor of the synchronous motor, it is normal to omit the negative sign of the armature current; hence, in the phasor two, we have done the same. For the synchronous motor, we will now create a full phasor diagram and also derive an equation for the excitation emf in each scenario. Below are three examples that we have (Figure 12.8):

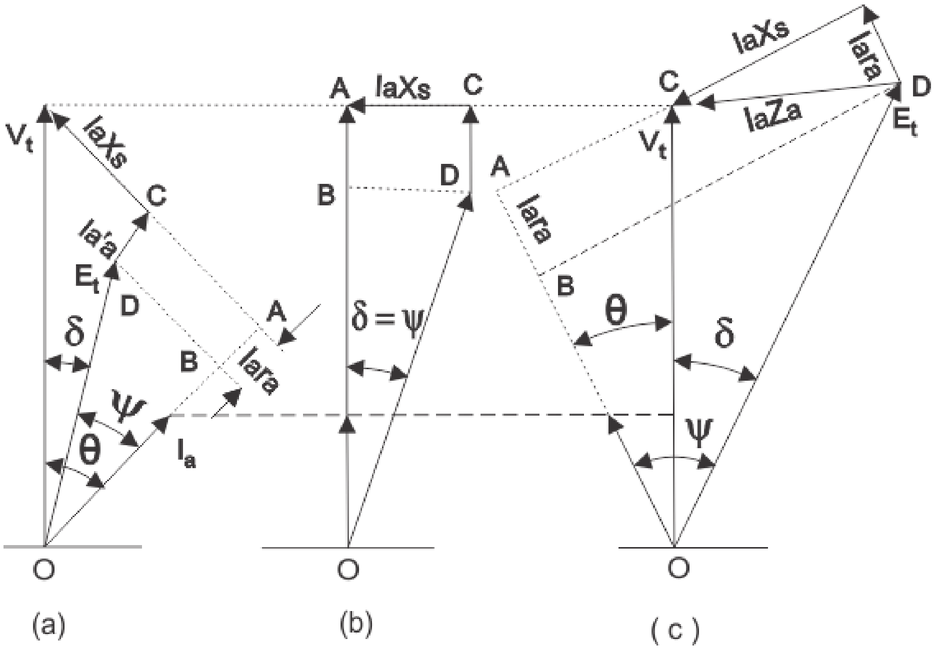


Figure 12.8 full phasor diagram for a synchronous motor

(A) The operating of a motor with a low power factor.

(b) Motor running with a power factor of 1.

(c) Running the motor at the highest power factor.

The phasor diagrams for each operation are shown below.

(a) Operation of motors with trailing power factor: We start by taking the component of the terminal voltage in the direction of armature current Ia in order to get the formula for the excitation emf for the lagging operation. Vtcos is a component that moves in the armature current direction.

Because the armature's direction is opposite that of the terminal voltage, the voltage drop will be in the negative direction (-Iara), and as a result, the total voltage drop is (Vtcos—Iara) along the armature current. In a similar manner, we may determine the voltage drop in the direction that is orthogonal to the armature current. It turns out that the overall voltage loss is (Vtsin - IaXs). We may construct the formula for excitation emf from the triangle BOD in the first phasor diagram as

$$E_f^2 = (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta - I_a \times X_s)^2$$

(b) Motoring operation at unity power factor: Once again, we start by taking the component of the terminal voltage in the direction of armature current Ia in order to obtain the formula for the excitation emf for the unity power factor operation. However, in this case, theta has a value of 0, thus we get =.

The formula for the excitation emf may be written directly from the triangle BOD in the second phasor diagram as

$$E_f^2 = (V_t - I_a \times r_a)^2 + (I_a \times X_s)^2$$

(c) Motoring operation at leading power factor: In order to derive the expression for the excitation emf for the leading power factor operation we again first take the component of the terminal voltage in the direction of armature current I_a. Component in the direction of armature current is $V_t\cos\Theta$.

As the direction of armature is opposite to that of the terminal voltage therefore voltage drop will be ($-I_a r_a$) hence the total voltage drop is ($V_t\cos\Theta - I_a r_a$) along the armature current. Similarly we can calculate the voltage drop along the direction perpendicular to armature current. The total voltage drop comes out to be ($V_t\sin\theta + I_a X_s$). From the triangle BOD in the first phasor diagram we can write the expression for excitation emf as

$$E_f^2 = (V_t cos\theta - I_a \times r_a)^2 + (V_t sin\theta + I_a \times X_s)^2$$

Advantages of Drawing Phasor Diagrams for Synchronous Motor

(1) Phasors are highly useful for gaining physical insight into the operation of the synchronous motors**.**
(2) We can derive mathematical expressions for various quantities easily with the help of phasor diagrams.

Voltage Regulation of a Synchronous Generator

When a synchronous generator's load is lowered from its full load rated value to zero while speed and field current stay constant, the voltage at the terminals rises. It is based on the load's power factor. When the load increases, there is always a voltage drop for unity and trailing power factors, but for a certain leading power, the whole load voltage regulation is zero.

The voltage regulation is given by the equation shown below:

$$\text{Per Unit Voltage Regulation} \triangleq \frac{|E_a| - |V|}{|V|} \quad \dots\dots\dots(1)$$

$$\text{Percentage Voltage Regulation} \triangleq \frac{|E_a| - |V|}{|V|} \quad \dots\dots\dots(2)$$

Where,

- **|E$_a$|** is the magnitude of a generated voltage per phase.
- **|V|** is the magnitude of rated terminal voltage per phase.

In this instance, the terminal voltage remains constant under all load circumstances as well as no load. The voltage rises as the load increases and the regulation is negative with lower leading power factors.

Voltage Regulation Determination

The voltage regulation of smooth cylindrical rotor type alternators is determined primarily using two ways. Both the direct load test technique and the indirect methods of voltage control are given those names. The Synchronous Impedance Approach, Ampere-turn Method, and Zero Power Factor Method are other classifications for the indirect method, as mention in below figure.

Direct Load Test

The terminal voltage of the alternator is set to its rated value of V as it operates at synchronous speed. When the Ammeter and Wattmeter show the rated values at the specified power factor, the load is adjusted. The speed, field excitation, and load are all reduced or eliminated. The open circuit and no-load voltage values are noted.

Additionally, it may be determined from the % voltage regulation, as demonstrated by the equation below:

$$\%\ \text{Voltage Regulation} = \frac{E_a - V}{V} \text{ x } 100\%$$

Only tiny alternators with a power rating of less than 5 kVA may be loaded directly.

Methods of Voltage Regulation Used Indirectly

The three indirect approaches listed below are used to calculate voltage regulation for big alternators:

- The EMF technique or the synchronised impedance method.
- The MMF technique or the ampere-turn method for voltage regulation
- Potier Method or Zero Power Factor Method

This is all about controlling the synchronous generator's voltage.

An alternator linked to the electricity grid requires synchronisation to operate.

