LECTURE NOTES
ON
ELECTRICAL TECHNOLOGY

B.Tech ECE

II YEAR I SEMESTER

(JNTUA-R15)

Mr . B NANDAKUMAR

ASSISTANT PROFESSOR
9703111084

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

MOTHER THERESA INSTITUTE OF ENGINEERING AND TECHNOLOGY

MELUMOI, PALAMANER, CHITTOOR (A.P) - 517408

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR

II B.Tech I-Sem (E.C.E)	T	Tu	C
	3	1	3

(15A02306) ELECTRICAL TECHNOLOGY

Objective:

Electrical Technology contains Single phase transformers, Induction motors, DC generators and motors which are widely used in industry are covered and their performance aspects will be studied.

UNIT- I DC GENERATORS

D.C. Generators – Principle of Operation – Constructional Features – E. M.F Equation–Numerical Problems – Methods of Excitation – Separately Excited and Self Excited Generators – Build-Up of E.M.F - Critical Field Resistance and Critical Speed - Load Characteristics of Shunt, Series and Compound Generators- Applications

UNIT – II D.C. MOTORS

D.C Motors – Principle of Operation – Back E.M.F. –Torque Equation – Characteristics and Application of Shunt, Series and Compound Motors-Speed Control of D.C. Motors: Armature Voltage and Field Flux Control Methods. Three Point Starter-Losses – Constant & Variable Losses – Calculation of Efficiency - Swinburne’s Test.

UNIT-III SINGLE PHASE TRANSFORMERS

Single Phase Transformers - Constructional Details- Emf Equation - Operation on No Load and on Load - Phasor Diagrams-Equivalent Circuit - Losses and Efficiency-Regulation-OC and SC Tests – Sumpner’s Test - Predetermination of Efficiency and Regulation.

UNIT-IV 3-PHASE INDUCTION MOTORS

Polyphase Induction Motors-Construction Details of Cage and Wound Rotor Machines- -Principle of Operation – Slip- Rotor Emf and Rotor Frequency - Torque Equation- Torque Slip Characteristics.

UNIT – V SYNCHRONOUS MACHINES

Principle And Constructional Features of Salient Pole and Round Rotor Machines – E.M.F Equation- Voltage Regulation by Synchronous Impedance Method- Theory of Operation of Synchronous Motor.

OUTCOME:

After going through this course the student gets a thorough knowledge on DC Motors & Generators, Transformers and Induction motors with which he/she can able to apply the above conceptual things to real-world problems and applications.

TEXT BOOKS:

1. Electric Machines –by I.J.Nagrath & D.P.Kothari,Tata Mc Graw Hill, 7th Edition.2005
2. Basic Electrical Engineering –By T.K.Nagasarkar and M.S. Sukhija Oxford University Press.

REFERENCE BOOKS:

1. Electrical and Electronic Technology, Hughes, Pearson Education.
2. Electrical Machines, P. S. Bimbhra, Khanna Publishers, 2011.
3. Basic Electrical Engineering, 2nd Edition, V.N. Mittle and Aravind Mittal, Mc Graw hill Education, 2006.

UNIT-I

DC GENERATORS

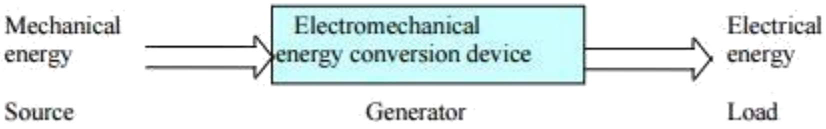
Generators

There are two types of generators, one is ac generator and other is dc generator. Whatever may be the types of generators, it always converts mechanical power to electrical power. An ac generator produces alternating power.

A DC generator produces direct power. Both of these generators produce electrical power, based on same fundamental principle of Faraday's law of electromagnetic induction. According to these law, when an conductor moves in a magnetic field it cuts magnetic lines force, due to which an emf is induced in the conductor. The magnitude of this induced emf depends upon the rate of change of flux (magnetic line force) linkage with the conductor. This emf will cause an current to flow if the conductor circuit is closed. Hence the most basic two essential parts of a generator are

1. a magnetic field
2. conductors which move inside that magnetic field.

The Input is mechanical energy (from the prime mover), and the output is electrical energy.



Constructional Features

A DC generator has the following parts

1. Yoke
2. Pole of generator
3. Field winding
4. Armature of DC generator
5. Brushes of generator
6. Bearing

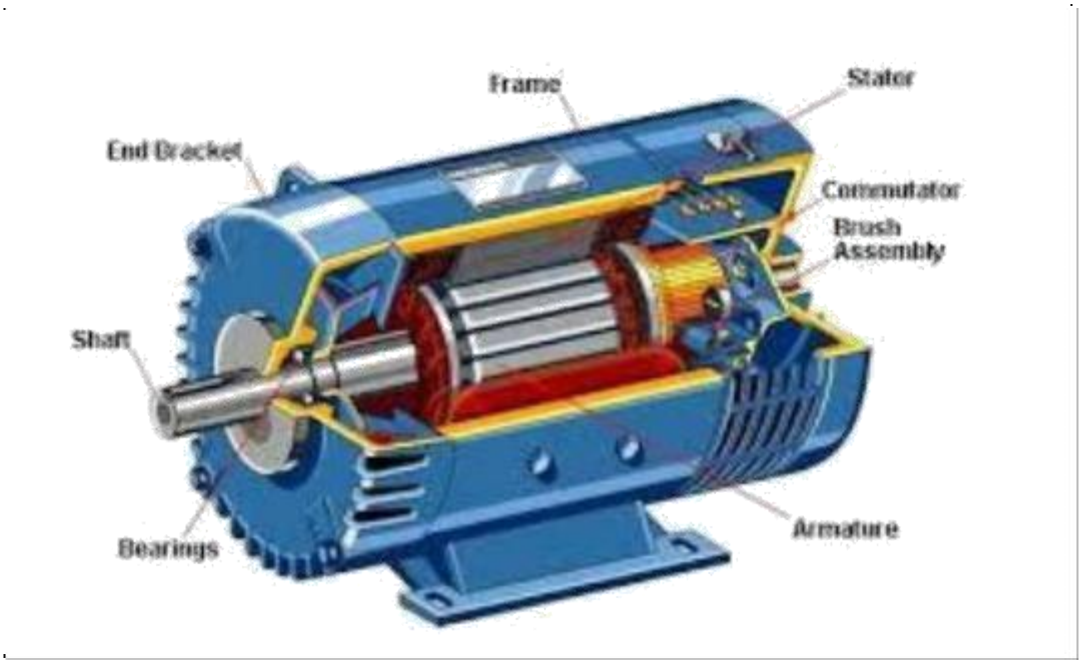


Fig. A Cut Away View Of Practical DC Generator

Yoke of DC Generator

Yoke of DC generator serves two purposes,

1. It holds the magnetic pole cores of the generator and acts as cover of the generator.
2. It carries the magnetic field flux.

In small generator, yoke are made of cast iron. Cast iron is cheaper in cost but heavier than steel. But for large construction of DC generator, where weight of the machine is concerned, lighter cast steel or rolled steel is preferable for constructing yoke of DC generator. Normally larger yokes are formed by rounding a rectangular steel slab and the edges are welded together at the bottom. Then feet, terminal box and hangers are welded to the outer periphery of the yoke frame.

Armature Core of DC Generator

The purpose of armature core is to hold the armature winding and provide low reluctance path for the flux through the armature from N pole to S pole. Although a DC generator provides direct current but induced current in the armature is alternating in nature. That is why, cylindrical or drum shaped armature core is build up of circular laminated sheet. In every circular lamination, slots are either die - cut or punched on the outer periphery and the key way is located on the inner periphery as shown. Air ducts are also punched of cut on each lamination for circulation of air through the core for providing better cooling.

Armature Winding of DC Generator

Armature winding are generally formed wound. These are first wound in the form of flat rectangular coils and are then pulled into their proper shape in a coil puller. Various conductors of the coils are insulated from each other. The conductors are placed in the armature slots, which are lined with tough insulating material. This slot insulation is folded over above the armature conductors placed in it and secured in place by special hard wooden or fiber wedges.

Commutator of DC Generator

The commutator plays a vital role in dc generator. It collects current from armature and sends it to the load as direct current. It actually takes alternating current from armature and converts it to direct current and then send it to external load. It is cylindrical structured and is build up of wedge - shaped segments of high conductivity, hard drawn or drop forged copper. Each segment is insulated from the shaft by means of insulated commutator segment shown below. Each commutator segment is connected with corresponding armature conductor through segment riser or lug.

Brushes of DC Generator

The brushes are made of carbon. These are rectangular block shaped. The only function of these carbon brushes of DC generator is to collect current from commutator segments. The brushes are housed in the rectangular box shaped brush holder. As shown in figure, the brush face is placed on the commutator segment with attached to the brush holder.

Bearing of DC Generator

For small machine, ball bearing is used and for heavy duty dc generator, roller bearing is used.
The bearing must always be lubricated properly for smooth operation and long life of generator.

Emf equation for dc generator

The derivation of EMF equation for DC generator has two parts:

1. Induced EMF of one conductor
2. Induced EMF of the generator

Derivation for Induced EMF of One Armature Conductor

For one revolution of the conductor,

Let,

Φ = Flux produced by each pole in weber (Wb) and P
= number of poles in the DC generator. therefore,
Total flux produced by all the poles = ø*p
And,
Time taken to complete one revolution = 60/N
Where,
N = speed of the armature conductor in rpm.

Now,according to Faraday's law of induction, the induced emf of the armature conductor is denoted by "e" which is equal to rate of cutting the flux.

Therefore,

$$e = \frac{d\phi}{dt} \ \ and\ e = \frac{total\ flux}{time\ take}$$

Induced emf of one conductor is

$$e = \frac{\phi P}{\frac{60}{N}} = \phi P\,\frac{N}{60}$$

Derivation for Induced EMF for DC Generator

Let us suppose there are Z total numbers of conductor in a generator, and arranged in such a manner that all parallel paths are always in series. Here,

Z = total numbers of conductor
A = number of parallel paths
Then,
Z/A = number of conductors connected in series
We know that induced emf in each path is same across the
line Therefore,
Induced emf of DC generator
E = emf of one conductor × number of conductor connected in series.

Induced emf of DC generator is

$$e = \phi P \frac{N}{60} X \frac{Z}{A}\, volts$$

Simple wave wound generator

Numbers of parallel paths are only 2 = A

Therefore,

Induced emf for wave type of winding generator is

$$\frac{\phi PN}{60} X \frac{Z}{2} = \frac{\phi ZPN}{120}\, volts$$

Simple lap-wound generator

Here, number of parallel paths is equal to number of conductors in one path i.e. P = A

Therefore,

Induced emf for lap-wound generator is

$$E_g = \frac{\phi ZN}{60} X \frac{P}{A}\, volt$$

Methods Of Excitation

An electric generator or electric motor consists of a rotor spinning in a magnetic field. The magnetic field may be produced by permanent magnets or by field coils. In the case of a machine with field coils, a current must flow in the coils to generate the field, otherwise no power is transferred to or from the rotor. The process of generating a magnetic field by means of an electric current is called ***excitation***.

For a machine using field coils, which is most large generators, the field current must be supplied, otherwise the generator will be useless. Thus it is important to have a reliable supply. Although the output of a generator can be used once it starts up, it is also critical to be able to start the generators reliably. In any case, it is important to be able to control the field since this will maintain the system voltage.

Types of excitation

(1)seperately excited generator.

(2)self excited generator.

self generator is classified into 3 types.

1.shunt generator.

2.series generator.

3.compound generator.

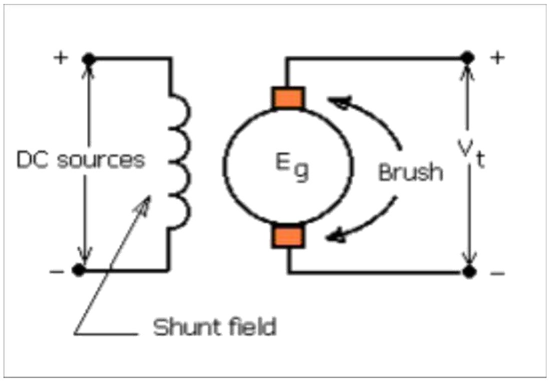
compoud generator is again classified into 2 types.

1.short shunt generator.

2.long shunt generator.

Separately excited generators.

These kind of generators has provided field exciter terminals which are external DC voltage source is supplies to produce separately magnetic field winding (shunt field) for magnetize of the generator as illustrated in figure as below.



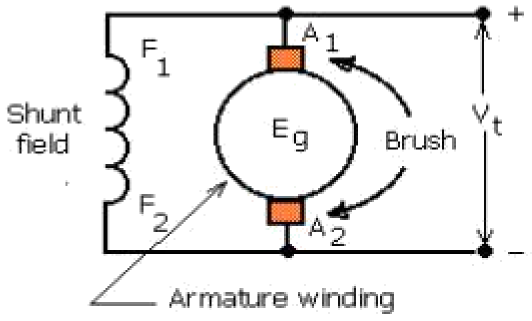
Separately excited generators.

Self excited field generators.

This type of generator has produced a magnetic field by itself without DC sources from an external. The electromotive force that produced by generator at armature winding is supply to a field winding (shunt field) instead of DC source from outside of the generator. Therefore, field winding is necessary connected to the armature winding. They may be further classified as

a) Shunt generator.

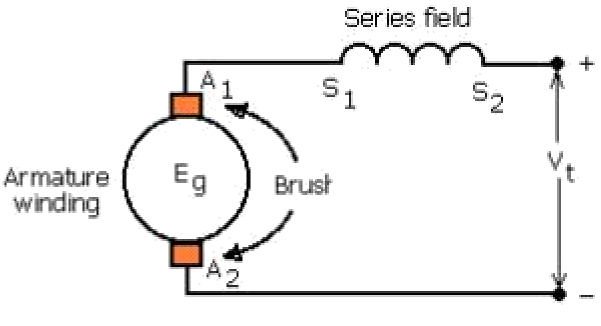
This generator, shunt field winding and armature winding are connected in parallel through commutator and carbon brush as illustrated in the figure below.



Shunt generator

b) Series generator

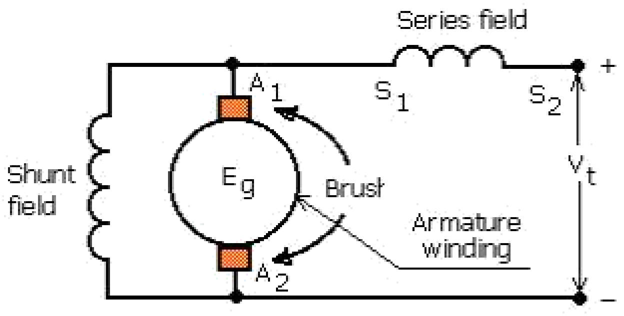
The field winding and armature winding is connected in series. There is different from shunt motor due to field winding is directly connected to the electric applications (load). Therefore, field winding conductor must be sized enough to carry the load current consumption and the basic circuit as illustrated below.



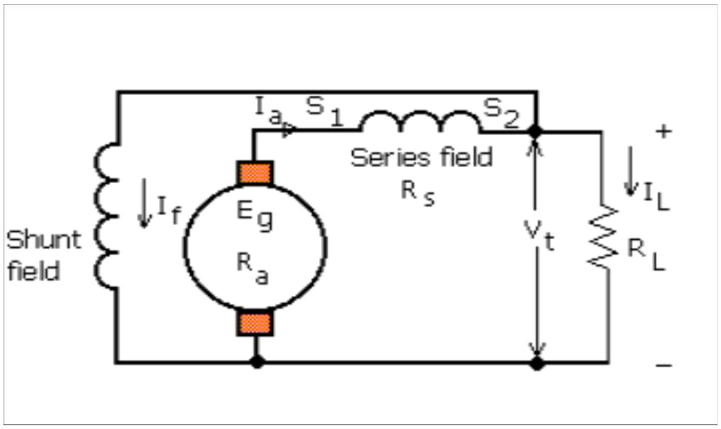
Series generator

c) Compound generator

The compound generator has provided with magnetic field in combine with excitation of shunt and series field winding, the shunt field has many turns of fine wire and caries of a small current, while the series field winding provided with a few turns of heavy wire since it is in series with an armature winding and caries the load current. There are two kinds of compound generator as illustrated in figure 5 and 6.



A short-shunt compound generator



A long-shunt compound generator

Characteristic of separately excited generator

The generated electromotive force (EMF) is proportional to both of a magnetic density of flux per pole and the speed of the armature rotated as expression by the relation as following.

$$Eg = \kappa \varphi n$$

Where

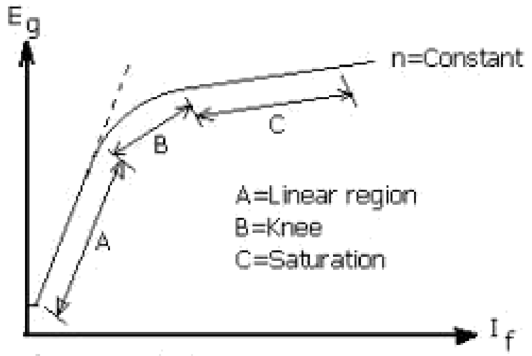
K = Constant for a specific machine

φ = The density of flux per pole

n = Speed of the armature rotation

Eg = Generator voltage

By holding the armature speed (n) at a constant value it can show that generator voltage (Eg) is directly proportional to the magnetic flux density. Which, flux density is proportionately to the amount of field current (If). The relation of field current and generate voltage as impressed by figure .



The magnetization curve on open circuit of the separately excited dc machine.

From the figure when the field current (If) is become zero a small generate voltage is produce due to a residual magnetism.

As the field current increases cause to increase generated voltage linearly up to the knee of the magnetization curve. Beyond this point by increasing the field current still further causes saturation of the magnetic structure.

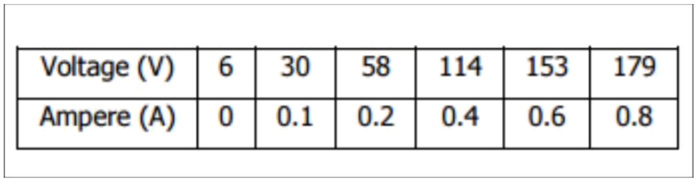
Generator voltage (Eg) is also directly to the armature speed. The formula and a magnetization curve can be both impressed about this relation.

$$E_g' = E_g \times \frac{n'}{n}$$

Where
Eg = Generator voltage or the value of EMF at speed n
Eg' = Generator voltage or the value of EMF at speed n’
n = Speed of the generator armature (n’ ≠ n)

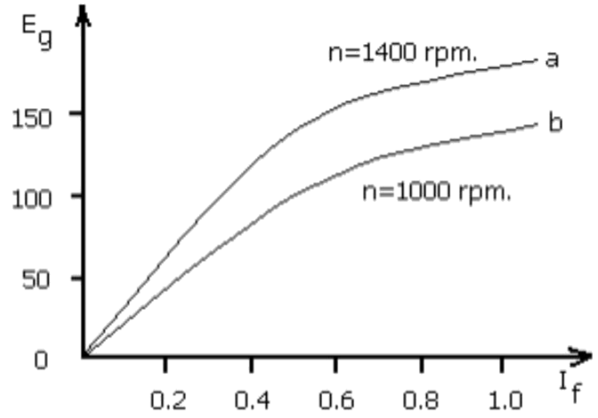
Example 1:

The open circuit terminal voltage versus the field current for a separately excited DC generator with provided the following test data at revolving speed 1400 rpm as show by the table1 below.



Voltage (V)	6	30	58	114	153	179
Ampere (A)	0	0.1	0.2	0.4	0.6	0.8

Table 1 No-load characteristic for 1400 rpm and 1000 rpm



Magnetic curve for example 3.1

Solution

Curve (a) in figure 8 shows the characteristic at revolving speed 1400 rpm obtained by the data as show in table 1. To obtain the characteristic at 1000 rpm, is made of the relation as Eg = Kφn

For instance, at a field current of 0.4 Amp the terminal voltage is 114 volts, when the speed is reached to 1400 rpm and kept its field current constant at this value, the open circuit voltage at 1000 rpm becomes.

$$E_g = 114 \times \frac{1000}{1400} = 81.40 \text{ Volts}$$

Voltage Regulation

When we add load on the generator, the terminal voltage will decrease due to

(a) The armature winding resistance is mainly of armature resistance. It is cause directly decrease in terminal voltage as following relation.

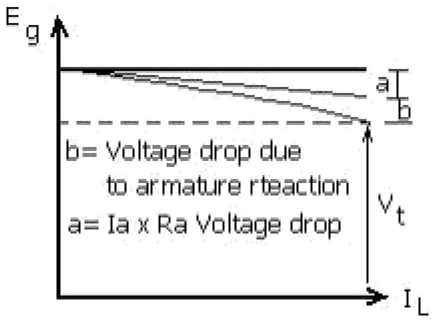
$$Vt = Eg - Ia\ Ra$$

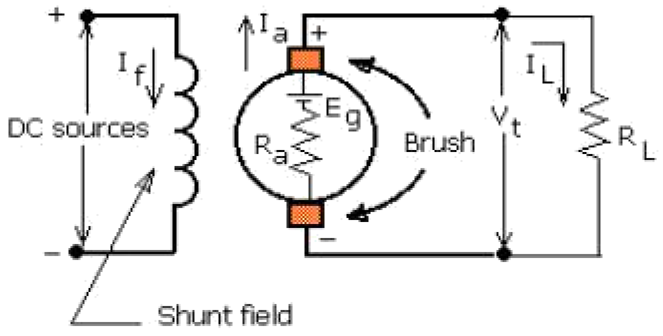
Where,

Vt = Terminal or output voltage

Ia = Armature current or load current

Ra = Armature resistance





(a) Load characteristic of a separately excited DC generator

(b) Circuit diagram

The decrease in magnetic flux due to armature reaction. The armature current establishes a magneto motive force (MMF), which it distorts to main flux, and makes result in weakened flux. We can put inter-pole between main field poles to reduce the armature reaction.

To have some measure by how much the terminal voltage change from no-load condition and on load condition, which is called “voltage regulation”.

$$\text{Voltage regulation} = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100 = \%$$

Where Vnl = No-load terminal voltage Vfl = Full-load terminal voltage

Remark:

A separately excited generator has disadvantage of requiring an external DC source. It is therefore used only where a wide range of terminal voltage required.

Example 2

The separately excited generator of example 1 is driven at revolving speed 1000 rpm and the field current is adjusted to 0.6 Amp. If the armature circuit resistance is 0.28 ohm, plot the output voltage as the load current is varied from 0 to 60 Amp. Neglect armature reaction effects. If the full-load current is 60 Amp, what is the voltage regulation?

Solution

From example 1, Eg = 153 volts when the field current is 0.6 Amp, which is the open circuit terminal voltage. When the generator is loaded, the terminal voltage is decreased by internal voltage drop,

namely.

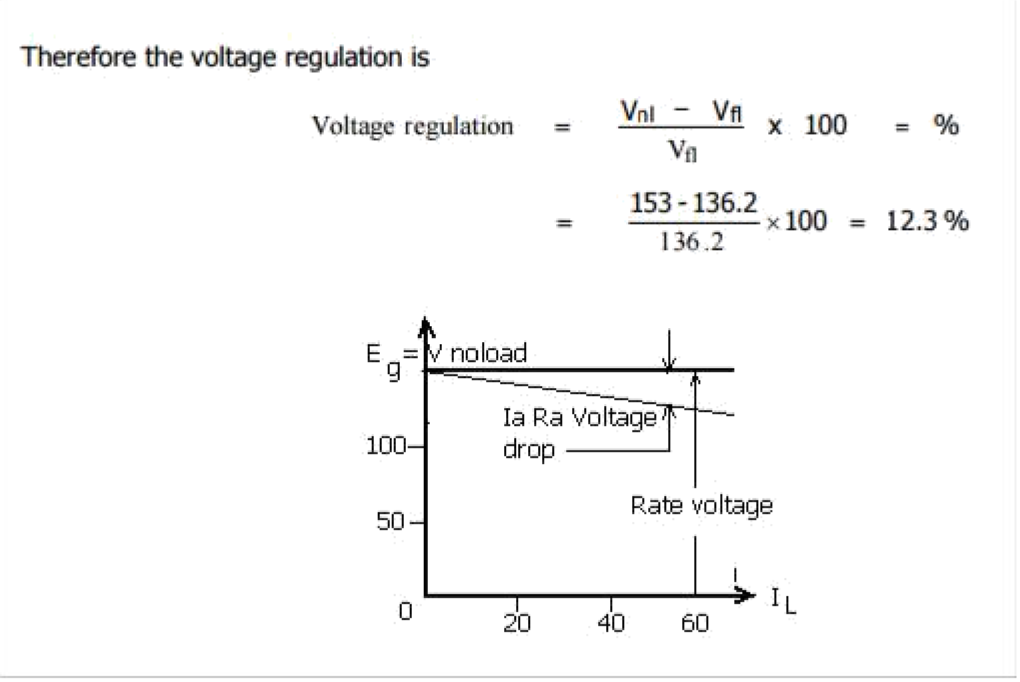
$$Vt = Eg - Ia\ Ra$$

For a load current of, say 40 Amp.

$$V_t = 153 - (40 \times 0.28) = 141.80 \text{ Volts.}$$

This calculation is for a number of load currents and the external characteristic can be plotted as show in fig. 10 at full load the terminal voltage.

$$V_t = 153 - (60 \times 0.28) = 136.20 \text{ Volts.}$$



Therefore the voltage regulation is

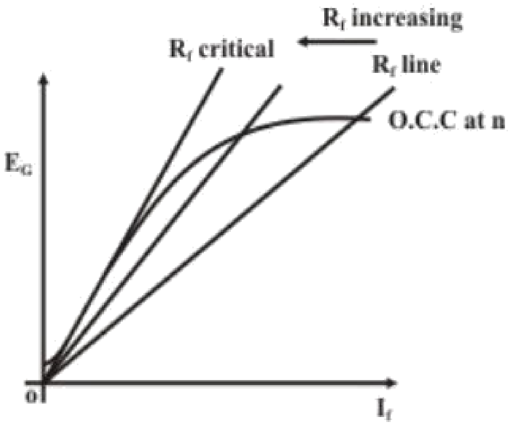
$$\text{Voltage regulation} = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100 = \%$$

$$= \frac{153 - 136.2}{136.2} \times 100 = 12.3\,\%$$

Calculated load characteristic of an example 3.2

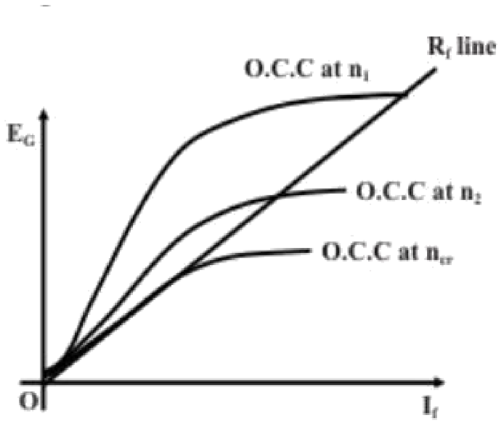
Critical Field Resistance And Critical Speed

The **critical field resistance** is the maximum field circuit resistance for a given speed with which the shunt generator would excite. The shunt generator will build up voltage only if field circuit resistance is less than critical field resistance. It is a tangent to the open circuit characteristics of the generator at a given speed.



Critical resistance

Suppose a shunt generator has built up voltage at a certain speed. Now if the speed of the prime mover is reduced without changing Rf, the developed voltage will be less as because the O.C.C at lower speed will come down (refer to figure). If speed is further reduced to a certain critical speed (ncr), the present field resistance line will become tangential to the O.C.C at ncr. For any speed below ncr, no voltage built up is possible in a shunt generator.

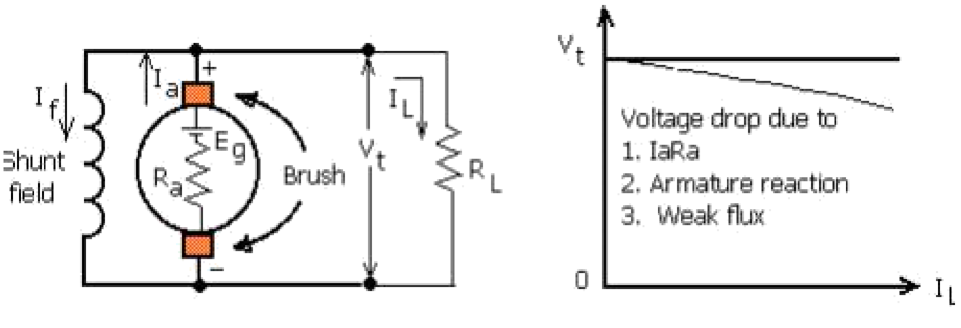


Critical Speed

Load characteristics

Self excited DC shunt generator

A shunt generator has its shunt field winding connected in parallel with the armature so that the machine provides it own excitation. For voltage to build up, there must be some residual magnetism in the field poles. There will be a small voltage (Er) generated.



(a) Shunt generator circuit (b) load characteristic of shunt generator

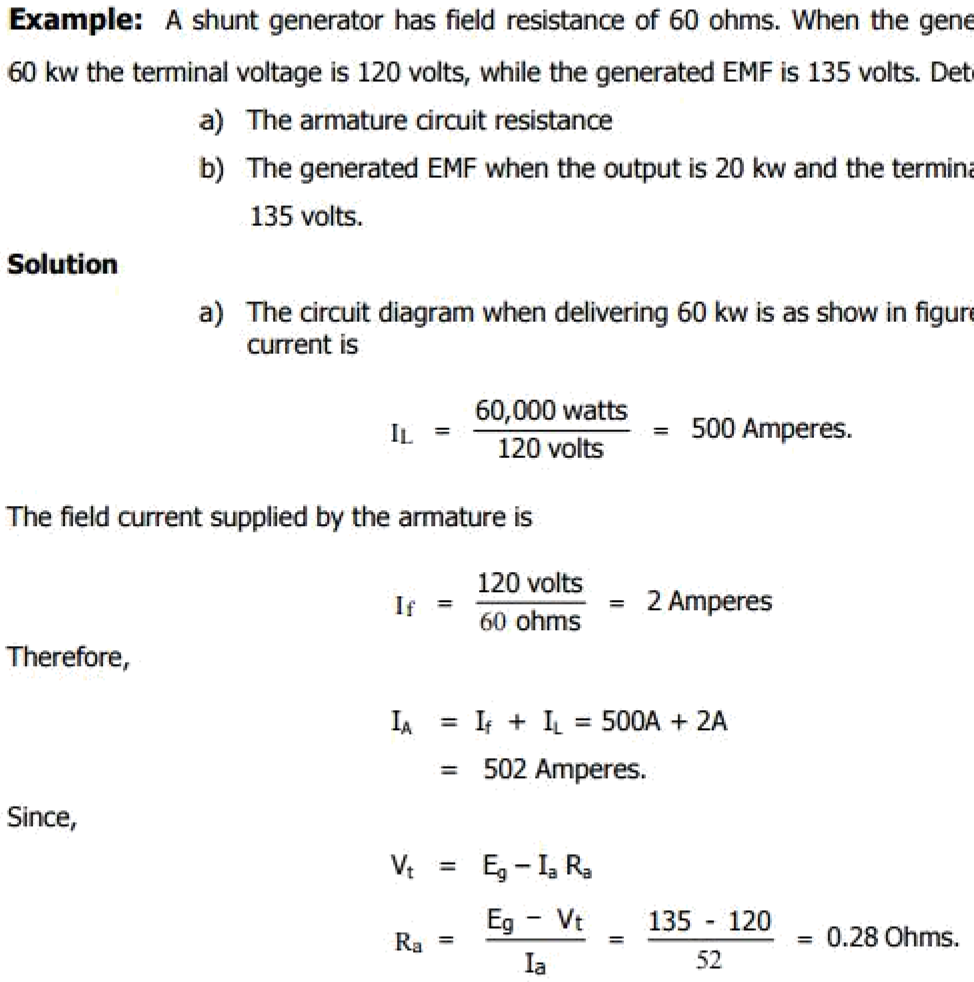
If the connection of the field and armature winding are such that the weak main pole flux aids to the residual flux, the induced voltage will become larger. Thus more voltage applied to the main field pole and cause to the terminal voltage increase rapidly to a large value.

When we add load on the generator, the terminal voltage will decrease due to.

a) The armature winding resistance

b) The armature reaction

c) The weakened flux due to the connection of the generator to aids or oppose to the residual flux.



Example: A shunt generator has field resistance of 60 ohms. When the generator delivers 60 kw the terminal voltage is 120 volts, while the generated EMF is 135 volts. Determine

a) The armature circuit resistance
b) The generated EMF when the output is 20 kw and the terminal voltage is 135 volts.

Solution

a) The circuit diagram when delivering 60 kw is as show in figure 11 the load current is

$$I_L = \frac{60{,}000 \text{ watts}}{120 \text{ volts}} = 500 \text{ Amperes.}$$

The field current supplied by the armature is

$$I_f = \frac{120 \text{ volts}}{60 \text{ ohms}} = 2 \text{ Amperes}$$

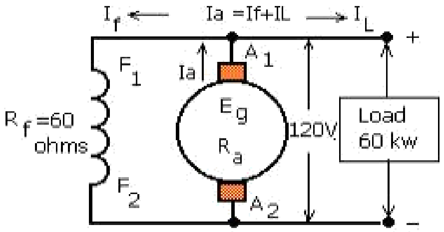
Therefore,

$$I_A = I_f + I_L = 500A + 2A$$
$$= 502 \text{ Amperes.}$$

Since,

$$V_t = E_g - I_a R_a$$

$$R_a = \frac{E_g - V_t}{I_a} = \frac{135 - 120}{52} = 0.28 \text{ Ohms.}$$



Circuit diagram for the solution of example 3

b) For a load of 20 kw when the terminal voltage is 135 volts, therefore the load current

$$I_L = \frac{20{,}000 \text{ watts}}{135 \text{ volts}} = 148.1 \text{ Amperes.}$$

And the field current is

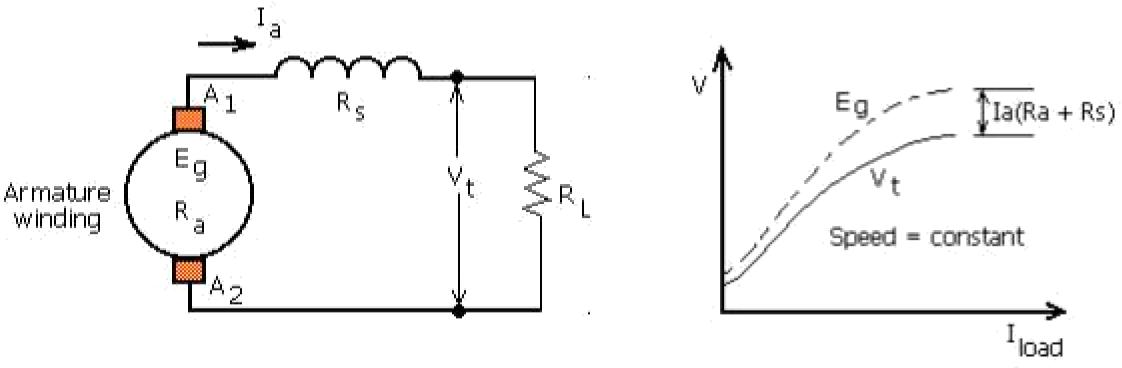
$$I_f = \frac{135 \text{ volts}}{60 \text{ ohms}} = 2.25 \text{ Amperes}$$

$$I_a = 148 + 2.25 = 150.25 \text{ Amperes}$$

$$\begin{aligned} E_g &= V_t + I_a R_a \\ &= 135 + (150.25 \times 0.28) \\ &= 177.07 \text{ volts} \end{aligned}$$

Series Generator

The field winding of a series generator is connect in series with the armature winding. Since it carries the load current, the series field winding consists of only a few turns of thick wire. At no-load, the generator voltage is small due to residual field flux only. When a load is added, the flux increase, and so does the generated voltage.



(a) Circuit diagram of series generator (b) load characteristics

Figure shows the load characteristic of a series generator driven at a certain speed. The dash line indicated the generated EMF of the same machine with the armature opencircuited and the field separated excited. The different between the two curves is simply the voltage drop (IR) in the series field and armature winding.

$$V_t = Eg - Ia\,Ra + Rf$$

Where

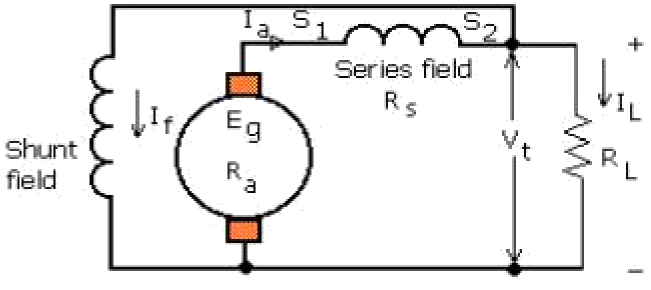
Rf = The series field winding resistance

Ra = The armature winding resistance

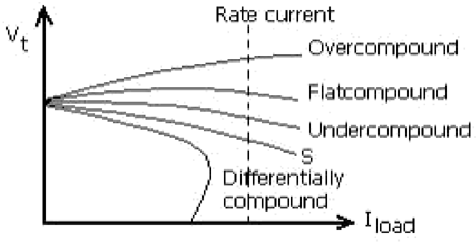
The series generators are obviously not suited for applications requiring good voltage regulation. Therefore, they have been used very little and only in special applications for example, as voltage booster. The generator is placed in series with a supply line. When the current consumption is increase, the generated voltage of the series machine goes up because the magnetic field current is increases.