Today, we'll talk about the procedures involved in synchronising synchronous generators or synchronous motors.

There are certain procedures used to synchronise synchronous generators or motors with the grid. Several factors need to be taken into account while synchronising these synchronous motor and generator.

The following are the essential actions to take into account while synchronising such equipment.

How Synchronous Motors are synchronized

Synchronization and genuine power sharing are key components of synchronous motor functioning in parallel.

We must make sure the new generator, when compared to the system, has the attributes listed below before the breaker is closed.

- An same RMS voltage.
- the same frequency
- The same phase order
- The same immediate phase position

All essential actions may be taken using the specialised apparatus known as synchronous scope, which can also automatically shut off the breaker.

If required, we may shut the manual using the synchronous copy's manual mode. Another option for synchronisation is a straightforward 3-lamp configuration; this is ideal for a parallel standby generator.

It employs the same synchronisation principle.

How to Synchronize the Synchronous Generators (Figure 12.9)

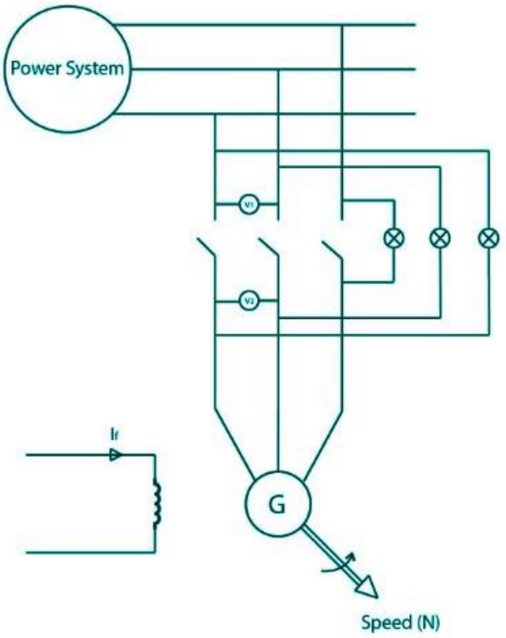


Figure 12.9 Synchronous Generators

1. Raise the generator voltage, which is a bit below the system voltage, and bring the generator speed closer to its synchronous speed.

2. The three bulbs now shown in the previous picture display a steady progression of dark, bright, dark brilliant (cycle time of dark- bright- sequence is determined by frequency difference)

3. Slowly increase the generator's speed until the "dark-bright" pattern becomes unresponsive, then increase it a bit more to start it up again very, very slowly. (Now that we know for sure, the generator frequency is only little higher than the system frequency)

4. Keep an eye on a few cycles of the "dark-bright" process, and shut off the breaker just before the lights get completely dark. (In order for the bulb to go completely black at the precise second the connections are closed.)

Syncing is possible by using the techniques mentioned above. To prevent harmful electromechanical transients, the breaker should be closed at the appropriate times.

To prevent reverse power flow immediately after this synchronisation, we should make sure that the generator frequency is slightly above the system frequency before closing the break.

Uncontrolled -dark-bright- sequencer rate may be used to identify an improper phase sequence. In such circumstances, we should turn off the generator, alter the wiring at the generator terminals, and then attempt the synchronisation procedure once again.

Synchronous Machine Power Angle Curve

Electrical output in relation to power angle is graphically represented by the synchronised machine's power angle curve. Given that power angle and load angle are synonymous terms, it can be claimed that this curve represents a graphical depiction of the generator's electrical output relative to load angle. We shall talk about the power angle curve and its significance in this post.

First of all, we should know the mathematical relation between the electrical output of synchronous machine in terms of load angle to get the graph of power versus load angle. Below is a list of the synchronous generator's electrical output.

Pe = (EfVt/Xs)Sinδ

Where Ef, Vt, Xs, and stand for the generator's terminal voltage, synchronous reactance, no-load excitation voltage, and load angle, respectively. To learn more about how the above formula of electrical output was derived, please read "Power Flow Equation via an Inductive Load".

Now, let's plot a graph between Pe and the load angle, supposing the other parameters remain constant (Figure 12.10).

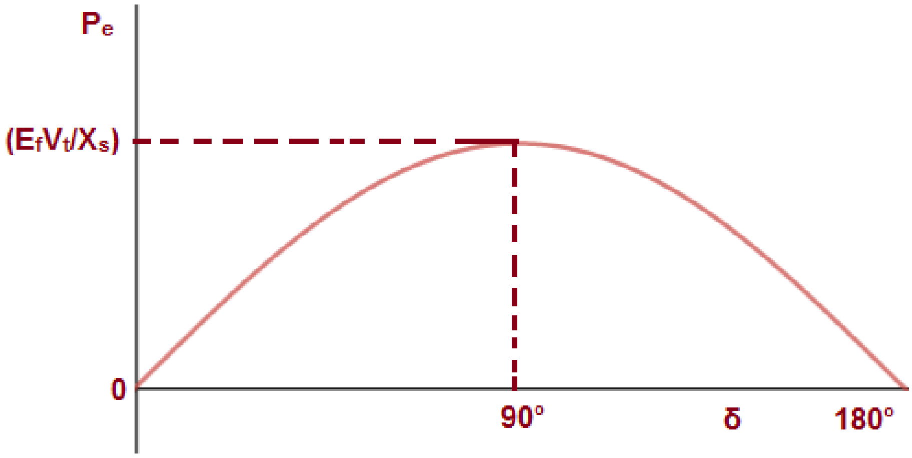


Figure 12.10 graph between Pe and the load angle

Power Angle Curve is the name of the graph that illustrates power in relation to. The aforementioned graph clearly shows that it is sinusoidal. Power angle curve is thus sinusoidal.

The value of the power angle curve

The electrical power output of a synchronous machine is shown by the power angle curve when the power angle is changed. This graph demonstrates that the output grows sinusoidally as we move from 0 to 90°. But when the power angle rises over 90°, the generator's electrical output falls. Why does this matter?

This only indicates that the electrical output of the generator is lower than the mechanical input. As a result, the machine's poles will begin to move apart, and ultimately synchronism will be lost. As a result, the generator as a machine becomes unstable. The highest amount of electricity that may pass through a certain place without losing synchronism is known as the steady state stability limit. As a result, the synchronous machine's maximum power in steady state corresponds to a load angle of 90 degrees. It will really be (EfVt/Xs).

The load angle at which a machine is working has an impact on both the steady state and transient stability limits. The transient state stability limit is essentially the highest power flow that can be achieved during a rapid disturbance without losing synchronism. By using a power angle curve and the Equal Area Criteria, the transient stability limit is established. Power angle curve is crucial for the analysis of the synchronous machine's stability limit.