Compound generator

The compound generator has both a shunt and a series winding. The series field winding usually wound on the top of a shunt field. The two winding are usually connected such that their ampere-turns act in the same direction. As such the generator is said to be cumulatively compound.



Simple circuit for compound generator



Terminal voltage characteristic of compound generator

(a) Curve s is represent the terminal voltage characteristic of shunt field winding alone. Under-compound, this condition the addition of series field winding too short it is cause the terminal voltage no rise to certain value and reduce while increasing in load current.

(b) Flat compound by increasing the number of a series field turns. It is cause to rise up in terminal voltage and when no-load and full load condition a terminal voltage is made nearly same value or equal.

(c) Over-compound, if the number of series field turns is more than necessary to compensated of the reduce voltage. In this case while a full load condition a terminal voltage is higher than a no-load voltage. Therefore over-compound generator may use where load is at some distance from generator. Voltage drop in the line has compensated by used of an over-compound generator.

(d) If a reversing the polarity of the series field occur this cause to the relation between series field and shunt field, the field will oppose to each other more and more as the load current increase. Therefore terminal voltage will drop, such generator is said to be a differentially compound.

The compound generator are used more extensively than the other type of dc generator because its design to have a wide variety of terminal voltage characteristics.

Machine Efficiency

The efficiency of any machine is the ratio of the ratio of the output power to the input power. The input power is provided by the prime mover to drive the generator. Because part of the energy delivered to the generator is converted into heat, it represents wasted energy. These losses are generally minimized in the design stage; however, some of these losses are unavoidable.

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100\% \quad \text{or}$$

$$\text{Efficiency} = \frac{\text{Output power} \times 100\%}{\text{Input power} + \text{losses}}$$

Losses of generator

The losses of generators may be classified as

1) Copper losses

   The copper losses are present because of the resistance of the windings. Currents flowing through these windings create ohmic losses. The windings that may be present in addition to the (I2 R) armature winding are the field windings, inter-pole and compensate windings.

2) Iron losses

   As the armature rotates in the magnetic field, the iron parts of the armature as well as the conductors cut the magnetic flux. Since iron is a good conductor of electricity, the EMF s induced in the iron parts courses to flow through these parts. These are the eddy currents. Another loss occurring in the iron is due to the Hysteresis loss is present in the armature core.

3) Other rotational losses consist
   of 3.1 bearing friction loss
   3.2 friction of the rushes riding on the commutator
   3.3 windage losses

Windage losses are those associated with overcoming air friction in setting up circulation currents of air inside the machine for cooling purposes. These losses are usually very small.

Applications Of Dc Generators

Applications of Separately Excited DC Generators

These types of DC generators are generally more expensive than self-excited DC generators because of their requirement of separate excitation source. Because of that their applications are restricted. They are generally used where the use of self-excited generators are unsatisfactory.

1. Because of their ability of giving wide range of voltage output, they are generally used for testing purpose in the laboratories.
2. Separately excited generators operate in a stable condition with any variation in field excitation. Because of this property they are used as supply source of DC motors, whose speeds are to be controlled for various applications. Example- Ward Leonard Systems of speed control.

Applications of Shunt Wound DC Generators

The application of shunt generators are very much restricted for its dropping voltage characteristic. They are used to supply power to the apparatus situated very close to its position. These type of DC generators generally give constant terminal voltage for small distance operation with the help of field regulators from no load to full load.

1. They are used for general lighting.
2. They are used to charge battery because they can be made to give constant output voltage.
3. They are used for giving the excitation to the alternators.
4. They are also used for small power supply.

Applications of Series Wound DC Generators

These types of generators are restricted for the use of power supply because of their increasing terminal voltage characteristic with the increase in load current from no load to full load. We can clearly see this characteristic from the characteristic curve of series wound generator. They give constant current in the dropping portion of the characteristic curve. For this property they can be used as constant current source and employed for various applications.

1.They are used for supplying field excitation current in DC locomotives for regenerative breaking.

2.This types of generators are used as boosters to compensate the voltage drop in the feeder in various types of distribution systems such as railway service.

3.In series arc lightening this type of generators are mainly used.

Applications of Compound Wound DC Generators

Among various types of DC generators, the compound wound DC generators are most widely used because of its compensating property. We can get desired terminal voltage by compensating the drop due to armature reaction and ohmic drop in the in the line. Such generators have various applications.

1. Cumulative compound wound generators are generally used lighting, power supply purpose and for heavy power services because of their constant voltage property. They are mainly made over compounded.
2. Cumulative compound wound generators are also used for driving a motor.
3. For small distance operation, such as power supply for hotels, offices, homes and lodges, the flat compounded generators are generally used.
4. The differential compound wound generators, because of their large demagnetization armature reaction, are used for arc welding where huge voltage drop and constant current is required.

At present time the **applications of DC generators** become very limited because of technical and economic reasons. Now a days the electric power is mainly generated in the form of alternating current with the help of various power electronics devices.

UNIT-II

DC MOTORS

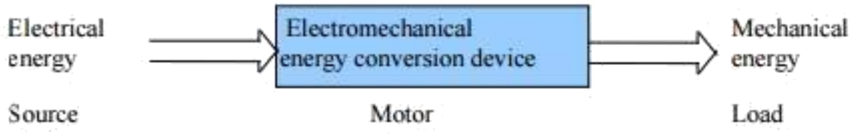
Direct Current Motor (DC motor)

DC motor is similar to dc generator; in fact the same machine can act as motor or generator. The only difference is that in a generator the EMF is greater than terminal voltage, whereas in motor the generated voltage EMF is less than terminal voltage. Thus the power flow is reversed, that is the motor converts electrical energy into mechanical energy. That is the reverse process of generator.

DC motors are highly versatile machines. For example, dc motors are better suited fore many processes that demand a high degree of flexibility in the control of speed and torque. The dc motor can provided high starting torque as well as high decelerating torque for application requiring quick stop or reversals.

DC motors are suited in speed control with over wide range is easily to achieve compare with others electromechanical.

The input is electrical energy (from the supply source), and the output is mechanical energy (to the load).



DC Motor Basic Principles

(a) Energy Conversion

If electrical energy is supplied to a conductor lying perpendicular to a magnetic field, the interaction of current flowing in the conductor and the magnetic field will produce mechanical force (and therefore, mechanical energy).

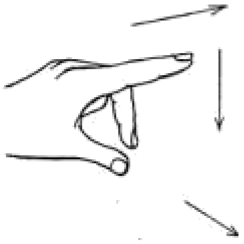
(b) Value of Mechanical Force

There are two conditions which are necessary to produce a force on the conductor. The conductor must be carrying current, and must be within a magnetic field. When these two conditions exist, a force will be applied to the conductor, which will attempt to move the conductor in a direction perpendicular to the magnetic field. This is the basic theory by which all DC motors operate.

The force exerted upon the conductor can be expressed as follows.

$$F = B\,i\,l \text{ Newton} \qquad (1)$$

where B is the density of the magnetic field, l is the length of conductor, and i the value of current flowing in the conductor. The direction of motion can be found using Fleming's Left Hand Rule.



Fleming's Left Hand Rule

The first finger points in the direction of the magnetic field (first - field), which goes from the North pole to the South pole. The second finger points in the direction of the current in the wire (second - current). The thumb then points in the direction the wire is thrust or pushed while in the magnetic field (thumb - torque or thrust).

Principle of operation

Consider a coil in a magnetic field of flux density B (figure). When the two ends of the coil are connected across a DC voltage source, current I flows through it. A force is exerted on the coil as a result of the interaction of magnetic field and electric current. The force on the two sides of the coil is such that the coil starts to move in the direction of force.

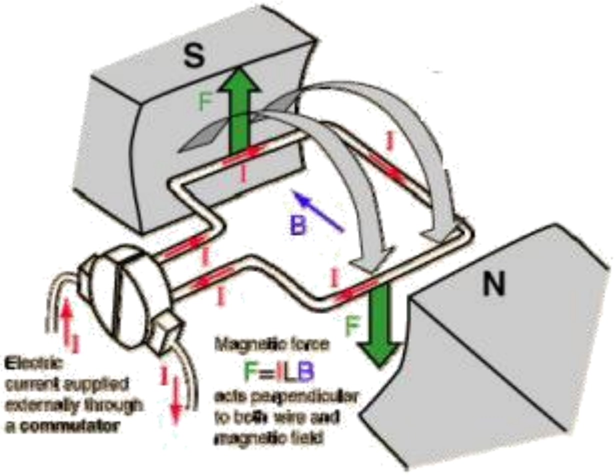


Fig.1. Torque production in a DC motor

In an actual DC motor, several such coils are wound on the rotor, all of which experience force, resulting in rotation. The greater the current in the wire, or the greater the magnetic field, the faster the wire moves because of the greater force created.

At the same time this torque is being produced, the conductors are moving in a magnetic field. At /dt) as shown inϕdifferent positions, the flux linked with it changes, which causes an emf to be induced (e = d figure 5. This voltage is in opposition to the voltage that causes current flow through the conductor and is referred to as a counter-voltage or back emf.

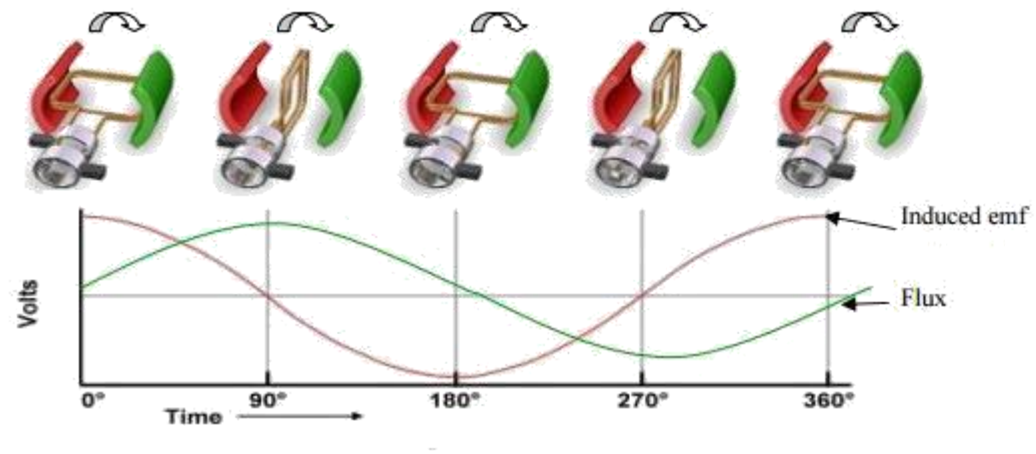


Fig.2. Induced voltage in the armature winding of DC motor

The value of current flowing through the armature is dependent upon the difference between the applied voltage and this counter-voltage. The current due to this counter-voltage tends to oppose the very cause for its production according to Lenz's law. It results in the rotor slowing down. Eventually, the rotor slows just enough so that the force created by the magnetic field (F = Bil) equals the load force applied on the shaft. Then the system moves at constant velocity.

Construction

DC motors consist of one set of coils, called armature winding, inside another set of coils or a set of permanent magnets, called the stator. Applying a voltage to the coils produces a torque in the armature, resulting in motion.

Stator

The stator is the stationary outside part of a motor.

- The stator of a permanent magnet dc motor is composed of two or more permanent magnet pole pieces.

- The magnetic field can alternatively be created by an electromagnet. In this case, a DC coil (field• winding) is wound around a magnetic material that forms part of the stator.

Rotor

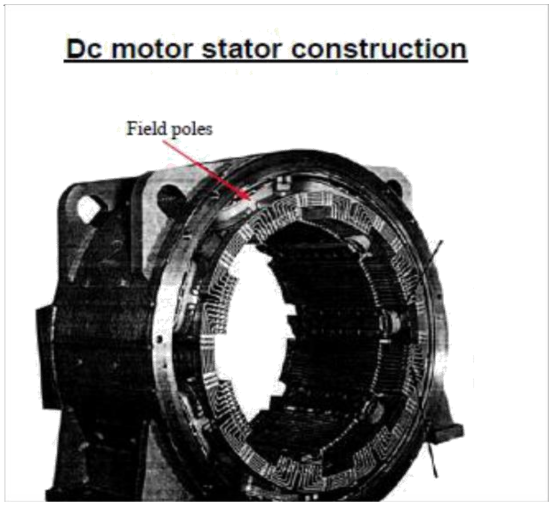
The rotor is the inner part which rotates.

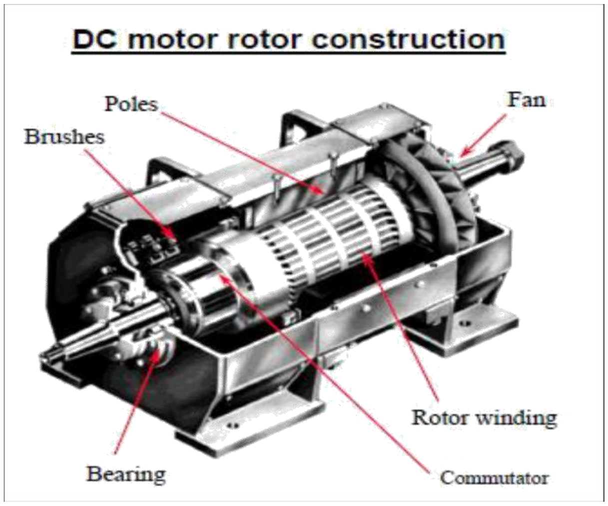
- The rotor is composed of windings (called armature windings) which are connected to the external circuit through a mechanical commutator. Both stator and rotor are made of ferromagnetic materials. The two are separated by air-gap.

Winding

A winding is made up of series or parallel connection of coils.

- Armature winding - The winding through which the voltage is applied or induced.
- Field winding - The winding through which a current is passed to produce flux (for the electromagnet)
- Windings are usually made of copper.





Torque Developed

The turning or twisting moment of a force about an axis is called torque. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius meter acted upon by a circumferential force of newton which causes it to rotate at rpm.

Then torque $T = F \times r$ newton-metre(N-m

Work done by this force in one revolution

=Force $\times$ distance

$= F \times 2\pi r$ joule

Power developed $= F \times 2\pi r \times N$ joule/second or watt $= \left(F \times r\right) \times 2\pi N$ watt

Now, $2\pi N$ = angular velocity ω in radian per second and $F \times r$ =torque T

Hence, power developed $= T \times \omega$ watt or $P = T\omega$ watt

Moreover, if N is in rpm, then

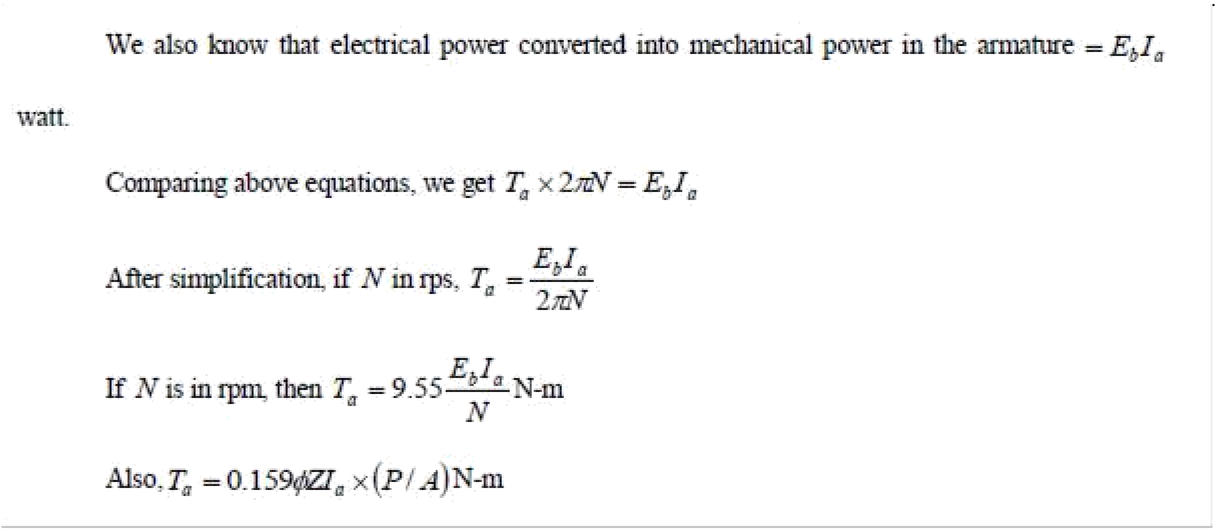
$\omega = 2\pi N / 60$ rad/s

Hence, $P = \frac{2\pi N}{60} \times T$ or $P = \frac{2\pi}{60} NT = \frac{NT}{9.55}$

Armature torque of a motor

Let T_a be the torque developed by the armature of a motor running at N rps. If T_a is in N-m, then

power developed $= T_a \times 2\pi N$ watt



We also know that electrical power converted into mechanical power in the armature $= E_b I_a$ watt.

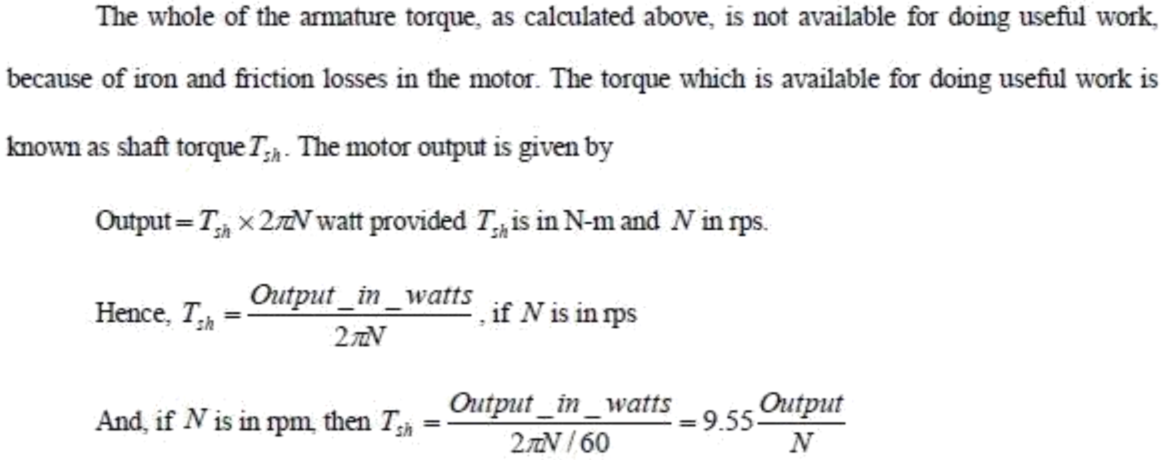
Comparing above equations, we get $T_a \times 2\pi N = E_b I_a$

After simplification, if N in rps, $T_a = \dfrac{E_b I_a}{2\pi N}$

If N is in rpm, then $T_a = 9.55 \dfrac{E_b I_a}{N}$ N-m

Also, $T_a = 0.159 \phi Z I_a \times (P/A)$ N-m

Shaft torque



The whole of the armature torque, as calculated above, is not available for doing useful work, because of iron and friction losses in the motor. The torque which is available for doing useful work is known as shaft torque T_{sh}. The motor output is given by

Output $= T_{sh} \times 2\pi N$ watt provided T_{sh} is in N-m and N in rps.

Hence, $T_{sh} = \dfrac{Output\_in\_watts}{2\pi N}$, if N is in rps

And, if N is in rpm, then $T_{sh} = \dfrac{Output\_in\_watts}{2\pi N/60} = 9.55 \dfrac{Output}{N}$

Induced Counter-voltage (Back emf):

Due to the rotation of this coil in the magnetic field, the flux linked with it changes at different positions, which causes an emf to be induced (refer to figure 2).

The induced emf in a single coil, $e = d\o_c/dt$

Since the flux linking the coil, $\phi c = \phi \mathrm{Sin}\omega$

Induced voltage , $e = \omega\, \phi \cos\omega t$ (4)

Note that equation (4) gives the emf induced in one coil. As there are several coils wound all around the rotor, each with a different emf depending on the amount of flux change through it, the total emf can be obtained by summing up the individual emfs.

The total emf induced in the motor by several such coils wound on the rotor can be obtained by integrating equation (4), and expressed as:

$$E_b = K \phi \omega_m \qquad (5)$$

where K is an armature constant, and is related to the geometry and magnetic properties of the motor, and ω_m is the speed of rotation.

The electrical power generated by the machine is given by:

$$P_{dev} = E_b I_a = K\phi\omega_m I_a \qquad (6)$$

DC Motor Equivalent circuit

The schematic diagram for a DC motor is shown below. A DC motor has two distinct circuits: Field circuit and armature circuit. The input is electrical power and the output is mechanical power. In this equivalent circuit, the field winding is supplied from a separate DC voltage source of voltage Vf. Rf and Lf represent the resistance and inductance of the field winding. The current If produced in the winding establishes the magnetic field necessary for motor operation. In the armature (rotor) circuit, VT is the voltage applied across the motor terminals, Ia is the current flowing in the armature circuit, Ra is the resistance of the armature winding, and Eb is the total voltage induced in the armature.

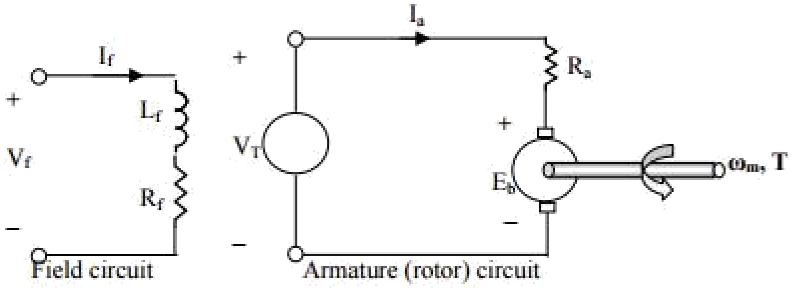


Fig.4. DC motor representation

Counter EMF in DC motor

When voltage is applied to dc motor, current will flow into the positive brush through the commutator into the armature winding. The motor armature winding is identical to the generator armature winding. Thus the conductors on the north field poles are carry current in one direction, while all conductors on the south field poles carry the current in opposite direction. When the armature carry current it will produce a magnetic field around the conductor of it own which interact with the main field. It is cause to the force developed on all conductors and tending to turn the armature.

The armature conductors continually cut through this resultant field. So that voltages are generated in the same conductors that experience force action. When operating the motor is simultaneously acting as generator. Naturally motor action is stronger than generator action.

Although the counter EMF is opposite with the supplied voltage, but it cannot exceed to applied voltage. The counter EMF is serves to limit the current in an armature winding. The armature current will be limited to the value just sufficient to take care of the developed power needed to drive the load.

In the case of no load is connected to the shaft. The counter EMF will almost equal to the applied voltage. The power develops by the armature in this case is just the power needed to overcome the rotational losses. It’s mean that the armature current IA is controlled and limited by counter EMF therefore

$$Ia = \frac{VL - Ea}{Ra}$$

Where:

VL = Line voltage across the armature winding

Ra = Resistance of the armature winding

Ea = Induced EMF or generated voltage

Ia = Armature current

Since, EA is induced or generated voltage it is depend on the flux per pole and the speed of the armature rotate (n) in rpm.

Therefore

$$E_a = K \varphi n$$

Where:

K = the constant value depending on armature winding and number of pole of machine.

φ = Rotation of the armature

And,

$$K = \frac{Z \times P}{a}$$

Where:

Z = Total number of conductor in the armature winding

a = Number of parallel circuit in the armature winding between positive and negative brushes. For wave wound armature “a” = 2

Lap wound armature “a” = P

Example

A dc motor operated at 1500 rpm when drawing 20 amps from 220 volts supply, if the armature resistance is 0.2 ohms. Calculate the no load speed assumed Ia = 0 amp (This amount to assuming the brushes and rotation loss are negligible)

Solution

When load condition Ia = 20 amps.

$$E_a = V_L - I_a R_a = 220 - 20\,(0.2) = 216 \text{ Volts.}$$

And

$$E_a = k \varphi n$$

$$216 = K\phi \times 1500$$

$$K\phi = 216/1500$$

$$= 0.144$$

At no load condition Ia = 0 Amp.

$$Ea = VL = 220 \text{ Volts.}$$

Hence

$$Ea = k\varphi n$$

$$n = 220/ k\varphi$$

$$= 220/ 0.144$$

$$= 1528 \text{ rpm.}$$

Mechanical power develop in dc motor (Pd)

Let,

Pd = Mechanical power develop

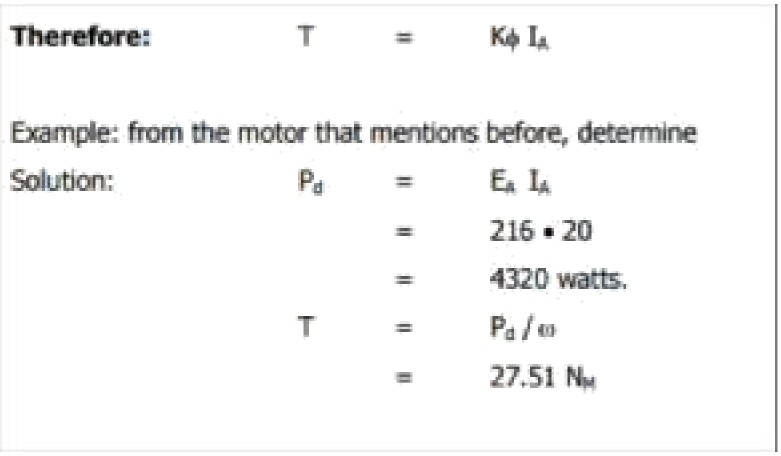
T = Torque exerted on the armature

$$Pd = \omega T$$

$$= \left(\frac{2\pi n}{60}\right) T$$

Where: $T = P_d / \omega$

$$= \frac{Ea \times Ia}{2\pi n / 60} = \frac{K\varphi n \times Ia}{(2\pi n)/60}$$



Therefore: $T = K\phi I_A$

Example: from the motor that mentions before, determine

Solution:

$$
\begin{aligned}
P_d &= E_A\, I_A \\
&= 216 \cdot 20 \\
&= 4320 \text{ watts.} \\
T &= P_d / \omega \\
&= 27.51\ N_M
\end{aligned}
$$

DC Machine Classification

DC Machines can be classified according to the electrical connections of the armature winding and the field windings. The different ways in which these windings are connected lead to machines operating with different characteristics. The field winding can be either self-excited or separately-excited, that is, the terminals of the winding can be connected across the input voltage terminals or fed from a separate voltage source (as in the previous section). Further, in self-excited motors, the field winding can be connected either in series or in parallel with the armature winding. These different types of connections give rise to very different types of machines, as we will study in this section.

(a) Separately excited machines

- The armature and field winding are electrically separate from each other.
- The field winding is excited by a separate DC source.

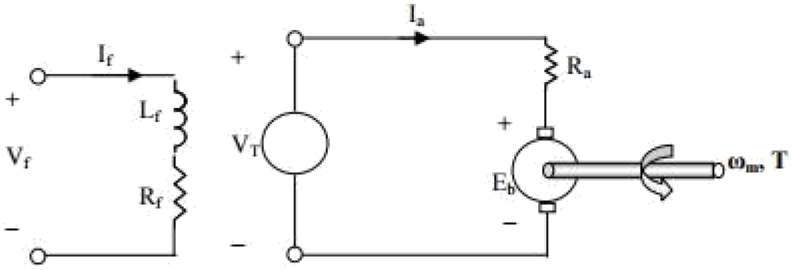


Fig.5. Separately excited dc motor

The voltage and power equations for this machine are same as those derived in the previous section. Note that the total input power = $V_f I_f + V_T I_a$

(b)Self excited machines

In these machines, instead of a separate voltage source, the field winding is connected across the main voltage terminals.

1.Shunt machine

- The armature and field winding are connected in parallel.
- The armature voltage and field voltage are the same.

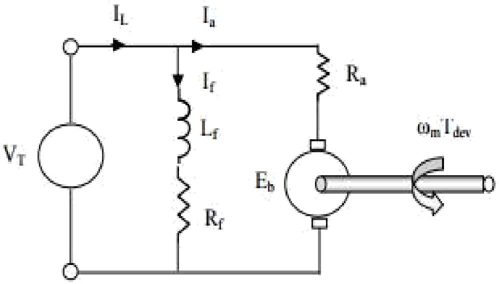


Fig.6. shunt motor

Total current drawn from the supply, IL = If + Ia

Total input power = VT IL

Voltage, current and power equations are given in equations (7), (8) and (9).

2.Series DC machine

- The field winding and armature winding are connected in series.
- The field winding carries the same current as the armature winding.

A series wound motor is also called a universal motor. It is universal in the sense that it will run equally well using either an ac or a dc voltage source.

Reversing the polarity of both the stator and the rotor cancel out. Thus the motor will always rotate the same direction regardless of the voltage polarity.

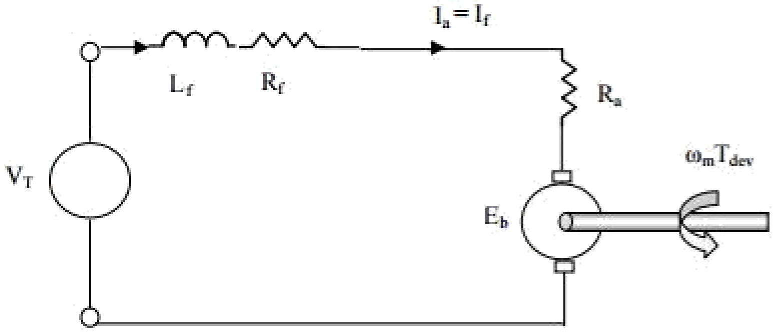


Fig.7.Series Motor

Compound DC machine

If both series and shunt field windings are used, the motor is said to be compounded. In a compound machine, the series field winding is connected in series with the armature, and the shunt field winding is connected in parallel. Two types of arrangements are possible in compound motors:

Cumulative compounding - If the magnetic fluxes produced by both series and shunt field windings are in the same direction (i.e., additive), the machine is called cumulative compound.

Differential compounding - If the two fluxes are in opposition, the machine is differential compound.

In both these types, the connection can be either short shunt or long shunt.

Speed control of DC motor

Many applications require the speed of a motor to be varied over a wide range. One of the most attractive features of DC motors in comparison with AC motors is the ease with which their speed can be varied.

We know that the back emf for a separately excited DC motor:.

$$E_b = K\phi\omega_m = V_T - I_a R_a$$

Rearranging the terms,

$$\text{Speed } \omega_m = (V_T - I_a R_a)/K\phi \qquad (7)$$

From the above equation, it is evident that the speed can be varied by using any of the following methods:

- Armature voltage control (By varying VT)
- Field Control (By Varying ϕ)
- Armature resistance control (By varying Ra)

Armature voltage control

This method is usually applicable to separately excited DC motors. In this method of speed control, Ra and ϕ are kept constant.

In normal operation, the drop across the armature resistance is small compared to Eb and therefore: $E_b \cong V_T$

Since, $E_b = K\phi\,\omega_m$

Angular speed can be expressed as:

$$\omega_m = V_T / K\phi \qquad (8)$$

From this equation, If flux is kept constant, the speed changes linearly with VT.

- As the terminal voltage is increased, the speed increases and vice versa.
- The relationship between speed and applied voltage is shown in figure 8. This method provides smooth variation of speed control.

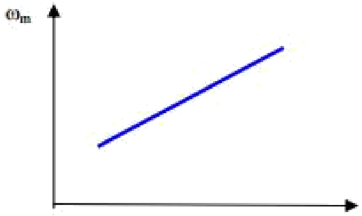


Fig.8.Variation of speed with applied voltage

Field Control , (ϕ)

In this method of speed control, Ra and VT remain fixed.

Therefore, from equation (7):

$$\omega_m \propto I/\phi$$

Assuming magnetic linearity, $\phi \propto$ If

$$\text{(OR)}\quad \omega_m \propto I/I_F \qquad (9)$$

i.e., Speed can be controlled by varying field current If.

- The field current can be changed by varying an adjustable rheostat in the field circuit (as shown in figure 9).
- By increasing the value of total field resistance, field current can be reduced, and therefore speed can be increased.

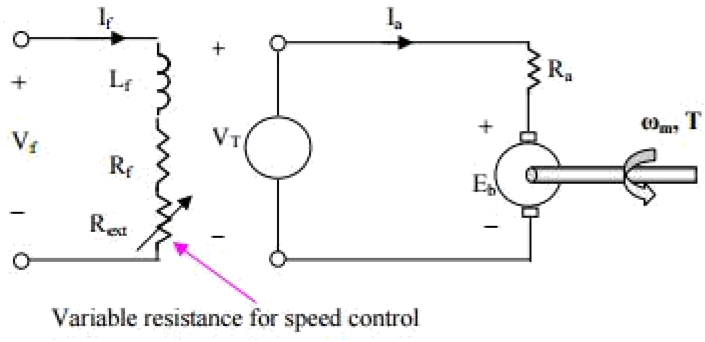


Fig.9.

The relationship between the field winding current and angular speed is shown in figure 10

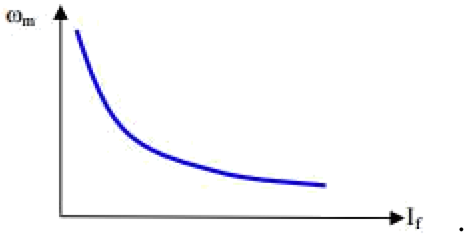


Fig.10: Variation of speed with field current

Armature Resistance Control

The voltage across the armature can be varied by inserting a variable resistance in series with the armature circuit.

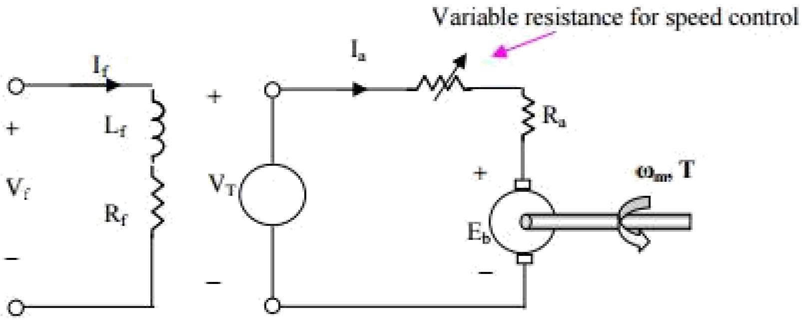


Fig.11. Armature resistance method for speed control

From speed-torque characteristics , we know that:

$$T_{dev} = \frac{K\phi}{R_a}(V_T - K\phi\omega_m)$$

For a load of constant torque V_T and ϕ are kept constant, as the armature resistance Ra is increased, speed decreases. As the actual resistance of the armature winding is fixed for a given motor, the overall resistance in the armature circuit can be increased by inserting an additional variable resistance in series with the armature. The variation if speed with respect to change in this external resistance is shown in figure 12. This method provides smooth control of speed..

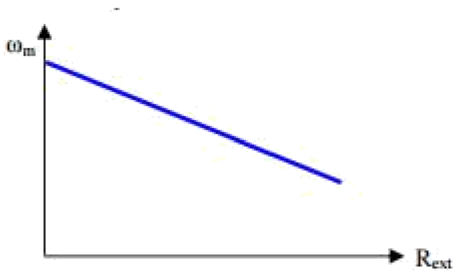


Fig. 12: Variation of speed with external armature resistance

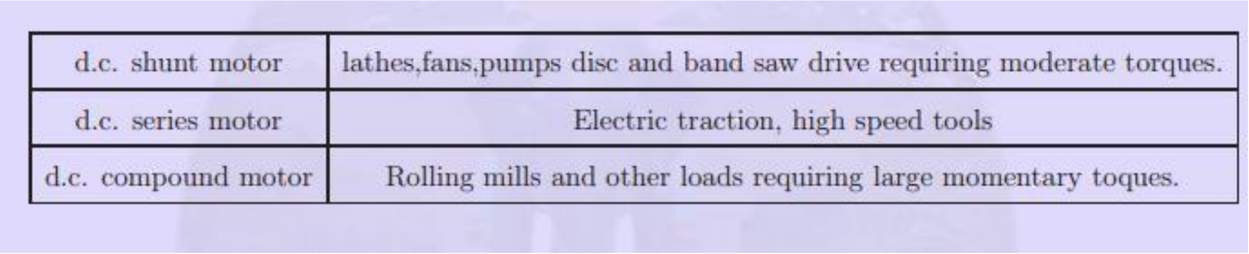
DC Shunt Motor speed control

All three methods described above can be used for controlling the speed of DC Shunt Motors.

Series Motor speed control

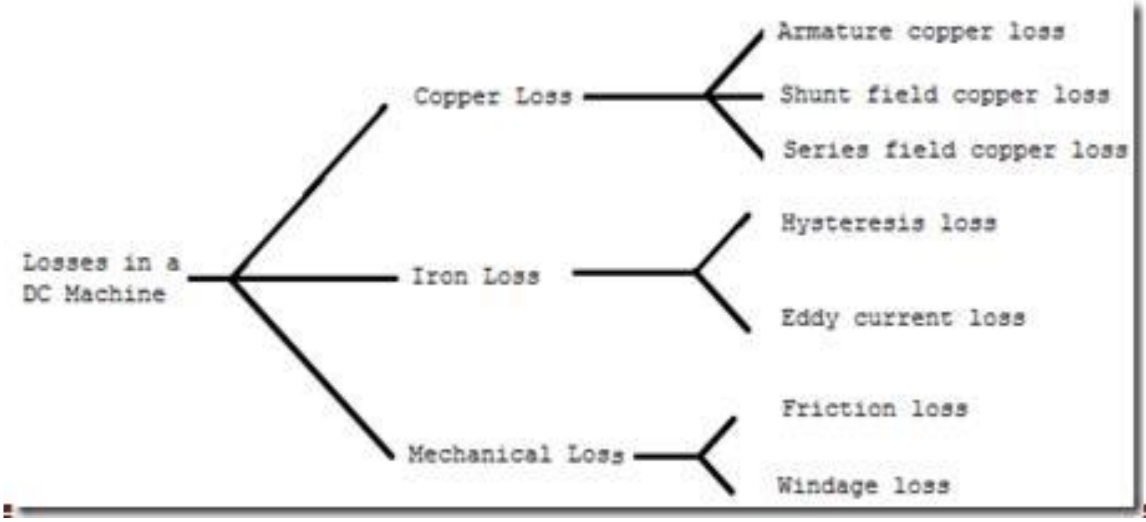
The speed is usually controlled by changing an external resistance in series with the armature. The other two methods described above are not applicable to DC series motor speed control.