Changing Field Excitation at Constant Load Has an Effect

The armature current Ia of a d.c. motor is calculated by multiplying the difference between V and Eb by the armature resistance Ra. Comparably, the voltage-phasor resultant (Er) between V and Eb is divided by the synchronous impedance Zs to get the stator current (Ia) in a synchronous motor. One of a synchronous motor's key characteristics is its ability to go from lagging to leading power factor operation by altering the field excitation. Consider a synchronous motor that drives a constant mechanical load at a set supply voltage. The power input to the motor (=3 V*Ia *cosθ) is constant since the mechanical load and speed are both constant. This implies that the supply-drawn in-phase component Ia cos will not change. Back e.m.f Eb varies if the field excitation is altered. For various levels of field excitation, this causes Ia's phase position with respect to V and the synchronous motor to vary. The power factor cos of the motor changes because the extrema of the current phasor Ia sit on the line AB. The synchronous motor's phasor diagram is shown in Fig.

(i) While excited

If the field excitation is set up such that Eb V, the motor is said to be under-excited. In such circumstances, the current Ia lags behind V, resulting in a lagging motor power factor, as seen in Fig (i). This is simply explained. Because Eb > V, the net voltage Er decreases and rotates in a clockwise direction. As the angle (= 90°) between Er and Ia is fixed, phasor Ia also rotates clockwise, which causes current Ia to trail supply voltage. As a result, the motor's power factor is trailing.

(ii) Regular excitement

In the event where Eb = V results from the field excitation, the motor is considered to be normally excited. Keep in mind that rising excitation (i.e., increasing Eb) causes the phasor Er and therefore Ia to rotate anticlockwise, meaning that Ia has gotten closer to phasor V. As a result, albeit still trailing, p.f. grows. Assuming that the input power (=3 V*Ia *cos) remains constant, the stator current Ia must drop as the p.f. rises.

Assume that the field excitation is raised until the applied voltage V and current Ia are in phase, bringing the synchronous motor's p.f. to unity. At unity p.f., the resulting Er and, therefore, Ia are minimal for a given load.

(iii) Over excitation

If the field excitation causes Eb to exceed V, the motor is considered to be overexcited. Such circumstances result in current Ia leading V and a leading motor power factor. Note that from the typical excitation position, Er and subsequently Ia turn much more anticlockwise. Ia then takes the lead over V. The synchronous motor has a trailing power factor if it is under-excited, according to the description above. The power factor rises with increasing excitation until it reaches unity at constant excitation. The current taken from the supply is at its lowest level under such circumstances. The motor power factor becomes leading if the excitation is further amplified (i.e., overexcited). Note. The armature current (Ia) is at its lowest value when the power factor is unity and rises as it deteriorates, either leading or trailing.

CHAPTER 13

Classification of Synchronous and Special Purpose Motor

M. Sashilal Singh, Associate Professor,
Department of Electrical, Jaipur National University, Jaipur, India,
Email Id- msashilal@jnujaipur.ac.in

Synchronous motors, often known as synchronous electric motors, are AC motors whose rotor (or shaft) rotation matches the frequency of the supply current. That is, the rotor's rotational period is equal to that of the spinning machine it is a part of:

For a minute, let's step back and describe what an electrical motor is.

An electro-mechanical device that transforms electrical energy into mechanical energy is an electrical motor. We have divided it into single phase and three phase motors based on the input type. Synchronous motors and induction motors are the two most popular types of three phase motors. An electrical field is created when three-phase electric conductors are arranged in certain geometrical locations (i.e., at a specific angle from one another). The synchronous speed is the rate of rotation of the rotating magnetic field.

If there is an electromagnet in this revolving magnetic field, it magnetically locks with the field and spins at the same rate as the spinning field.Because the motor's rotor rotates at the same speed as the magnetic field, this is where the phrase "synchronous motor" originates.

Because it only has one speed, synchronous speed, it is a fixed speed motor. The supply frequency and this speed are in harmony. Given by is the synchronous speed:

$$N_s = \frac{120f}{p}$$

Where:

- N= The Synchronous Speed (*in RPM – i.e. Rotations Per Minute*)
- f = The Supply Frequency (*in Hz*)
- p = The number of Poles

Construction of Synchronous Motor

With the exception of the fact that here we feed DC to the rotor for a purpose we will explain later, its design is often virtually identical to that of a three phase induction motor. Let's first go over the fundamental design of this kind of motor. It is evident from the image above how we would create a machine of this kind. We provide the stator with three phase power and the rotor with DC power.

Key Characteristics of Synchronous Motors

1. Synchronous motors can't start themselves by nature. Before they are synchronised, they need some external methods to increase their speed near to synchronous speed.

2. Because their operating speed is synchronised with the supply frequency, they operate as constant speed motors regardless of the load status.
3. This motor has the distinct ability to function regardless of electrical power factor. This enables it to be utilised for improving electrical power factor.

Synchronous motor operating system

Synchronous motors are doubly excited machines, meaning that they receive two electrical inputs. The stator winding on it is made up of a We deliver DC to the rotor winding and three-phase electricity to the three-phase stator winding.

Three-phase rotating magnetic flux is produced by a three-phase stator coil carrying three-phase currents. A steady flux is also produced by the rotor bearing the DC supply. From the relationship above, we can see that the three-phase rotating flux spins at a rate of around 3000 revolutions per minute or 50 revolutions per second when the power frequency is 50 Hz.

The rotor may experience an attracting force one moment when the stator and rotor poles are of the same polarity (N-N or S-S), and a repulsive force the next.

However, the rotor's inertia prevents it from rotating in either direction as a result of the attracting or repulsive forces, and it stays in a standstill state. Therefore, a synchronous motor cannot start on its own.

Here, we use certain mechanical ways to accelerate the rotor to speeds very near to synchronous speed by rotating it initially in the same direction as the magnetic field. After reaching synchronous speed, magnetic locking takes place, and the synchronous motor keeps spinning even when external mechanical assistance is removed.

However, the rotor's inertia prevents it from rotating in either direction as a result of the attracting or repulsive forces, and it stays in a standstill state. Therefore, a synchronous motor cannot start on its own.

Here we use some mechanical means which initially rotates the rotor in the same direction as the magnetic field to speed very close to synchronous speed. After reaching synchronous speed, magnetic locking takes place, and the synchronous motor keeps spinning even when external mechanical assistance is removed.

Starting Synchronous Motor Techniques

Using an external prime to start a motor Synchronous motors are mechanically connected to another motor, the mover. Either a DC shunt motor or a three-phase induction motor might be used. Here, initial DC excitation is not used. We then apply the DC excitation when the rotational speed approaches that of its synchronous rotation. When magnetic locking occurs after some time, the external motor's supply is shut off.

Damper winding

The extra winding is positioned on the rotor pole face of the salient pole type synchronous motor in this instance. The requisite beginning torque is generated initially while the rotor is not spinning due to the great relative speed between the damper winding and rotating air gap flux. Emf and torque both decrease as speed gets closer to synchronous speed, and eventually, when magnetic locking happens, torque also goes away entirely. Because of this, the synchronous motor in this instance initially operates as a three-phase induction motor utilising an extra winding before being synced with the frequency.

Synchronous motor applications

Synchronous motors are used for several purposes, such as:

To increase power factor, a synchronous motor without a load attached to its shaft is employed. It is employed in power systems in cases where static capacitors are costly due to its ability to behave at any electrical power factor.

Synchronous motors are used in situations when great power is needed but operating speed is low (about 500 rpm). The size, weight, and price of the appropriate three-phase induction motor are quite high for power needs between 35 kW and 2500 KW. Therefore, it is preferable to utilise these motors. Ex: rolling mills, compressors, and reciprocating pumps.

By imagining the stator windings coupled to a three-phase alternating-current source, it is possible to comprehend the basic workings of synchronous motors. The stator current has the effect of creating a magnetic field that rotates at 120 f/p rotations per minute for f hertz and for p poles. A magnetic field revolving at rotor speed will also be created by a direct current in a p-pole field winding on the rotor. These two magnetic fields will tend to align with one another if the rotor speed is set to be equal to that of the stator field and there is no load torque. The rotor slides back a few degrees in relation to the stator's revolving field when mechanical force is applied, creating torque and continuing to be dragged around by this rotating field. As the load torque is increased, the angle between the fields widens. When the rotor field trails the stator field by a 90° angle, the maximum possible torque is attained. More load torque applied to the motor will cause it to stall.

Another benefit of synchronous motors is that they can function at unity power factor because the magnetic field of the machine may be created by the direct current in the field winding, which reduces the amount of current required from the stator windings. The stator windings' heating and losses are reduced by this circumstance.

By adjusting the field current, the power factor of the stator's electrical input may be directly regulated. The stator current changes to include a component to account for this overmagnetization if the field current is raised over the level necessary to maintain the magnetic field. A total stator current that is in phase with the stator voltage will occur, giving the power system the reactive volt-amperes it needs to magnetise other devices linked to it, such transformers and induction motors. To improve the overall power factor of the electrical loads in a manufacturing facility and prevent higher electric supply rates from being assessed for low power-factor loads, a big synchronous motor may be operated at such a leading power factor.

Three-phase synchronous motors are mostly used in industrial settings where a large, generally stable mechanical load typically more than 300 kilowatts and the benefit of operating at a leading power factor are important factors. Synchronous machines often cost more than induction machines below this power level.

A shaft-mounted rectifier with a spinning transformer or generator or, in the case of bigger motors, an externally operated rectifier via slip rings may provide the field current.

A synchronous motor would not be self-starting if it just had a field winding conveying direct current. Its rotor would suffer an oscillating torque of zero average value at any speed other than synchronous speed when the spinning magnetic field continually passed the more slowly moving rotor. To increase beginning torque to the rotor, a short-circuited winding like that of an induction motor is often added. In order to protect the field winding from high induced voltage, the field winding is often short-circuited before the motor is started, either with full or decreased stator voltage, and brought up to around 95% of synchronous speed. The rotor then pulls into synchronism with the rotating field once the field current is delivered.

This extra rotor winding, which dampens oscillations that can be brought on by rapid changes in the load on the rotor while in synchronism, is sometimes referred to as a damper winding. The angle by which the rotor field lags the stator field must be changed in order to adapt to variations in load, which necessitates temporary changes in instantaneous speed. These result in the induction of currents in the damper windings, creating a torque that works to counteract the speed shift.

The protection used with big induction motors is similar to that used with synchronous motors. Both the stator and the field windings can detect temperature, which may be utilised to turn off the electricity. Due to the significant heating that occurs during beginning, timers are typically placed to prevent multiple starts within a short period of time.

Starting of Synchronous motors

Synchronous motors run at synchronous speed.

The synchronous speed of a motor depends on the supply frequency and the number of poles in the motor.

Synchronous speed is given by

$$N_s = \frac{120f}{p}$$

Where, f = supply frequency and p = number of poles.

We can change the synchronous speed of the motor by changing the supply frequency and the number of poles. But the motor would always run with this speed for a given supply frequency and the number of poles.

Synchronous motors offer many benefits, but one main drawback is that they cannot start themselves, unlike three-phase induction motors. In synchronous motors, the rotor is excited by a DC supply while the stator, which contains three phase windings, is stimulated by a three phase supply. While the DC supply produces constant flux, the three phase windings provide rotating flux.

Rather of being unidirectional, the torque generated on the rotor pulses. The above relation shows that, at a frequency of 50 Hz, the three-phase rotating flux spins at a rate of around 3000 revolutions per minute, or 50 revolutions per second. The rotor may experience an attracting force at one point when the stator and rotor poles are of the same polarity (N-N or S-S), and a repulsive force at another point when they are N-S. However, because of the rotor's inertia, it cannot spin in either direction owing to an attracted or repelling force and instead remains in a standstill state. The motor cannot start on its own as a result. External methods must be used to accelerate the synchronous motor's rotor to synchronous speed.

The methods utilised to start a synchronous motor are listed below:

Starting of a Synchronous Motor Using a Motor Induction

Before turning on the synchronous motor, the rotor must be brought to synchronous speed. Because of this, we immediately connect a tiny induction motor, often known as a pony motor, to the synchronous motor. The induction motor's number of poles must be lower than that of the synchronous motor in order for it to ever reach the synchronous speed of the synchronous motor. This is due to the fact that an induction motor's speed is always lower than the synchronous speed, and that speed must be raised for the induction motor to match the synchronous speed of the synchronous motor. We turn on the DC supply to the rotor after the synchronous motor's rotor has reached synchronous speed. The induction motor is then easily disconnected from the synchronous motor shaft after that.

Using a DC Machine to Start a Synchronous Motor

There is a little variation between it and the procedure above. The synchronous motor is linked to a DC machine. Initially operating like a DC motor, the DC machine speeds up the synchronous motor. The DC machine functions as a DC generator after it reaches synchronous speed and feeds DC to the synchronous motor's rotor. Compared to the former strategy, this one provides simple beginning and more effectiveness.

Using the Damper Windings to Start a Synchronous Motor

With this technique, the motor begins as an induction motor initially and transitions to a synchronous motor once it reaches synchronous speed. Damper windings are used for this. Additional windings called damper windings are made of copper bars and are inserted into the slots on the pole faces.

The copper bars' ends have been short-circuited. These windings have an induction motor's rotor behaviour. The motor begins operating as an induction motor at a speed below synchronous speed when three-phase electricity is applied to it. The rotor receives a DC supply after a period of time. After a brief period of time, the motor is brought into synchronism and begins to function as a synchronous motor. The damper windings have no influence on the motor's operation after it achieves synchronous speed since there is no longer any induced emf there. This method is the one that synchronous motors are started using the most often.

Starting a Synchronous Motor at Step 23 Slip Ring Induction Motor Use

Here, one external rheostat is connected in series with the rotor. Initial starting of the motor occurs as a slip ring induction motor. As the motor speeds up, the resistance progressively disappears. The rotor is given DC stimulation once it reaches almost synchronous speed, at which point it is brought into synchronism. After then, it begins to rotate like a synchronous motor.