Applications of dc motors



d.c. shunt motor	lathes,fans,pumps disc and band saw drive requiring moderate torques.
d.c. series motor	Electric traction, high speed tools
d.c. compound motor	Rolling mills and other loads requiring large momentary toques.

Types of Losses in a DC Machines



The losses can be divided into three types in a dc machine (Generator or Motor). They are

1. Copper losses
2. Iron or core losses and
3. Mechanical losses.

All these losses seem as heat and therefore increase the temperature of the machine. Further the efficiency of the machine will reduce.

1. Copper Losses:

This loss generally occurs due to current in the various windings on of the machine. The different winding losses are;

Armature copper loss = $I^2_a R_a$

Shunt field copper loss = $I^2_{sh} R_{sh}$

Series field copper loss = $I^2_{se} R_{se}$

Note: There's additionally brush contact loss attributable to brush contact resistance (i.e., resistance in the middle of the surface of brush and commutator). This loss is mostly enclosed in armature copper loss.

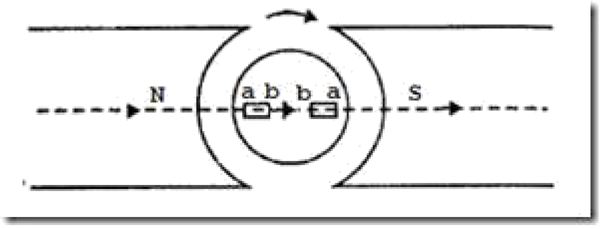
2. Iron Losses

This loss occurs within the armature of a d.c. machine and are attributable to the rotation of armature within the magnetic field of the poles. They're of 2 sorts viz.,

(i) Hysteresis loss

(ii) eddy current loss.

Hysteresis loss:



Hysteresis loss happens in the armature winding of the d.c. machine since any given part of the armature is exposed to magnetic field of reverses as it passes underneath sequence poles. The above fig shows the 2 pole DC machine of rotating armature. Consider a tiny low piece ab of the armature winding. Once the piece ab is underneath N-pole, the magnetic lines pass from a to b. Half a revolution well along, identical piece of iron is underneath S-pole and magnetic lines pass from b to a in order that magnetism within the iron is overturned. So as to reverse constantly the molecular magnets within the armature core, particular quantity of power must be spent that is named hysteresis loss. It's given by Steinmetz formula.

The steinmetz formula is

$$\text{Hysteresis loss } P_h = \eta B^{16}_{max} fV \text{ watts}$$

Where,

η = Steinmetz hysteresis co-efficient

B_{max} = Maximum flux Density in armature winding

F = Frequency of magnetic reversals

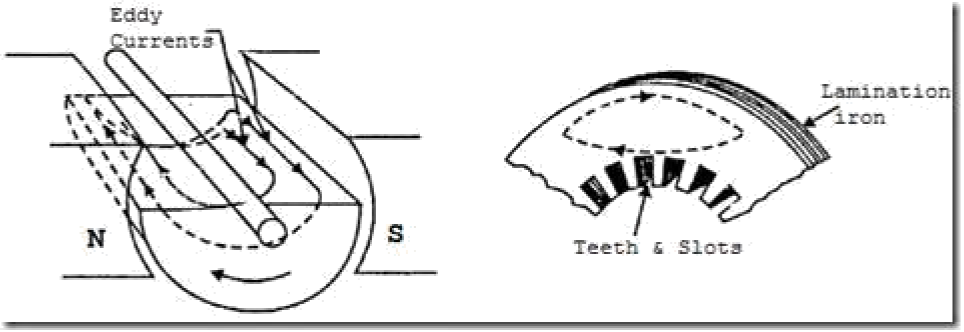
= NP/120 (N is in RPM)

V = Volume of armature in m^3

If you want to cut back this loss in a d.c. machine, armature core is created of such materials that have an lesser value of Steinmetz hysteresis co-efficient e.g., silicon steel.

Eddy current loss:

In addition to the voltages evoked within the armature conductors, some of other voltages evoked within the armature core. These voltages turn out current currents within the coil core as shown in Fig. These are referred to as eddy currents and power loss attributable to their flow is named eddy current loss. This loss seems as heat that increases the temperature of the machine and efficiency will decrease.



If never-ending cast-iron core is employed, the resistance to eddy current path is tiny attributable to massive cross-sectional space of the core. Consequently, the magnitude of eddy current and therefore eddy current loss are massive. The magnitudes of eddy current are often decreased by creating core resistance as high as sensible. The core resistances are often greatly exaggerated by making the core of skinny, spherical iron sheets referred to as lamination's shown in the fig. The lamination's are insulated from one another with a layer of varnish. The insulating layer features a high resistance, thus only small amount of current flows from one lamination to the opposite. Also, as a result of every lamination is extremely skinny, the resistance to current passing over the breadth of a lamination is additionally quite massive. Therefore laminating a core will increase the core resistance that drops the eddy current and therefore the eddy current loss.

$$\text{Eddy Current loss } P_e = K_e B^2_{max} f^2 t^2 V \text{ Watts}$$

Where, k_e = constant

B_{max} = Maximum flux density in wb/m^2

T = Thickness of lamination in m

V = Volume of core in m^3

Note: Constant (**K_e**) depend upon the resistance of core and system of unit used.

It may well be noted that eddy current loss be subject to upon the sq. of lamination thickness. For this reason, lamination thickness ought to be unbroken as tiny as potential.

3.Mechanical Loss

These losses are attributable to friction and windage.

- Friction loss occurs due to the friction in bearing, brushes etc.
- windage loss occurs due to the air friction of rotating coil.

These losses rely on the speed of the machine. Except for a given speed, they're much constant.

Constant and Variable Losses

The losses in a d.c. machine is also further classified into (i) constant losses (ii) variable losses.

Constant losses

Those losses in a d.c. generator that stay constant at all loads are referred to as constant losses. The constant losses in a very d.c. generator are:
(a)iron losses

(b)mechanical losses

(c)shunt field losses

Variable losses

Those losses in a d.c. generator that differ with load are referred to as variable losses. The variable losses in a very d.c. generator are:

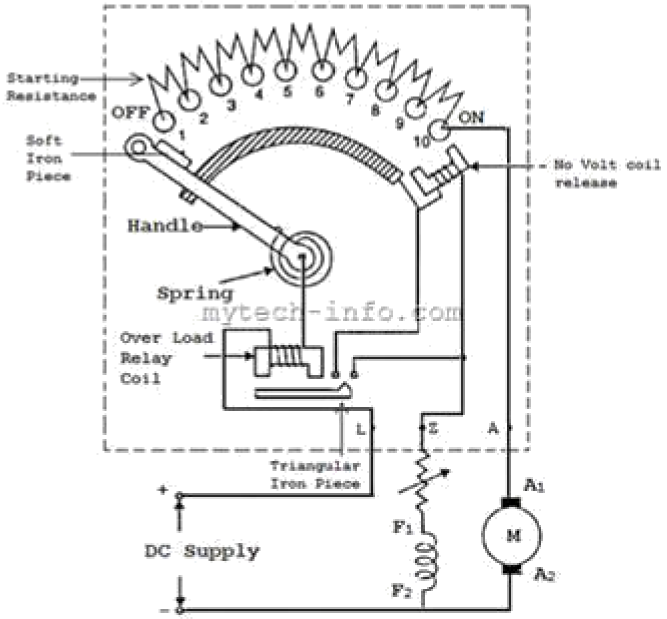
Copper loss in armature winding (I^2R_a)

Copper loss in series field winding ($I^2_{se}R_{se}$)

Total losses = Constant losses + Variable losses.

Generally this copper loss is constant for shunt and compound generators.

Three point starter



The figure above shows that typical representation diagram of a 3 point starter for DC shunt motors with its protective devices. It contains 3 terminals namely L, Z, & A; hence named 3 point starter. The starter is made up of of starting resistances divided into many section and which are connected in series within the armature. The each tapping point on the starting resistances is carried out to a no. of studs. The starter 3 terminals L,Z & A are connected to the positive terminal of line, shunt field and armature terminal of motor respectively. The remaining terminal of the shunt and armature are connected to the negative line terminal. The No volt coil release is connected in series with field winding. The handle one end is connected to the L terminal by means of over load release coil. Then another end of handle travels against the twisting spring & make touching base with every single stud in the course of starting operation, tripping out the starting resistance as it moves above every stud in clockwise.

Armature Reaction in DC Motor

Working:

- Initially the DC supply is turned on with the handle is in OFF position.
- Now the handle is moved towards clockwise direction to the 1st stud. Once it contacts with the 1st stud, immediately the shunt field coil is connected to the supply, however the entire starting resistances is injected with armature circuit in series.
- As the handle moved gradually towards the final stud, so that the starting resistance is cut out step by step in armature circuit. And finally the handle is detained magnetically by the No volt coil release since it is energized by the filed winding.
- In case if the shunt field winding excitation is cut out by accident or else the supply is interrupted then the no volt coil release gets demagnetized and handle returned back to the original position under the influence of spring.

Note: If we were not used No volt coil release; then if the supply is cut off the handle would remain in the same position, causing an extreme current in armature.

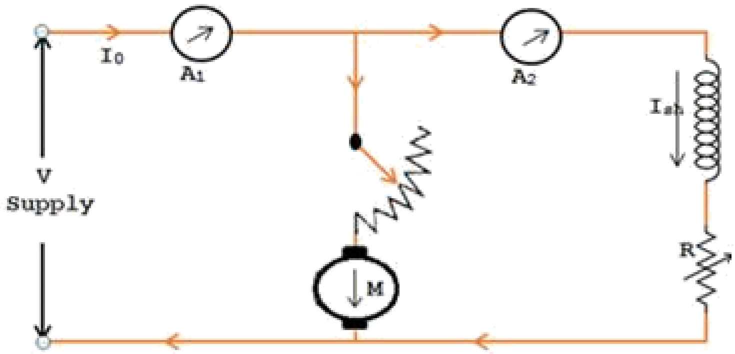
- If any fault occurs on motor or overload, it will draw extreme current from the source. This current raise the ampere turns of OLR coil (over load relay) and pull the armature Coil, in consequence short circuiting the NVR coil (No volt relay coil). The NVR coil gets demagnetized and handle comes to the rest position under the influence of spring. Therefore the motor disconnected from the supply automatically.

Characteristic of DC Shunt Motor

Disadvantage:

In point starter, no volt relay coil is connected in series with field circuit; hence it carries shunt current in the field. When the speed control of DC motor through field regulator, it may be weakened the shunt field current to such extent the no volt coil release might not in a position to hold the starter handle in ON position. This might the motor disconnected from the source when it is not anticipated. This can be overcome by using the point starter.

Swinburne’s Test for DC Machines



In this technique, the DC Generator or DC Motor is run as a motor at no load; with that losses of the DC machines are determined. When the losses of DC machine well-known, then we can find the efficiency of a DC machine in advance at any desired load. In DC machines this test is applicable only throughout the flux is constant at all load (DC Shunt machine and DC Compound Machine). This test maintains of two steps;

Determination of Hot Resistance of Windings:

The resistance of armature windings and shunt field windings are measured with the help of a battery, ammeter and voltmeter. Since these armature and shunt filed resistances are measured while the DC machine is cold, it should be transformed to values equivalent to the temperature at which the DC machine would work at full load. These values are measured generally when the room temperature increases above 40^{O}C. Take on the hot resistance of armature winding and shunt field winding be R_a and R_{sh} correspondingly.

- **Condition for maximum Efficiency in DC Machine**

Determination of Constant Losses:

On no load the DC machine run as a motor with the supply voltage is varied to the normal rated voltage. With the use of the field regulator R the motor speed is varied to run the rated speed which is shown in the figure.

Let

V = Supply Voltage

I_0 = No load current read by A_1

I_{sh} = Shunt Field current ready by A_2

No load armature current $I_{ao} = I_0 – I_{sh}$

No load Input power to motor = VI_0

No load Input power to motor = VI_{a0}

$$= V (I_0 – I_{sh})$$

As the output power is nil, the no loads input power to the armature provides Iron loss, armature copper loss, friction loss and windage loss.

Constant loss W_c = Input power to Motor – Armature copper loss

$$W_c = VI_0 – (I_0 – I_{sh}{}^2R_a)$$

As the constant losses are identified, the efficiency of the DC machine at any loads can be determined. Suppose it is desired to determine the DC machine efficiency at no load current. Then, Armature current $I_a = I-I_{sh}$ (For Motoring)

$I_a = I+I_{sh}$ (For Generating)

To find the Efficiency when running as a motor:

Input power to motor = VI

Armature copper loss $=I_a^2R_a = (I-I_{sh}^2R_a)$

Constant Loss = W_c

Total Loss = $(I-I_{sh}2R_a)+W_c$

Motor Efficiency η = (Input power – Losses)/ Input

η **= {VI – (I-I$_{sh}^2$R$_a$)} / VI**

- **Condition for maximum Efficiency in DC Machine**

To find the Efficiency when running as a Generator:

Output Power of Generator = VI

Armature copper loss $=I_a^2R_a = (I+I_{sh}^2R_a)$

Constant Loss = W_c

Total Loss = $(I+I_{sh}^2R_a)+W_c$

Motor Efficiency η= Output power/ (Output power + Losses)

η **= VI / {VI + (I+I$_{sh}^2$R$_a$) + W$_c$}**

Merits:

- Since this test is no load test, power required is less. Hence the cost is economic.
- The efficiency of the machine can be found very easily, because the constant losses are well known.
- This test is appropriate.

Demerits:

- When the DC machine is loaded, this test does not deliberate the stray load loss that occurs.
- Using this method we cannot check the DC machine performances at full load.

Example: It does not indicate the commutation performance is satisfactory on full load and cannot indicate the specified limit of temperature rise.

- Using this test we cannot determine the accurate efficiency of DC machine, because iron loss at actual loads is greater than at no load. This is primarily owed to armature reaction interfere with field.

UNIT-III

SINGLE PHASE TRANSFORMERS

TRANSFORMERS

The transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency. Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electrical power system and distribution systems.

SINGLE PHASE TRANSFORMERS

INTRODUCTION

In its simplest form a single-phase transformer consists of two windings, wound on an iron core one of the windings is connected to an ac source of supply f. The source supplies a current to this winding (called primary winding) which in turn produces a flux in the iron core. This flux is alternating in nature (Refer Figure 4.1). If the supplied voltage has a frequency f, the flux in the core also alternates at a frequency f. the alternating flux linking with the second winding, induces a voltage E2 in the second winding (called secondary winding). [Note that this alternating flux linking with primary winding will also induce a voltage in the primary winding, denoted as E1. Applied voltage V1 is very nearly equal to E1]. If the number of turns in the primary and secondary windings is N1 and N2 respectively, we shall see later in this unit that

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

The load is connected across the secondary winding, between the terminals a1, a2. Thus, the load can be supplied at a voltage higher or lower than the supply voltage, depending upon the ratio N1/N2

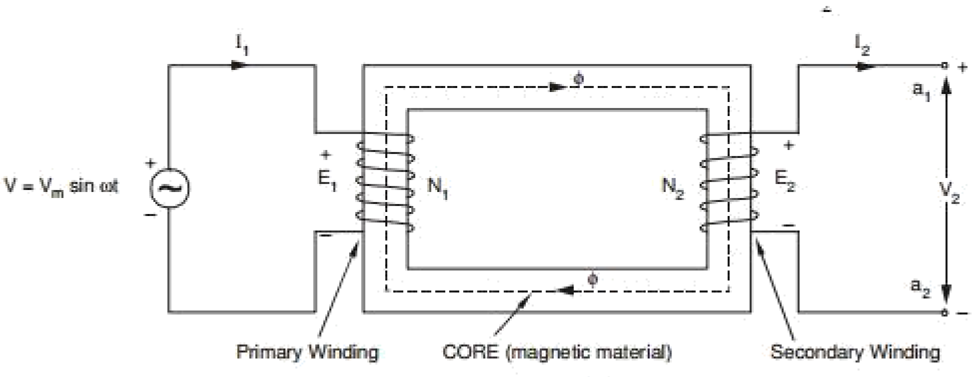


Figure 4.1 : Basic Arrangement of Transformer

When a load is connected across the secondary winding it carries a current I2, called load current. The primary current correspondingly increases to provide for the load current, in addition to the small no load current. The transfer of power from the primary side (or source) to the secondary side (or load) is through the mutual flux and core. There is no direct electrical connection between the primary and secondary sides.

In an actual transformer, when the iron core carries alternating flux, there is a power loss in the core called core loss, iron loss or no load loss. Further, the primary and secondary windings have a resistance, and the currents in primary and secondary windings give rise to I 2 R losses in transformer windings, also called copper losses. The losses lead to production of heat in the transformers, and a consequent temperature rise. Therefore, in transformer, cooling methods are adopted to ensure that the temperature remains within limit so that no damage is done to windings' insulation and material.

In the Figure 4.1 of a single-phase transformer, the primary winding has been shown connected to a source of constant sinusoidal voltage of frequency f Hz and the secondary terminals are kept open. The primary winding of N1 turns draws a small amount of alternating current of instantaneous value i0, called the exciting current. This current establishes flux φ in the core (+ve direction marked on diagram). The strong coupling enables all of the flux φ to be confined to the core (i.e. there is no leakage of flux).

CONSTRUCTION OF A TRANSFORMER

There are two basic parts of a transformer:

1. Magnetic core
2. Winding or coils

MAGNETIC CORE:

The core of a transformer is either square or rectangular in size. It is further divided in two parts. The vertical portion on which the coils are bound is called limb, while the top and bottom horizontal portion is called yoke of the core as shown in fig. 2.

Core is made up of laminations. Because of laminated type of construction, eddy current losses get minimized. Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminations are insulated from each other by using insulation like varnish. All laminations are

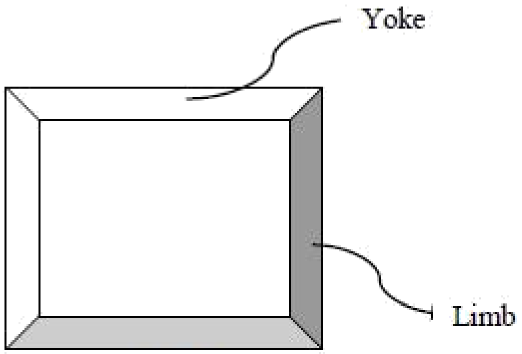


Fig. 2

varnished. Laminations are overlapped so that to avoid the airgap at the joints. For this generally ‗L' shaped or ‗I' shaped laminations are used which are shown in the fig. 3 below.

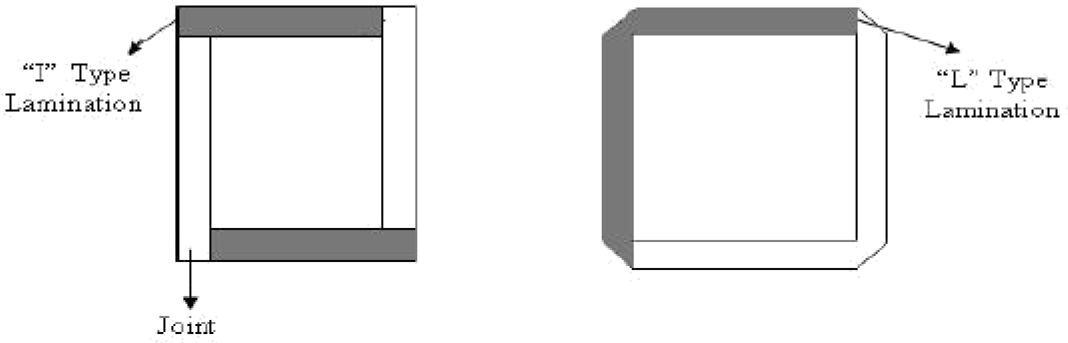


Fig. 3

WINDING:

There are two windings, which are wound on the two limbs of the core, which are insulated from each other and from the limbs as shown in fig. 4. The windings are made up of copper, so that, they possess a very small resistance. The winding which is connected to the load is called secondary winding and the winding which is connected to the supply is called primary winding. The primary winding has N_1 number of turns and the secondary windings have N_2 number of turns.

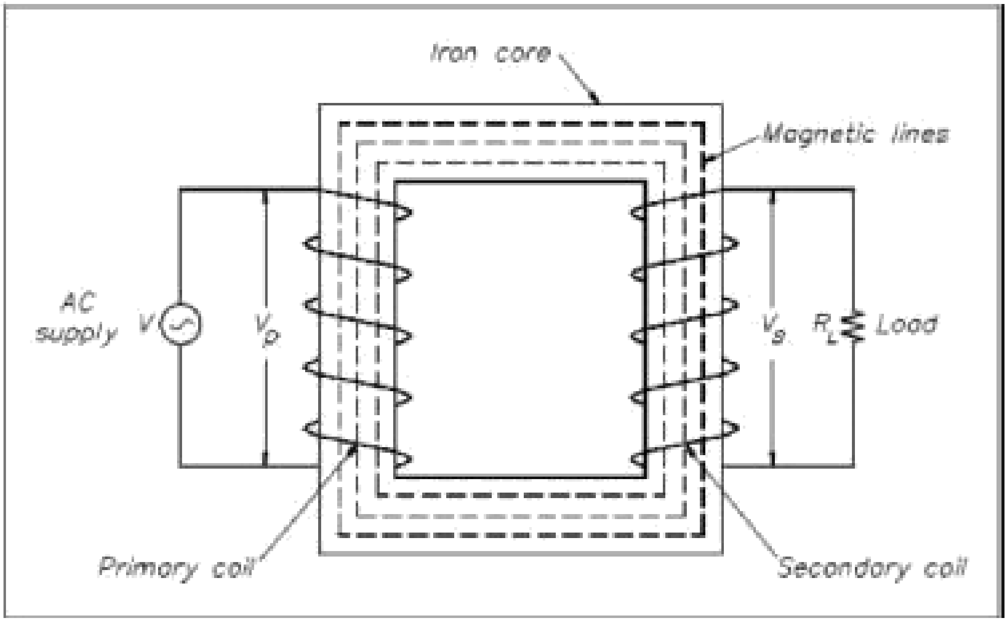
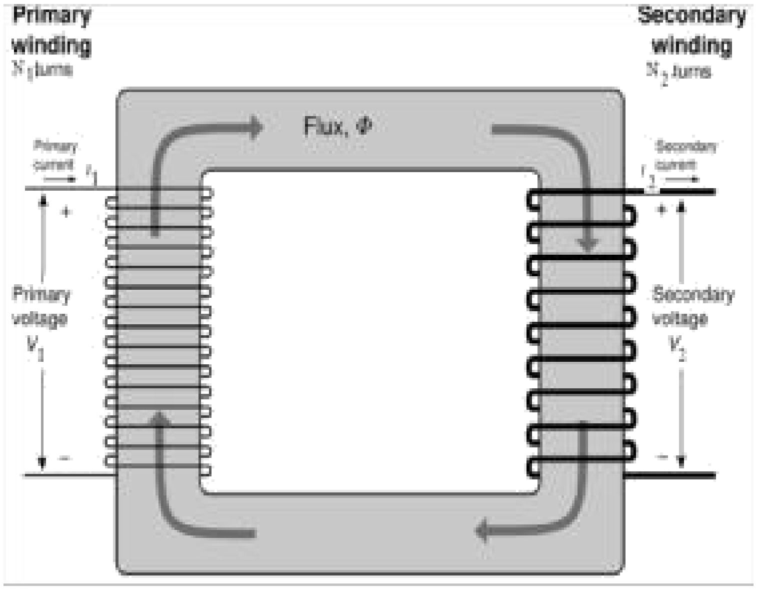


Fig. 4 Single Phase Transformer

PRINCIPLE OF OPERATION OF A SINGLE PHASE TRANSFORMER



A single phase transformer works on the principle of mutual induction between two magnetically coupled coils. When the primary winding is connected to an alternating voltage of r.m.s value, V1 volts, an alternating current flows through the primary winding and setup an alternating flux ϕ in the material of the core. This alternating flux ϕ, links not only the primary windings but also the secondary windings. Therefore, an e.m.f e1 is induced in the primary winding and an e.m.f e2 is induced in the secondary winding, e1 and e2 are given:

$$e1 = -N1\frac{d\varphi}{dt} \text{ --------- (a)}$$

$$e2 = -N2\frac{d\varphi}{dt} \text{ ----------(b)}$$

If the induced e.m.f is e1 and e2 are represented by their rms values E1 and E2 respectively, then

$$E1 = -N1\frac{d\varphi}{dt} \text{ --------- (1)}$$

$$E2 = -N2\frac{d\varphi}{dt} \text{ ---------- (2)}$$

$$\text{Therefore, } \frac{E2}{E1} = \frac{N2}{N1} = k \text{ ---------------- (3)}$$

K is known as the transformation ratio of the transformer. When a load is connected to the secondary winding, a current I2 flows through the load, V2 is the terminal voltage across the load. As the power transfered from the primary winding to the secondary winding is same, Power input to the primary winding = Power output from the secondary winding.

$E_1I_1 = E_2I_2$

(Assuming that the power factor of the primary is equal to the secondary).

Or, $\frac{E2}{E1} = \frac{I1}{I2} = k$ ------- (4)

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

$\frac{E2}{E1} = \frac{N2}{N1} = \frac{I1}{I2} = k$ --------------- (5)

The directions of emf‘s E1 and E2 induced in the primary and secondary windings are such that, they always oppose the primary applied voltage V1.

EMF Equation of a transformer:

Consider a transformer having,

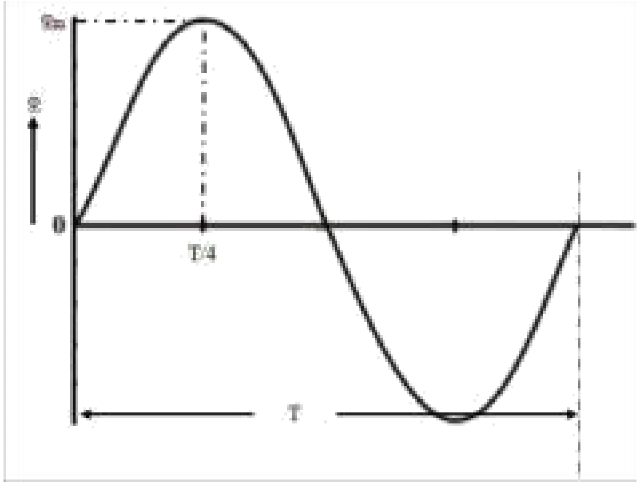
N1 =Primary turns

N2 = Secondary turns

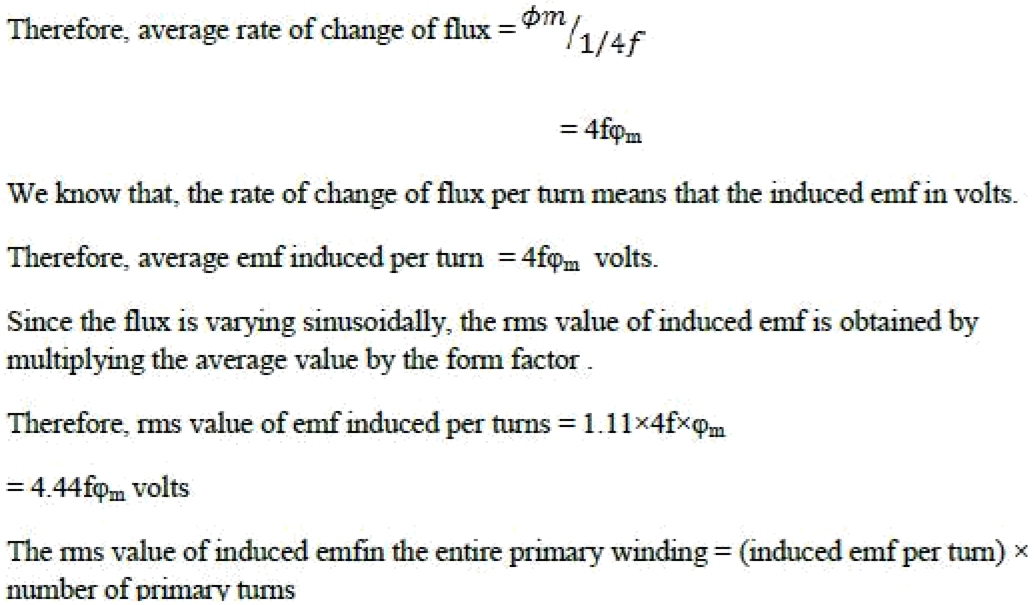
Φm = Maximum flux in the core

Φm = Bm × A webers

f= frequency of ac input in hertz (Hz)



The flux in the core will vary sinusoidal as shown in figure, so that it increases from zero to maximum "ϕm" in one quarter of the cycle i.e, 1/4f second.



Therefore, average rate of change of flux = ${}^{\phi m}/_{1/4f}$

$$= 4f\varphi_m$$

We know that, the rate of change of flux per turn means that the induced emf in volts.

Therefore, average emf induced per turn $= 4f\varphi_m$ volts.

Since the flux is varying sinusoidally, the rms value of induced emf is obtained by multiplying the average value by the form factor .

Therefore, rms value of emf induced per turns $= 1.11 \times 4f \times \varphi_m$

$= 4.44f\varphi_m$ volts

The rms value of induced emfin the entire primary winding = (induced emf per turn) × number of primary turns

i.e, $E_1 = 4.44f\varphi_m \times N_1 = 4.44fB_m \times A \times N_1$

Similarly;

$E_2 = 4.44\ f\ \varphi_m \times N_2 = 4.44\ f\ B_m \times A \times N_2$

Transformation Ratio:

(1) Voltage Transformation Ratio

(2) Current Transformation Ratio

Voltage Transformation Ratio:

Voltage transformation ratio can be defined as the ratio of the secondary voltage to the primary voltage denoted by K.

Mathematically given as $K = \frac{Secondary\ Voltage}{PrimarPrimar\ Voltage} = \frac{V_2}{V_1}$

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

$$K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Current Transformation Ratio:

Consider an ideal transformer and we have the input voltampere is equal to output voltampere. Mathematically, Input Voltampere = Output Voltampere

$$V_1 I_1 = V_2 I_2$$

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

$$\therefore,\ K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

TRANSFORMER ON NO-LOAD

Theory of Transformer On No-load, and Having No Winding Resistance and No Leakage Reactance of Transformer

Let us consider one electrical transformer with only core losses, which means, it has only core losses but no copper loss and no leakage reactance of transformer. When an alternating source is applied in the primary, the source will supply the current for magnetizing the core of transformer.

But this current is not the actual magnetizing current, it is little bit greater than actual magnetizing current. Actually, total current supplied from the source has two components, one is magnetizing current which is merely utilized for magnetizing the core and other component of the source current is consumed for compensating the core losses in transformer. Because of this core loss component, the source current in **transformer on no-load** condition supplied from the source as source current is not exactly at 90° lags of supply voltage, but it lags behind an angle θ is less than 90°. If total current supplied from source is I_o, it will have one component in phase with supply voltage V_1 and this component of the current I_w is core loss component. This component is taken in phase with source voltage, because it is associated with active or working losses in transformer. Other component of the source current is denoted as I_μ. This component produces the alternating magnetic flux in the core, so it is watt-less; means it is reactive part of the transformer source current. Hence I_μ will be in quadrature with V_1 and in phase with alternating flux Φ.

Hence, total primary current in **transformer on no-load** condition can be represented as

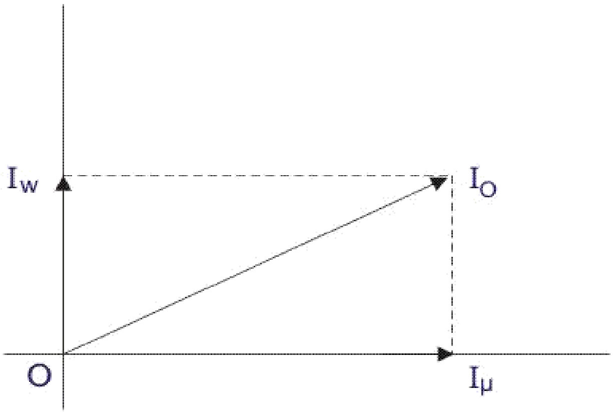
$$I_0 = I_\mu + I_w$$

$$|I_\mu| = |I_0| \cos\theta$$

$$|I_w| = |I_0| \sin\theta$$

$$|I_w| = \sqrt{|I_\mu|^2 + |I_w|^2}$$

Now you have seen how simple is to explain the **theory of transformer** in no-load.

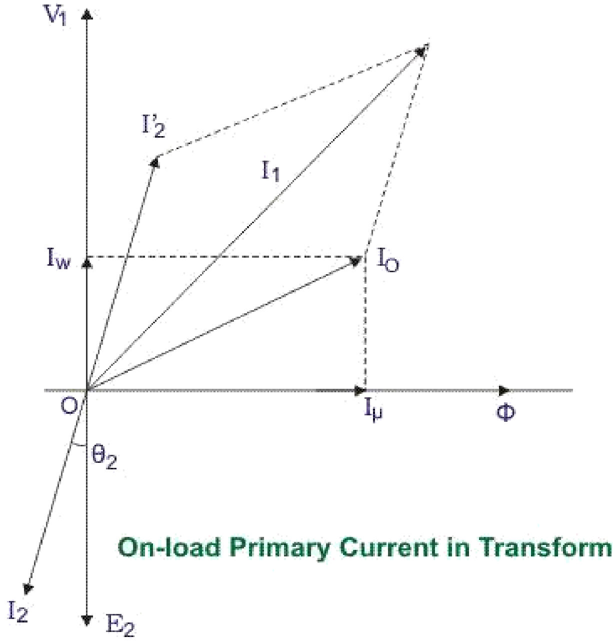


Excitation Current of Transformer

TRANSFORMER ON LOAD

Theory of Transformer On Load But Having No Winding Resistance and Leakage Reactance

Now we will examine the behavior of above said **transformer on load**, that means load is connected to the secondary terminals. Consider, transformer having core loss but no copper loss and leakage reactance. Whenever load is connected to the secondary winding, load current will start to flow through the load as well as secondary winding. This load current solely depends upon the characteristics of the load and also upon secondary voltage of the transformer. This current is called secondary current or load current, here it is denoted as I_2. As I_2 is flowing through the secondary, a self mmf in secondary winding will be produced. Here it is N_2I_2, where, N_2 is the number of turns of the secondary winding of transformer.



On-load Primary Current in Transformer

This mmf or magneto motive force in the secondary winding produces flux φ_2. This φ_2 will oppose the main magnetizing flux and momentarily weakens the main flux and tries to reduce primary self induced emf E_1. If E_1 falls down below the primary source voltage V_1, there will be an extra current flowing from source to primary winding. This extra primary current I_2' produces extra flux φ′ in the core which will neutralize the secondary counter flux φ_2. Hence the main magnetizing flux of core, Φ remains unchanged irrespective of load.

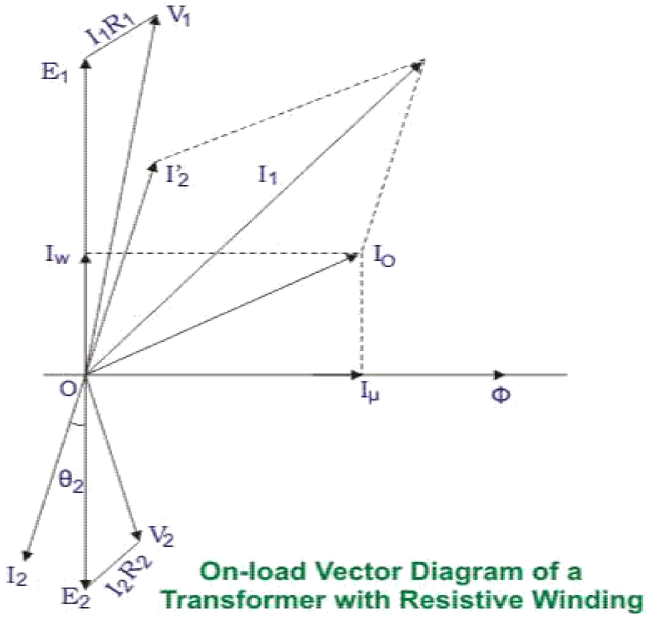
So total current, this transformer draws from source can be divided into two components, first one is utilized for magnetizing the core and compensating the core loss i.e. I_o. It is no-load component of the primary current. Second one is utilized for compensating the counter flux of the secondary winding. It is known as load component of the primary current. Hence total no load primary current I_1 of a electrical power transformer having no winding resistance and leakage reactance can be represented as follows

$$I_1 = I_0 + I_2'$$

Where θ_2 is the angle between Secondary Voltage and Secondary Current of transformer. Now we will proceed one further step toward more practical aspect of a transformer.

Transformer On Load, With Resistive Winding, But No Leakage Reactance

Now, consider the winding resistance of transformer but no leakage reactance. So far we have discussed about the transformer which has ideal windings, means winding with no resistance and leakage reactance, but now we will consider one transformer which has internal resistance in the winding but no leakage reactance. As the windings are resistive, there would be a voltage drop in the windings.