When studying three phase synchronous motor operations, the word "hunting" is used. The term "hunting" is employed because the rotor must look for or "hunt" for its new equilibrium position after the abrupt application of stress. Hunting in a synchronous motor is the term used to describe such behaviour. Let's now learn what the synchronous motor's equilibrium condition is.

The electromagnetic torque must be equal to and in opposition to the load torque for a synchronous motor to operate in a steady state. In a steady state, the torque angle () is maintained by the rotor running at synchronous speed. The equilibrium is upset by a quick change in load torque, which produces a torque that alters the motor's speed.

Hunting

A synchronous machine with no load has a zero load angle. The load angle will progressively rise as shaft load rises. Let's assume that load P1 is abruptly introduced to the unloaded machine shaft, causing the machine to briefly slow down. Additionally, the load angle rises from 0 to 1 degrees.

Electrical power generated on the initial swing is equivalent to mechanical load P1. Since equilibrium is not reached, the rotor swings even further. The load angle surpasses 1 and changes to 2. The amount of electricity produced right now is more than it was before. Rotor speeds up to synchronisation. However, it does not remain at synchronous speed and will keep growing beyond synchronous speed. The load angle falls as a consequence of rotor acceleration above synchronous speed.

Therefore, no balance is achieved once again. Rotor swings or oscillates as a result around the new equilibrium point. Hunting or phase swinging are two names for this behaviour. Hunting happens when the load is suddenly changed in synchronous generators as well as synchronous motors.

Causes of Synchronous Motor Hunting

1. An abrupt shift in load.
2. An abrupt shift in the field current.
3. A load that produces harmonic torque
4. A supply system flaw.

Hunting's effects on synchronised motor

A. Loss of synchronism might result.
B. Subjects the rotor shaft to mechanical stresses.
C. Causes temperature to rise and increases machine losses.
D. Increase current and power flow spikes.
E. It raises the likelihood of resonance.

Hunting in Synchronous Motors is reduced

Hunting should be minimised using two strategies. These include

Use of Damper Winding: It consists of low electrical resistance copper / aluminum brush embedded in slots of pole faces in salient pole machine. By creating torque in the opposite direction of rotor slip, the damper winding dampens out hunting. The slip speed is inversely correlated with the damping torque's magnitude.

Use of Flywheels: A large, weighty flywheel is supplied for the primary mover. This raises the primary mover's inertia and aids in keeping the rotor speed constant.

Creating synchronous machines with appropriate power coefficients for synchronisation.

Synchronous motor damper winding

Pole-shoe slots on synchronous motors are designed to hold copper bars. The copper bars are inserted into these slots and massive copper rings are used as short-circuits at both ends (like squirrel cage rotor of induction motors). This configuration is referred to as a synchronous motor's damper winding.

Role of Damper Winding in Synchronous Motor

The *damper winding in synchronous motor* performs two functions:

1. Provides starting torque and
2. Prevents hunting in the synchronous motor

When the rotor is rotating at synchronous speed, then the relative velocity between the RMF (rotating magnetic field of the stator) and the rotor is zero. Hence induced EMF in the damper winding is zero.

Thus, under normal running conditions, damper winding in synchronous machine does not carry any current (Figure 13.1).

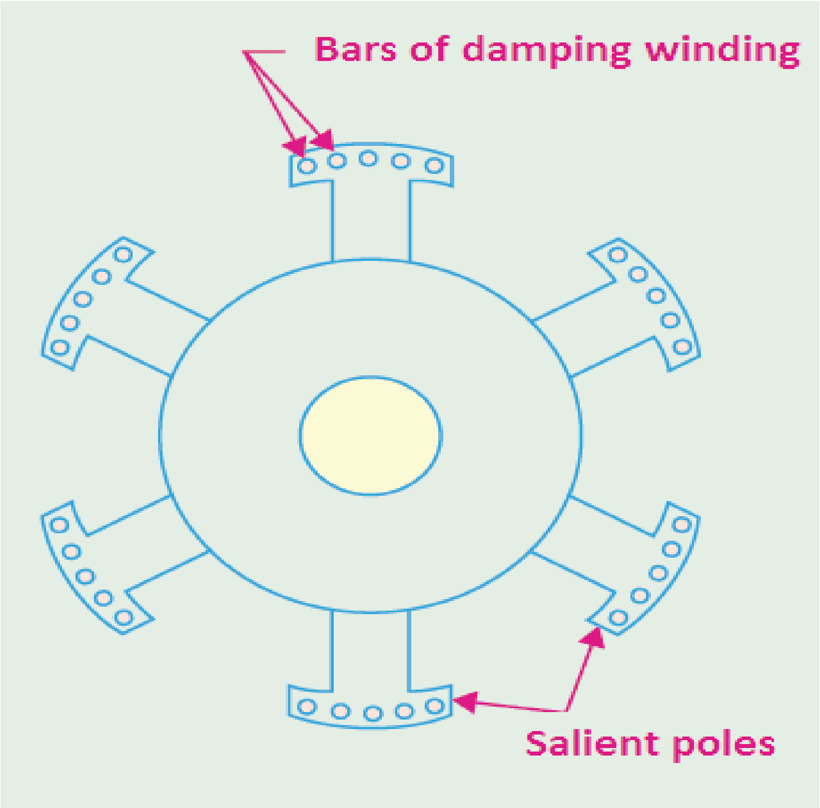


Figure 13.1 damper winding in synchronous machine

Hunting in Synchronous Motor

Magnetic locking causes the stator and rotor poles of a synchronous motor to operate at the same synchronous speed. However, the two poles' centerlines do not meet at the same point. By a little angle, the rotor slides back behind the stator poles. The load angle or torque angle is the name given to this angle. The development of motor torque depends on the rotor shifting rearward.

The rearward shift of the rotor poles grows by a higher angle as the load on the motor rises, yet the rotor poles continue to operate synchronously. The load that the motor is carrying determines the load angle's value. The stator current is likewise governed by this load angle. The value of will increase, while the value of the stator armature current will decrease. The motor requires greater input power to handle the additional load, which is why this is the case. A synchronous motor will halt if too much load is applied to it because the rotor will be pushed out of synchronism (Figure 13.2).