On-load Vector Diagram of a Transformer with Resistive Winding

We have proved earlier that, total primary current from the source on load is I_1. The voltage drop in the primary winding with resistance, R_1 is R_1I_1. Obviously, induced emf across primary winding E_1, is not exactly equal to source voltage V_1. E_1 is less than V_1 by voltage drop I_1R_1.

$$V_1 = E_1 + I_1R_1$$

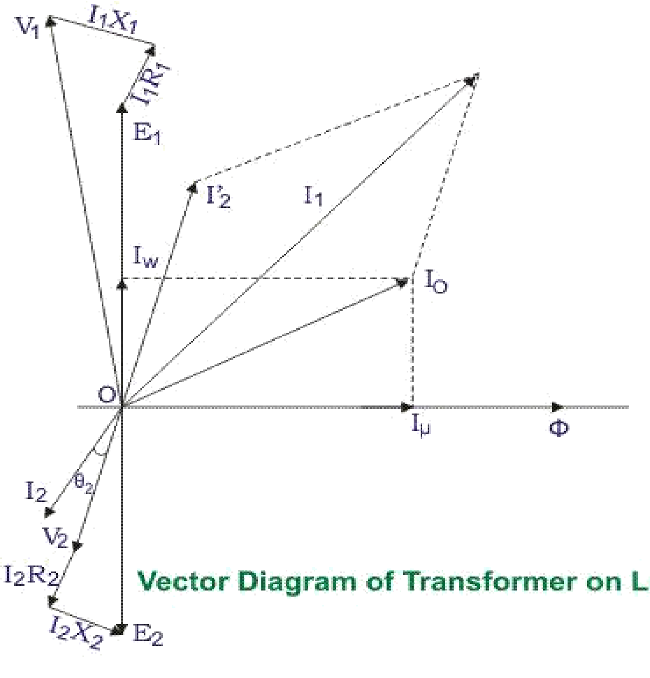
Again in the case of secondary, the voltage induced across the secondary winding, E_2 does not totally appear across the load since it also drops by an amount I_2R_2, where R_2 is the secondary winding resistance and I_2 is secondary current or load current.

Similarly, voltage equation of the secondary side of the transformer will be

$$V_2 = E_2 - I_2R_2$$

Theory of Transformer On Load, With Resistance As Well As Leakage Reactance in Transformer Windings

Now we will consider the condition, when there is leakage reactance of transformer as well as winding resistance of transformer.



Vector Diagram of Transformer on Load

Let leakage reactances of primary and secondary windings of the transformer are X_1 and X_2 respectively.

Hence total impedance of primary and secondary winding of transformer with resistance R_1 and R_2 respectively, can be represented as,

$$Z_1 = R_1 + jX_1 \ (impedance\ of\ primary\ winding)$$

$$Z_2 = R_2 + jX_2 \ (impedance\ of\ secondary\ winding)$$

We have already established the voltage equation of a **transformer on load**, with only resistances in the windings, where voltage drops in the windings occur only due to resistive voltage drop. But when we consider leakage reactances of transformer windings, voltage drop occurs in the winding not only because of resistance, it is because of impedance of transformer windings. Hence, actual voltage equation of a transformer can easily be determined by just replacing resistances R_1 & R_2 in the previously established voltage equations by Z_1 and Z_2.

Therefore, the voltage equations are,

$$V_1 = E_1 + I_1Z_1 \ \& \ V_2 = E_2 - I_2Z_2$$

$$V_1 = E_1 + I_1(R_1 + jX_1)$$

$$\Rightarrow V_1 = E_1 + I_1R_1 + jI_1X_1$$

$$V_2 = E_2 - I_2(R_2 + jX_2)$$

$$\Rightarrow V_2 = E_2 - I_2R_2 - jI_2X_2$$

Resistance drops are in the direction of current vector but, reactive drop will be perpendicular to the current vector as shown in the above **vector diagram** of **transformer**.

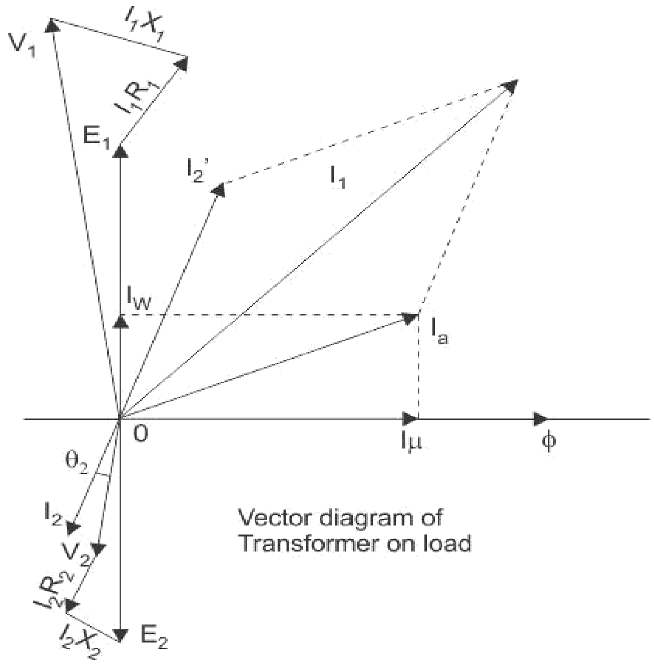
Equivalent Circuit of Transformer

Equivalent impedance of transformer is essential to be calculated because the electrical power transformer is an electrical power system equipment for estimating different parameters of electrical power system which may be required to calculate total internal impedance of an electrical power transformer, viewing from primary side or secondary side as per requirement. This calculation requires equivalent circuit of transformer referred to primary **or** equivalent circuit of transformer referred to secondary sides respectively. Percentage impedance is also very essential parameter of transformer. Special attention is to be given to this parameter during installing a transformer in an existing electrical power system. Percentage impedance of different power transformers should be properly matched during parallel operation of power transformers. The percentage impedance can be derived from equivalent impedance of transformer so, it can be said that equivalent circuit of transformer is also required during calculation of % impedance.

Equivalent Circuit of Transformer Referred to Primary

For drawing equivalent circuit of transformer referred to primary, first we have to establish general equivalent circuit of transformer then, we will modify it for referring from primary side. For doing this, first we need to recall the complete vector diagram of a transformer which is shown in the figure below

.



Vector diagram of Transformer on load

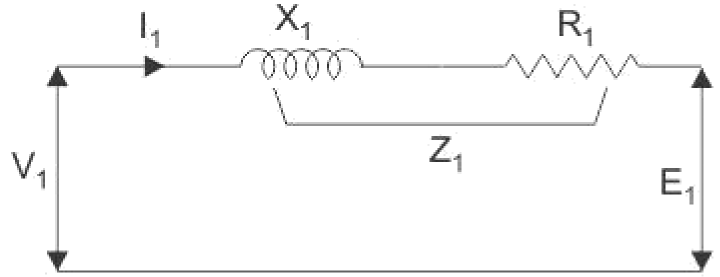
Let us consider the transformation ratio be,

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

In the figure above, the applied voltage to the primary is V_1 and voltage across the primary winding is E_1. Total current supplied to primary is I_1. So the voltage V_1 applied to the primary is partly dropped by I_1Z_1 or $I_1R_1 + j.I_1X_1$ before it appears across primary winding. The voltage appeared across winding is countered by primary induced emf E_1. So voltage equation of this portion of the transformer can be written as,

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

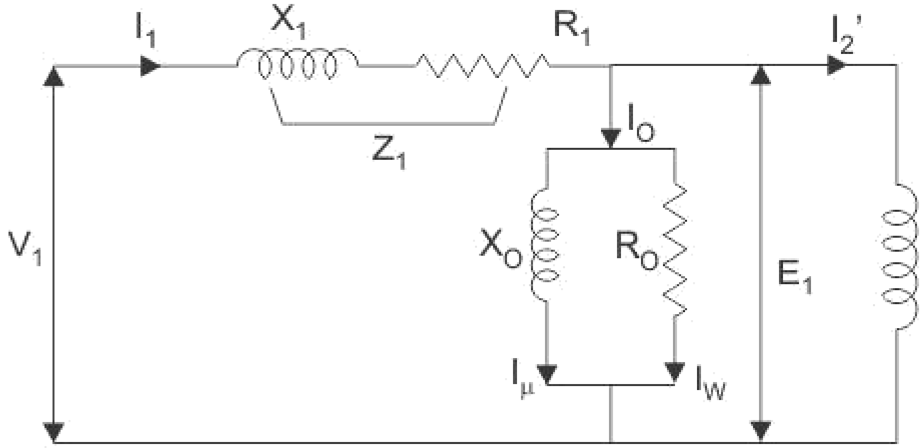
The equivalent circuit for that equation can be drawn as below,



Equivalent Circuit

From the vector diagram above, it is found that the total primary current I_1 has two components, one is no - load component I_o and the other is load component I_2'. As this primary current has two components or branches, so there must be a parallel path with primary winding of transformer. This parallel path of current is known as excitation branch of equivalent circuit of transformer. The resistive and reactive branches of the excitation circuit can be represented as

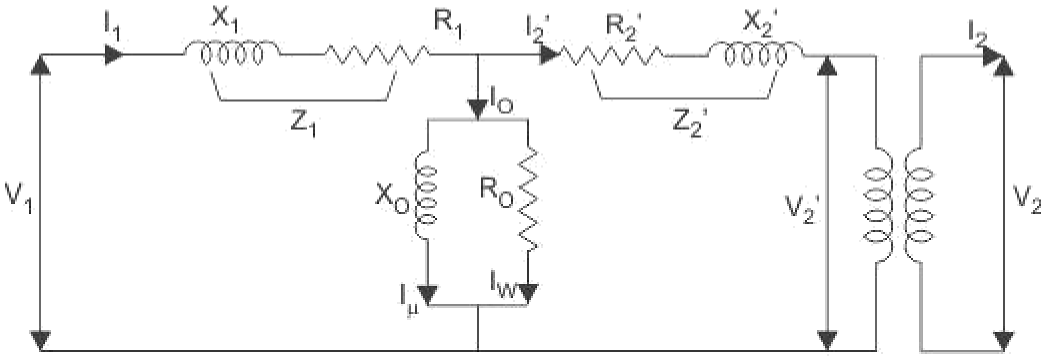
$$R_0 = \frac{E_1}{I_w}\ and\ X_0 = \frac{E_1}{I_\mu}$$



Equivalent Circuit of Primary Side of Transformer

The load component I_2' flows through the primary winding of transformer and induced voltage across the winding is E_1 as shown in the figure right. This induced voltage E_1 transforms to secondary and it is E_2 and load component of primary current I_2' is transformed to secondary as secondary current I_2. Current of secondary is I_2. So the voltage E_2 across secondary winding is partly dropped by I_2Z_2 or $I_2R_2 + j.I_2X_2$ before it appears across load. The load voltage is V_2.

The complete equivalent circuit of transformer is shown below.



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,

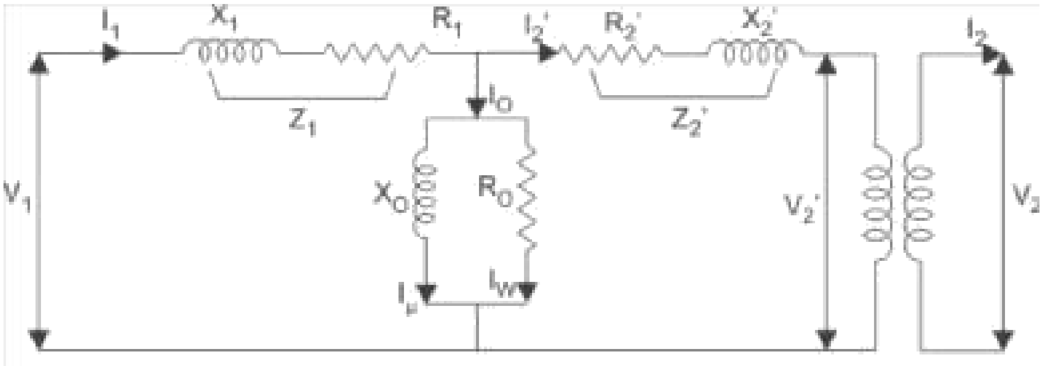
$$KZ_2I_2 = KZ_2KI_2' = K^2Z_2I_2'$$

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 below,

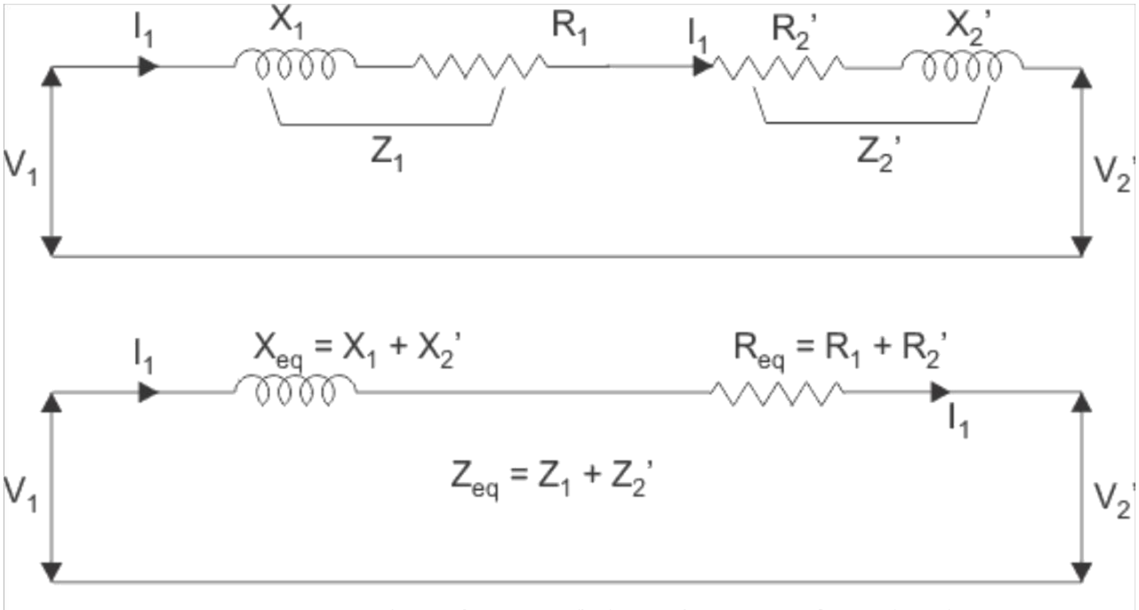


Equivalent Circuit of Transformer referred to Primary

Approximate Equivalent Circuit of Transformer

Since I_o is very small compared to I_1, it is less than 5% of full load primary current, I_o changes the voltage drop insignificantly. Hence, it is good approximation to ignore the excitation circuit in approximate equivalent circuit of transformer. The winding resistance and reactance being in series can now be combined into equivalent resistance and reactance of transformer, referred to any particular side. In this case it is side 1 or primary side.

$$\boxed{Here,\ V_2' = KV_2}$$



Approximate Equivalent Circuit of Transformer referred to Primary

Equivalent Circuit of Transformer Referred to Secondary

In similar way, approximate equivalent circuit of transformer referred to secondary can be drawn.

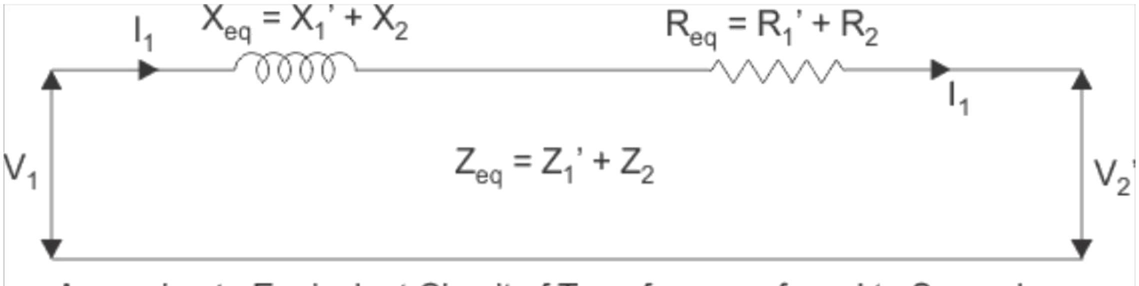
Where equivalent impedance of transformer referred to secondary, can be derived as

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

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

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

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



Approximate Equivalent Circuit of Transformer referred to Secondary

Losses in Transformer:

Losses of transformer are divided mainly into two types:

1. Iron Loss
2. Copper Losses

IRON LOSS:

This is the power loss that occurs in the iron part. This loss is due to the alternating frequency of the emf. Iron loss in further classified into two other losses.

a) Eddy current loss

b) Hysterisis loss

a) Eddy Current Loss:

This power loss is due to the alternating flux linking the core, which will induced an emf in the core called the eddy emf, due to which a current called the eddy current is being circulated in the core. As there is some resistance in the core with this eddy current circulation converts into heat called the eddy current power loss. Eddy current loss is proportional to the square of the supply frequency.

b) Hysterisis Loss:

This is the loss in the iron core, due to the magnetic reversal of the flux in the core, which results in the form of heat in the core. This loss is directly proportional to the supply frequency.

Eddy current loss can be minimized by using the core made of thin sheets of silicon steel material, and each lamination is coated with varnish insulation to suppress the path of the eddy currents. Hysterisis loss can be minimized by using the core material having high permeability.

COPPER LOSS:

This is the power loss that occurs in the primary and secondary coils when the transformer is on load. This power is wasted in the form of heat due to the resistance of the coils. This loss is proportional to the sequence of the load hence it is called the Variable loss where as the Iron loss is called as the Constant loss as the supply voltage and frequency are constants

EFFICIENCY:

It is the ratio of the output power to the input power of a transformer

Input = Output + Total losses

= Output + Iron loss + Copper loss

Efficiency =

$$\eta = \frac{outputpower}{outputpower + Ironloss + copperloss}$$

$$= \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + W_{eron} + W_{copper}}$$

Where, V_2 is the secondary (output) voltage, I_2 is the secondary (output) current and cosΦ is the power factor of the load.

The transformers are normally specified with their ratings as KVA,

Therefore,

$$Efficiency; \eta = \frac{(KVA) \times 10^3 \times cos\varphi}{(KVA) \times 10^3 \times cos\varphi \times W_{iron} + W_{copper}}$$

Since the copper loss varies as the square of the load the efficiency of the transformer at any desired load *n* is given by

$$Efficiency; \eta = \frac{n \times (KVA) \times 10^3 \times cos\varphi}{n \times (KVA) \times 10^3 \times cos\varphi \times W_{iron} + n^2 \times W_{copper}}$$

where,

Wcopper is the copper loss at full load

Wcopper = I^2R watts

CONDITION FOR MAXIMUM EFFICIENCY:

In general for the efficiency to be maximum for any device the losses must be minimum. Between the iron and copper losses the iron loss is the fixed loss and the copper loss is the variable loss. When these two losses are equal and also minimum the efficiency will be maximum.