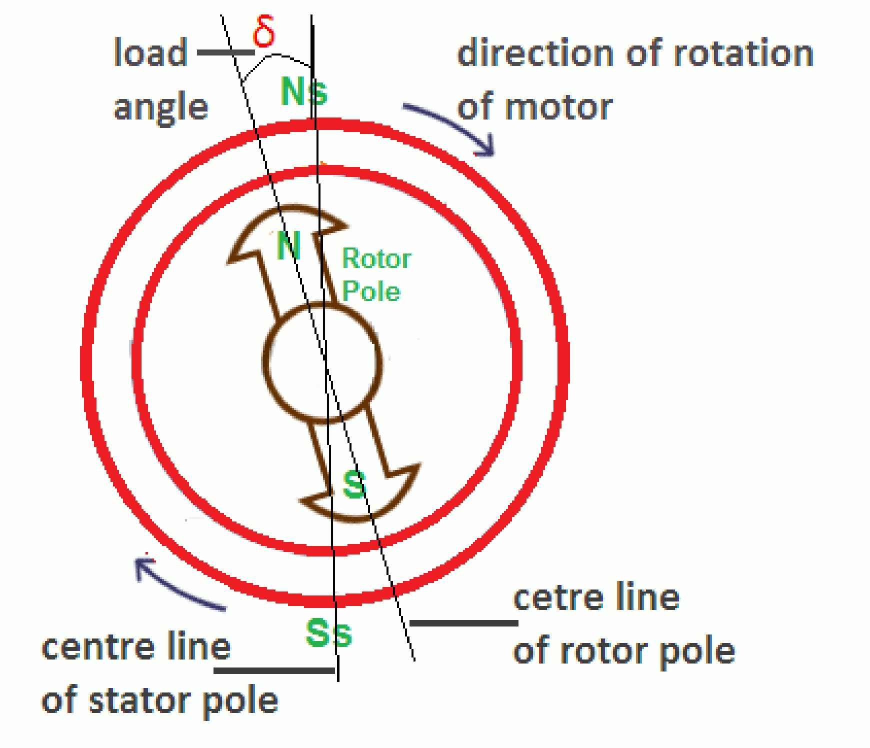


Figure 13.2 Hunting in Synchronous Motor

The rotor moves to a new position smoothly as the load on the motor is progressively raised. However, if the motor load is abruptly altered, the rotor will not be able to smoothly adjust to its new position in relation to the new value of. The rotor must first spend some time circling about its proper location due to inertia before it finally settles into place. In synchronous motors, it is referred to as hunting.

Because of hunting, the value of is always changing.

When changes, the back EMF Eb also changes, causing the armature current Ia to fluctuate constantly. The other appliances connected to the same AC line may have issues as a result of this continually fluctuating armature current.

If the load changes often, inertia will cause the rotor to swing around in its new location.

The rotor swings' amplitude rises and the motor may get out of sync if the oscillations' frequency matches the motor's natural frequency.

Hunting relies heavily on the synchronous motor's damper winding. The relative motion between RMF and the rotor is no longer zero when it oscillates. As a result, an EMF is generated in the damper winding proportionate to relative motion. The direction of this produced EMF will attempt to counteract its origin (Lenz's law). In this case, hunting-related relative motion is the reason. As a result, hunting decreases fast as a result of damper winding.

"Setting time" refers to how long it takes the rotor to return to equilibrium after searching. It ought to be as brief as possible. In synchronous motors, the application of damper winding drastically lowers settling time.

Synchronous generator's damper winding

A synchronous generator is similarly susceptible to the hunting. Hunting oscillations are created in the rotor in this instance as well owing to an abrupt shift in the electrical output or mechanical input. This may be avoided by including damper winding in the synchronous generator.

Special Purpose Motors

Stepper Motors

Although stepper motors are a form of brushless DC motor, they share many characteristics with synchronous motors, permanent magnet motors, and synchronous motors. The details of each may be found in our pages on brushless DC motors, synchronous motors, and permanent magnet motors, however be aware that the term "brushless" just refers to the absence of the brushes and commutators present in other common DC motors. They consist of a stator and a rotor, and the stator includes distinct, uniformly spaced windings of conductor wire that are referred to as poles. These poles will draw the magnetic rotor and move it in distinct fractions of revolutions, or "steps," when the stator windings are powered. In other words, the rotor rotates precisely and equitably by moving from one magnetic pole to the next. Stepper motors are a desirable example of a "open feedback" design since this also implies that the precise location of the rotor is known at all times and does not need adjustment, or "closed feedback". A stepper motor is a form of DC synchronous motor because the rotation of the output shaft is also exactly proportional to the frequency of the input current.

The Function of Stepper Motors

In essence, stepper motors are permanent magnet DC motors, meaning that their rotor is made of magnets with positioned north-south poles that resemble the teeth of gear wheels. A unique set of poles, constructed of wire windings around protrusions within the housing, is used by the stator. The windings of the stator are stimulated by DC current to produce magnetic fields, and they do this "in phase" by only energising certain pole pairs at any one moment. The rotor is magnetically drawn from one stator pole to the next in succession as a result of these stator pole groups being turned on and off by pulsating DC current (generating the distinct phases), resulting in discrete, stepwise rotation.

As a result of their discontinuous rotational output, it is necessary to regulate the input power in some manner in order to accurately activate and de-energize the stator pole groups. This is done by employing stepper controllers, also known as drives, which are ICs or prebuilt circuits that power the poles in various configurations to provide discrete motions of a given magnitude. Although there are more variations, these drives typically come in four basic categories: wave drives, full step drives, half step drives, and microstepping drives. These are all distinct pulse-patterns that alternately excite the stator's poles, altering the rotor's motion. The graphs in below figureshow the pulses passing through each drive, and the greyscale bars underneath them indicate the discrete locations of the rotor as it is drawn to the magnetic fields created by these pulses.

Stepper motors may imitate continuous rotation while maintaining accuracy by adding additional poles to the rotor and stator or by employing a microstepping drive. This is due to the small angle of rotational difference between each discrete step, which approximates continuity. These motors are vitally necessary for accurate positioning technology, which requires halting and maintaining rotation at precise angles, although not being entirely continuous.

Specifications for stepper motors

The specifications listed below aid designers in selecting the best stepper motor for their project. Due to the fact that stepper motors often serve quite distinct functions from induction motors and other related subtypes, their parameters vary from those used to choose them.

Holding Torque maximum

When the motor is energised but not spinning, the maximum holding torque is the highest torque. This is helpful in situations where it is necessary to maintain constant angular locations while the motor shaft is under external torque.

Rotor Momentum

The rotor inertia determines how "simple" or "difficult" it is to start or stop the rotor. It is used to determine the acceleration torque, or how quickly the torque varies as the engine approaches its rated speed.

A current rating

The amount of current that constantly enters the stator windings when the motor is at rest is known as the rated current. It is generated from the increase in motor temperature during rest.

Error in Angular Transmission and Basic Step Angle

The rotor's fundamental step angle is the number of degrees it travels from one input pulse. In theory, it describes each "step" in the motor. A more accurate measure of the discrepancy between the fundamental step angle and the actual output shaft angle is the angular transmission error. The amount of "wiggle" the output shaft suffers while it is stationary, or backlash, may be to blame for this.

Maximum and Permissible Torque

Unsurprisingly, the permitted torque is the maximum torque that may be applied to the motor. The motor will be harmed if any torque valueduring startup, acceleration, steady-state, and deceleration exceeds this parameter. The maximum torque is the highest torque value attained, often for a brief period of time and while the engine is starting up or slowing down.

Allowed speed range

The stepper motor may operate within this speed range while rotating the output shaft. For the greatest outcomes and to avoid motor problems, the motor should always run within this range.

Applications and Requirements

These motors do tasks that many other electric motors are unable to due to their accuracy and open feedback architecture. Although they aren't the best option for high speed or continuous output activities, they have great repeatable movement with non-cumulative error, are reversible, dependable, simple to build, and can function at a variety of speeds. Stepper motors' main significant drawback is that they must be electronically regulated, and any disruption in the electronics will have an immediate impact on output quality. They are also less efficient than conventional DC motors, and because of the way their poles alternate continually, they are often uncontrolled at high speeds. These motors are available in a wide range of sizes, forms, and ratings, making them suitable for different applications. Small-wattage models are ideal for robots, hard drives, computer control systems, electric watch drives, printers, and medical equipment. Military equipment, machine tools, scientific exploration equipment, and other items benefit from the large-wattage sizes.Stepper motors are a wonderful general purpose option because of how easy they are to useboth in terms of design and operationand how widely available they are. A stepper motor could merely work unless a project requires really high input currents, speeds, or power. As usual, determine the appropriate requirements and desired output qualities before using what you've learned here to determine if a stepper motor is the appropriate tool for the task.

Universal Motor

The term "Universal Motor" refers to motors that may be utilised with both a single-phase AC source and a DC source of supply and voltages. A different name for it is Single Phase Series Motor. A commutation-type motor is a universal motor. A DC series motor will keep spinning in the same direction even if the polarity of its line terminals is switched.The polarity of the field and the flow of current through the armature both influence the direction. Because of the relationship between torque, flux, and armature current. Let's connect the DC series motor to a single-phase AC supply. Because the armature and field windings both get the same current. The field flux polarity and the direction of the current through the armature will be affected by the AC reversal from positive to negative or vice versa.The rotation will continue to rotate in the same direction as previously, and the created torque will continue to be in a positive direction. According to the waveform below, the torque will have a pulsing character and a frequency that is double that of line frequency. A universal motor may thus operate on both AC and DC. But if it uses a single-phase AC supply, a series motor that is primarily built for DC operation has the following problems:

Hysteresis and eddy current losses cause the efficiency to decrease.

There is excessive sparking at the brushes, which contributes to the poor power factor caused by the high reactance of the field and the armature windings.

A DC series motor is modified in a specific way so that it can operate on AC current in order to get beyond the problems mentioned above and the ones that follow. These are what they are:

The field core is constructed of a low hysteresis loss material. In order to minimise eddy current loss, it is laminated.

To lower the flux density, the field poles' surface area is raised. Iron loss and reactive voltage drop are thereby decreased.

The armature's conductor count is raised to provide the needed torque.

To lessen the impact of the armature response and enhance the commutation process, a compensatory winding is utilised. As shown in the following diagram, the winding is inserted into the stator slots.

The series motor with the compensated winding is shown in the Figure 12.3 below:

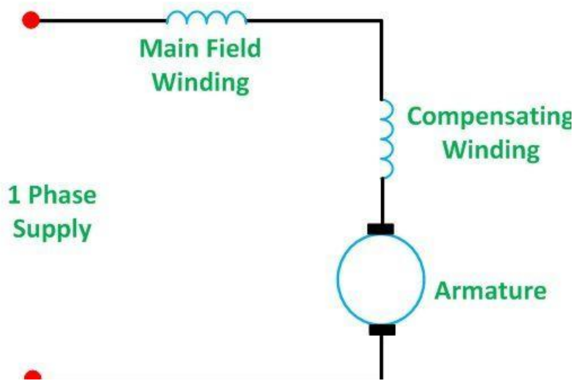


Figure 12.3 series motor with the compensated winding

The stator slot is filled with the winding. The primary field axis and the compensatory winding's axis are at a 90 degree angle. The compensating winding is connected in series with both the armature and the field, hence, it is called conductively compensated.

The motor is described as being inductively compensated if the compensating winding is short-circuited. Below is a connecting Figure 12.4:

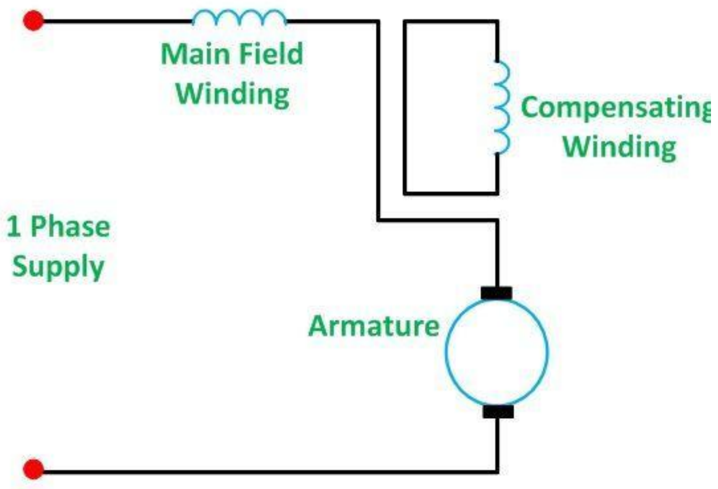


Figure 12.4 compensating winding

The series motor's construction is the same as that of the universal motor. High resistance brushes with larger brush areas are utilised to lessen the commutation issue. The stator core and yoke are laminated in order to minimise Eddy current losses. The universal motor is less complicated and expensive. It is often used for ratings up to 750 W.The Universal motor's characteristics are comparable to those of the DC series motor. The series motor produces less torque when powered by an AC source. The direction of rotation may be changed by switching the connections between the fields and the armature.

Solid-state electronics are used to get the universal motors' speed under control. This motor works well in situations that call for high speeds. Since these motors may run at up to 20,000 rpm and their speed is not limited by the frequency of the power source,

Uses for universal motors

The Universal motor is utilised in applications where high speeds and speed control are required. The following are some of the uses for the universal motor:

Portable drills are used in table fans, grinders, and hair dryers.

Blowers, polishers, and kitchen appliances all employ universal motors.

Shaded Pole Induction Motor

A self-starting single-phase induction motor with one of its poles shaded by a copper ring is what is meant by a "shaded pole induction motor." The shaded ring is another name for the copper ring. This copper ring serves as the motor's secondary winding. The shaded pole motor can only spin in one way; it cannot move in the other direction.

The power losses in the shaded pole induction motor are quite significant, and the motor's power factor is poor. The induction motor's starting torque is likewise very low. The motor is inefficient for the reasons listed below. As a result, they maintain compact designs, and the motor has modest power ratings.

Shaded Pole Induction Motor Construction

Two or four poles may be included in the shaded pole motor. For the purpose of simplicity, we employ a two-pole motor in this post. The ratio of the motor's pole count to its speed is inversely proportional.

Stator - The shaded pole motor's stator has a salient pole. The salient pole denotes that the magnet's poles are directed toward the motor's armature. The stimulating coil of the motor excites each of its poles. The loops are shaded by the copper rings. The shading coil is the term for the loops.

The motor's poles are laminated. Lamination describes the process of creating the poles from numerous layers of material. so that the pole's strength improves.

A distance between the slot's construction and the poles' edge. This hole is used to insert the shorted-circuit copper coil. The portion that a copper ring covers is referred to as the shaded portion, while the portion that is not covered by the rings is referred to as the unshaded portion.

Rotor: The squirrel cage rotor is used in shaded pole motors. The rotor's bars are skewed at a 60o angle. To have a better beginning torque, the skew may be performed.

The lack of a commutator, brushes, collector rings, etc., makes the motor's construction very simple. The induction motor with shaded poles lacks a centrifugal switch. Therefore, there is a lower likelihood of the motor failing.

The electrical switch known as a centrifugal switch begins to function by using the centrifugal force produced by the revolving shaft. Additionally, it is used to regulate the shaft's speed.

Working Shaded Pole Induction Motor

The rotor's core experiences an alternating flux when the supply is linked to the windings. Due to its short circuit, the little section of the flux link connected to the motor's shaded coil. The circulating current is brought about by the flux fluctuation, which also causes a change in the ring's internal voltage.

The circulating current creates a flux in the ring that is opposed to the motor's primary flux. The flux induced in the motor's shaded and unshaded regions, respectively, a and b, have a different phase. The spatial displacement of the main motor flux and the shaded ring flux is also 90°.

Below is a hookup schematic for a shaded pole motor (Figure 12.5):

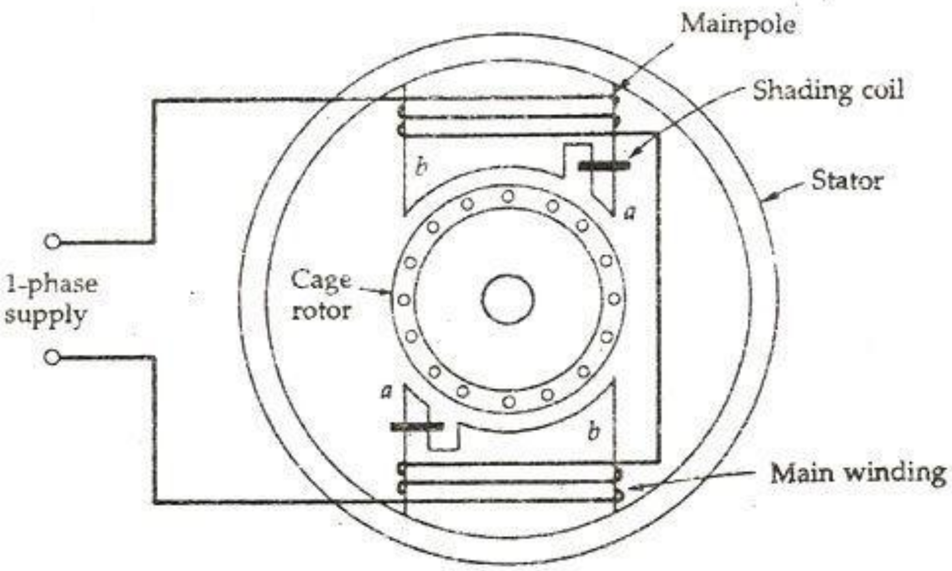


Figure 12.5 shaded pole motor

The rotating magnetic field induces in the coil due to the time and space displacement between the two fluxes. The motor's starting torque is produced by the revolving magnetic field. The field rotates from the motor's shaded area to its unlit area.

Shaded pole induction motor applications

The following are some of the shaded poles motor's many uses:

Due to their inexpensive price and simplicity of beginning, they are appropriate for tiny devices like relays and fans.

Record players, tape recorders, projectors, photocopiers, hairdryers, table fans, electronic clocks, single-phase synchronous timing motors, air conditioning and refrigeration equipment all of which need fans as well as hairdryers.

This kind of motor is used to power equipment with a minimal beginning torque requirement.

Questions for Practice

1. What is a Transformer?
2. What do you understand by the rating of a transformer?
3. How is the rated capacity of a transformer expressed and why?
4. What is the power factor of a transformer?
5. What are the essential parts of a transformer?
6. What is the name of the winding from which the supply is taken for load connecting?
7. What material is used for the cores of a transformer and why
8. Why Transformer Rate In kVA, Not in KW?
9. Why Motor rated in kW instead of kVA?
10. Why AC (Air-condition) rating in Ton, not kW or kVA?
11. Why Alternator rated in kVA, not in kW?
12. Why Battery rated in Ah and not in VA?
13. Why Power Plant Capacity Rated in MW and not in MVA?
14. Why we can’t store AC in Batteries instead of DC?
15. Why Earth Pin is thicker and Longer in a 3-Pin Plug?
16. What are the Colored Aerial Marker Balls on Power Lines For?
17. What is the condition for maximum torque in induction motor?
18. Slip ring induction motor advantages and disadvantages compared to squirrel cage motors?
19. Methods to control speed of Wound Rotor Motors?
20. Explain how Torque-Slip Characteristics vary when adding resistance to rotor circuit?
21. What happen when Induction motor run at synchronous speed?
22. What are different types of Induction Motors available?

Reference Book for Further Reading

1. B. L.Theraja, A.K. Theraja, Textbook of Electrical Technology Volume I –, S. Chand & Co.
2. E. Fitzgerald, Arvin Grabel, David E. Higginbotham, Textbook of Basic Electrical Engineering –TMH Publishing Co.
3. A. Patel, Textbook of Elements of Electrical Engineering, Mahajan Publishing House, Ahmedabad.
4. Nagrath, Basic Electrical Engineering, TMH Publishing Co. Ltd.
5. Vincent Del Toro, Textbook of Principles of Electrical Engg., Prentice Hall of India Pvt. Ltd., New Delhi.
6. S. Samaddar, Textbook of Electric Wiring, New Central Book Agency (P) Ltd., Calcutta.
7. Surjit Singh, Textbook of Electrical Design Estimating and Costing, Dhanpat Rai & Sons.
8. Robert Boylestad, Louis Mashlsky, Electronics Devices and Circuit theory, Peerson
9. Morris Mano, Digital logic and computer Design, PHI
10. Standard Handbook for Electrical Engineers by Surya Santoso
11. American Electricians Handbook by Terrell Croft, Frederic Hartwell
12. Practical Electrical Engineering by Sergey Makarov and Reinhold Ludwig
13. Offshore Electrical Engineering Manual by Geoff Macangus-Gerrard
14. Basic Electricity by Dover Books
15. Electrical Engineering 101 by Darren Ashby
16. Modern Control Systems by Richard C. Dorf and Robert Bishop
17. Power Systems Analysis and Design by J. Duncan Glover