Therefore the condition for maximum efficiency in a transformer

is Copper loss = Iron loss

VOLTAGE REGULATION:

The voltage regulation of a transformer is defined as the change in the secondary terminal voltage between no load and full load at a specified power factor expressed as a percentage of the full load terminal voltage.

$$\%Voltage\ Regulation = \frac{(no\ load\ Sec.Voltage) - (full\ load\ Sec.Voltage)}{full\ load\ Sec.Voltage} \times 100$$

Voltage regulation is a measure of the change in the terminal voltage of a transformer between No load and Full load. A good transformer has least value of the regulation of the order of **±5%**

O.C. and S.C. Tests on Single Phase Transformer

The efficiency and regulation of a transformer on any load condition and at any power factor condition can be predetermined by indirect loading method. In this method, the actual load is not used on transformer. But the equivalent circuit parameters of a transformer are determined by conducting two tests on a transformer which are,

1. Open circuit test (O.C Test)
2. Short circuit test (S.C.Test)

The parameters calculated from these test results are effective in determining the regulation and efficiency of a transformer at any load and power factor condition, without actually loading the transformer. The advantage of this method is that without much power loss the tests can be performed and results can be obtained. Let us discuss in detail how to perform these tests and how to use the results to calculate equivalent circuit parameters.

Open Circuit Test (O.C. Test)

The experimental circuit to conduct O.C test is shown in the Fig. 1.

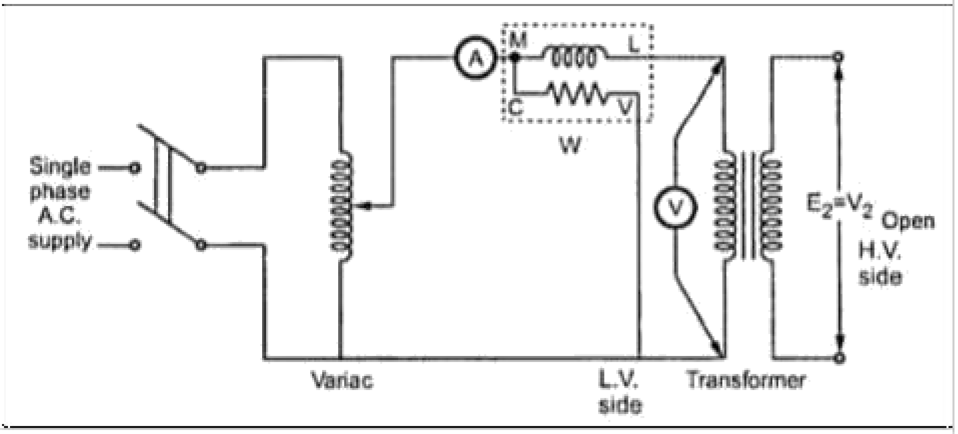


Fig 1. Experimental circuit for O.C. test

The transformer primary is connected to a.c. supply through ammeter, wattmeter and variac. The secondary of transformer is kept open. Usually low voltage side is used as primary and high voltage side as secondary to conduct O.C test.

The primary is excited by rated voltage, which is adjusted precisely with the help of a variac. The wattmeter measures input power. The ammeter measures input current. The voltemeter gives the value of rated primary voltage applied at rated frequency.

Sometimes a voltmeter may be connected across secondary to measure secondary voltage which is $V_2 = E_2$ when primary is supplied with rated voltage. As voltmeter resistance is very high, though voltmeter is connected, secondary is treated to be open circuit as voltmeter current is always negligibly small.

When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeter and wattmeter are to be recorded.

Let,

V_o = Rated voltage

W_o = Input power

I_o = Input current = no load current

As transformer secondary is open, it is on no load. So current drawn by the primary is no load current I_o. The two components of this no load current are,

$$I_m = I_o \sin \Phi_o$$

$$I_c = I_o \cos \Phi_o$$

where $\cos \Phi_o$ = No load power factor

And hence power input can be written as,

$$W_o = V_o I_o \cos \Phi_o$$

The phasor diagram is shown in the Fig.

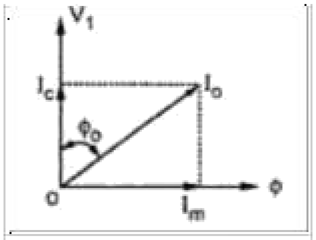


Fig.

As secondary is open, $I_2 = 0$. Thus its reflected current on primary is also zero. So we have primary current $I_1 = I_o$. The transformer no load current is always very small, hardly 2 to 4 % of its full load value. As $I_2 = 0$, secondary copper losses are zero. And $I_1 = I_o$ is very low hence copper losses on primary are also very very low. Thus the total copper losses in O.C. test are negligibly small. As against this the input voltage is rated at rated frequency hence flux density in the core is at its maximum value. Hence iron losses are at rated voltage. As output power is zero and copper losses are very low, the total input power is used to supply iron losses. This power is measured by the wattmeter i.e. W_o. Hence the wattmeter in O.C. test gives iron losses which remain constant for all the loads.

$$\therefore \quad W_o = P_i = \text{Iron losses}$$

Calculations : We know that,

$$W_o = V_o I_o \cos \Phi$$

$$\cos \Phi_o = W_o / (V_o I_o) = \text{no load power factor}$$

Once $\cos \Phi_o$ is known we can obtain,

$$I_c = I_o \cos \Phi_o$$

and $$I_m = I_o \sin \Phi_o$$

Once I_c and I_m are known we can determine exciting circuit parameters as,

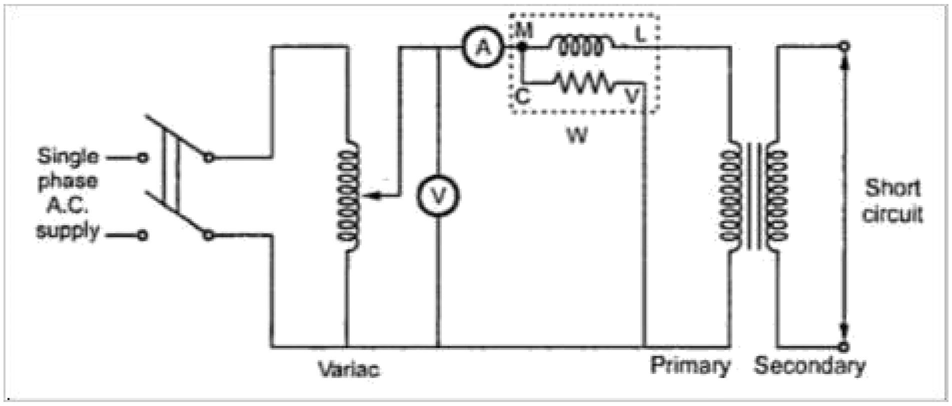
$$R_o = V_o / I_c \ \Omega$$

and $$X_o = V_o / I_m \ \Omega$$

Key Point : The no load power factor $\cos \Phi_o$ is very low hence wattmeter used must be low power factor type otherwise there might be error in the results. If the meters are connected on secondary and primary is kept open then from O.C. test we get $R_o'$and X_o' with which we can obtain R_o and X_o knowing the transformation ratio K.

Short Circuit Test (S.C. Test)

In this test, primary is connected to a.c. supply through variac, ammeter and voltmeter as shown in the Fig. 3.



Experimental circuit for O.C. test

The secondary is short circuited with the help of thick copper wire or solid link. As high voltage side is always low current side, it is convenient to connect high voltage side to supply and shorting the low voltage side.

As secondary is shorted, its resistance is very very small and on rated voltage it may draw very large current. Such large current can cause overheating and burning of the transformer. To limit this short circuit current, primary is supplied with low voltage which is just enough to cause rated current to flow through primary which can be observed on an ammeter. The low voltage can be adjusted with the help of variac. Hence this test is also called low voltage test or reduced voltage test. The wattmeter reading as well as voltmeter, ammeter readings are recorded.

Now the current flowing through the windings are rated current hence the total copper loss is full load copper loss. Now the voltage supplied is low which is a small fraction of the rated voltage. The iron losses are function of applied voltage. So the iron losses in reduced voltage test are very small. Hence the wattmeter reading is the power loss which is equal to full load copper losses as iron losses are very low.

$\therefore$ $W_{sc} = (P_{cu})$ F.L. = Full load copper loss

Calculations : From S.C. test readings we can write,

$W_{sc} = V_{sc} I_{sc} \cos \Phi_{sc}$

$\therefore$ $\cos \Phi sc = V_{sc} I_{sc} / W_{sc}$ = short circuit power factor

$W_{sc} = I_{sc}^2 R_{1e}$ = copper loss

$\therefore$ $R_{1e} = W_{sc} / I_{sc}^2$

while $Z_{1e} = V_{sc} / I_{sc} = \sqrt{(R_{1e}^2 + X_{1e}^2)}$

$\therefore$ $X_{1e} = \sqrt{(Z_{1e}^2 - R_{1e}^2)}$

Thus we get the equivalent circuit parameters R_{1e}, X_{1e} and Z_{1e}. Knowing the transformation ratio K, the equivalent circuit parameters referred to secondary also can be obtained.

Important Note : If the transformer is step up transformer, its primary is L.V. while secondary is H.V. winding. In S.C. test, supply is given to H.V. winding and L.V is shorted. In such case we connect meters on H.V. side which is transformer secondary through for S.C. test purpose H.V side acts as primary. In such case the parameters calculated from S.C. test readings are referred to secondary which are R_{2e}, Z_{2e} and X_{2e}. So before doing calculations it is necessary to find out where the readings are recorded on transformer primary or secondary and accordingly the parameters are to be determined. In step down transformer, primary is high voltage itself to which supply is given in S.C. test. So in such case test results give us parameters referred to primary i.e. R_{1e}, Z_{1e} and X_{1e}.

Key point : In short, if meters are connected to primary of transformer in S.C. test, calculations give us R_{1e} and Z_{1e} if meters are connected to secondary of transformer in S.C. test calculations give us R_{2e} and Z_{2e}.

Calculation of Efficiency from O.C. and S.C. Tests

We know that,

From O.C. test, $W_o = P_i$

From S.C. test, $W_{sc} = (P_{cu})$ F.L.

$$\therefore \quad \%\,\eta \text{ on full load} = \frac{V_2\,(I_2)\,\text{F.L.}\cos\phi}{V_2\,(I_2)\,\text{F.L.}\cos + W_o + W_{sc}} \times 100$$

Thus for any p.f. $\cos \Phi_2$ the efficiency can be predetermined. Similarly at any load which is fraction of full load then also efficiency can be predetermined as,

$$\boxed{\%\,\eta \text{ at any load} = \frac{n \times (\text{VA rating}) \times \cos\phi}{n \times (\text{VA rating}) \times \cos\phi + W_o + n^2\,W_{sc}} \times 100}$$

where n = fraction of full load

$$\text{or} \qquad \% \eta = \frac{n V_2 I_2 \cos\phi}{n V_2 I_2 \cos\phi + W_o + n^2 W_{sc}} \times 100$$

where $I_2 = n (I_2)$ F.L.

Calculation of Regulation

From S.C. test we get the equivalent circuit parameters referred to primary or secondary.

The rated voltages V_1, V_2 and rated currents (I_1) F.L. and (I_2) F.L. are known for the given transformer. Hence the regulation can be determined as,

$$\boxed{\begin{aligned} \% R &= \frac{I_2 R_{2e} \cos\phi \pm I_2 X_{2e} \sin\phi}{V_2} \times 100 \\ &= \frac{I_1 R_{1e} \cos\phi \pm I_1 X_{1e} \sin\phi}{V_1} \times 100 \end{aligned}}$$

where I_1, I_2 are rated currents for full load regulation.

For any other load the currents I_1, I_2 must be changed by fraction n.

∴ I_1, I_2 at any other load = n (I_1) F.L., n (I_2) F.L.

Key Point : Thus regulation at any load and any power factor can be predetermined, without actually loading the transformer.

Example 1 : A 5 KVA, 500/250 V, 50 Hz, single phase transformer gave the following readings,

O.C. Test : 500 V, 1 A, 50 W (L.V. side open)

S.C. Test : 25 V, 10 A, 60 W (L.V. side shorted)

Determine : i) The efficiency on full load, 0.8 lagging p.f.

ii) The voltage regulation on full load, 0.8 leading p.f.

iii) The efficiency on 60% of full load, 0.8 leading p.f.

iv) Draw the equivalent circuit referred to primary and insert all the values in it.

Solution : In both the tests, meters are on H.V. side which is primary of the transformer. Hence the parameters obtained from test results will be referred to primary.

From O.C. test, $V_o = 500$ V, $I_o = 1$ A, $W_o = 50$ W

∴ $\cos \Phi_o = W_o / V_o I_o = 50/(500 \text{x} 1) = 0.1$

∴ $I_c = I_o \cos = 1 \text{ x } 0.1 = 0.1$ A and $I_m = I_o \sin \Phi_o = 1 \times 0.9949 = 0.9949$ A

∴ $R_o = V_o / I_c = 500/0.1 = 5000\ \Omega$

and $X_o = V_o/I_m = 500/0.9949 = 502.52\ \Omega$

and $W_o = P_i$ = iron losses = 50 W

From S.C. test, $V_{sc} = 25$ V, $I_{sc} = 10$ A, $W_{sc} = 60$ W

∴ $R_{1e} = W_{sc} / I_{sc}^2 = 60/(10)^2 = 0.6\ \Omega$

$Z_{1e} = V_{sc} / I_{sc} = 25/10 = 2.5\ \Omega$

∴ $X_{1e} = \sqrt{(2.5^2 - 0.6^2)} = 2.4269\ \Omega$

(I_1) F.L. = VA rating/V_1

$= (5 \times 10^3)/500 = 10$ A

and $I_{sc} = (I_1)$ F.L.

∴ $W_{sc} = (P_{cu})$ F.L. = 60 W

i) η on full load, cos = 0.8 lagging

$$\% \eta = \frac{(\text{VA rating}) \cos \phi_2}{(\text{VA rating}) \cos \phi_2 + P_i + (P_{cu})\text{ F. L.}} \times 100$$

$$= \frac{5 \times 10^3 \times 0.8}{5 \times 10^3 \times 0.8 + 50 + 60} \times 100 = \mathbf{97.32\ \%}$$

ii) Regulation on full load, cos Φ_2 = 0.8 leading

$$\% R = \frac{(I_1)\text{ F. L. } R_{1e} \cos \phi - (I_1)\text{ F. L. } X_{1e} \sin \phi}{V_1} \times 100$$

$$= \frac{10 \times 0.6 \times 0.8 - 10 \times 2.4269 \times 0.6}{500} \times 100$$

$= -1.95\ \%$

iii) For 60% of full load, n = 0.6 and cos Φ_2 = 0.8 leading]

∴ P_{cu} = copper loss on new load = $n^2 \times (P_{cu})$ F.L.

$= (0.6)^2 \times 60 = 21.6$ W

$= 97.103\ \%$

iv) The equivalent circuit referred to primary is shown in the Fig. 4.

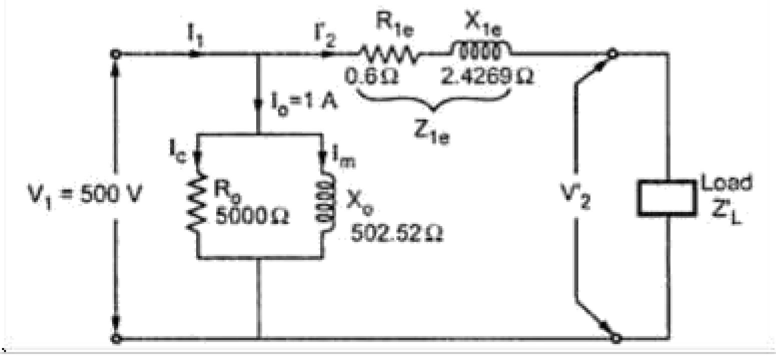


Fig. 4

Example 2 : The open circuit and short circuit tests on a 10 KVA, 125/250 V, 50 Hz, single phase transformer gave the following results :

O.C. test : 125 V, 0.6 A, 50 W (on L.V. side)

S.C. test : 15 V, 30 A. 100 W (on H.V. side)

Calculate : i) copper loss on full load

ii) full load efficiency at 0.8 leading p.f.

iii) half load efficiency at 0.8 leading p.f.

iv) regulation at full load, 0.9 leading p.f.

Solution : From O.C. test we can weite,

$W_o = P_i$ = 50 W = Iron loss

From S.C. test we can find the parameters of equivalent circuit. Now S.C. test is conducted on H.V. side i.e. meters are on H.V. side which is transformer secondary. Hence parameters from S.C. test results will be referred to secondary.

V_{sc} = 15 V, I_{sc} = 30 A, W_{sc} = 100 W

$\therefore \quad R_{2e} = W_{sc}/(I_{sc})^2 = 10/(30)^2 = 0.111\Omega$

$Z_{1e} = V_{sc}/I_{sc} = 15/30 = 0.5\ \Omega$

$\therefore \quad X_{2e} = \sqrt{(Z_{2e}^2 - R_{2e}^2)} = 0.4875\ \Omega$

i) Copper loss on full load

(I_2) F.L. = VA rating/V_2 = $(10 \times 10^3)/250$ = 40 A

In short circuit test, I_{sc} = 30 A and not equal to full load value 40 A.

Hence W_{sc} does not give copper loss on full load

∴ $W_{sc} = P_{cu}$ at 30 A = 100 W

Now $P_{cu} \, \alpha \, I^2$

(P_{cu} at 30 A)/(P_{cu} at 40 A) = $(30/40)^2$

100/(P_{cu} at 40 A) = 900/1600

P_{cu} at 40 A = 177.78 W

∴ (P_{cu}) F.L. = 177.78 W

ii) Full load η , cos Φ_2 = 0.8

$$\% \eta \text{ on full load} = \frac{V_2(I_2)\text{ F. L. } \cos\phi_2}{V_2(I_2)\text{ F. L.} \cos\phi_2 + P_i + (P_{cu})\text{ F. L.}} \times 100$$

$$= \frac{250 \times 40 \times 0.8}{250 \times 40 \times 0.8 + 50 + 177.78} \times 100 = \mathbf{97.23\ \%}$$

iii) Half load η , cos Φ_2 = 0.8

n = 0.5 as half load, (I_2) H.L. = 0.5 x 40 = 20

$$\therefore \quad \% \eta \text{ on half load} = \frac{V_2(I_2)\text{ H. L. } \cos\phi_2}{V_2(I_2)\text{ H. L.} \cos\phi_2 + P_i + n^2(P_{cu})\text{ F. L.}} \times 100$$

$$= \frac{n\,(\text{VA rating}) \cos\phi_2}{n\,(\text{VA rating}) \cos\phi_2 + P_i + n^2(P_{cu})\text{ F. L.}} \times 100$$

$$= \frac{0.5 \times 10 \times 10^3 \times 0.8}{0.5 \times 10 \times 10^3 \times 0.8 + 50 + (0.5)^2 \times 177.78} \times 100$$

= 97.69%

iv) Regulation at full load, cos Φ = 0.9 leading

$$\% R = \frac{(I_2)\text{ F.L.} R_{2e} \cos\phi - (I_2)\text{ F.L. } X_{2e} \sin\phi}{V_2} \times 100$$

$$= \frac{40 \times 0.111 \times 0.9 - 40 \times 0.4875 \times 0.4358}{250} \times 100$$

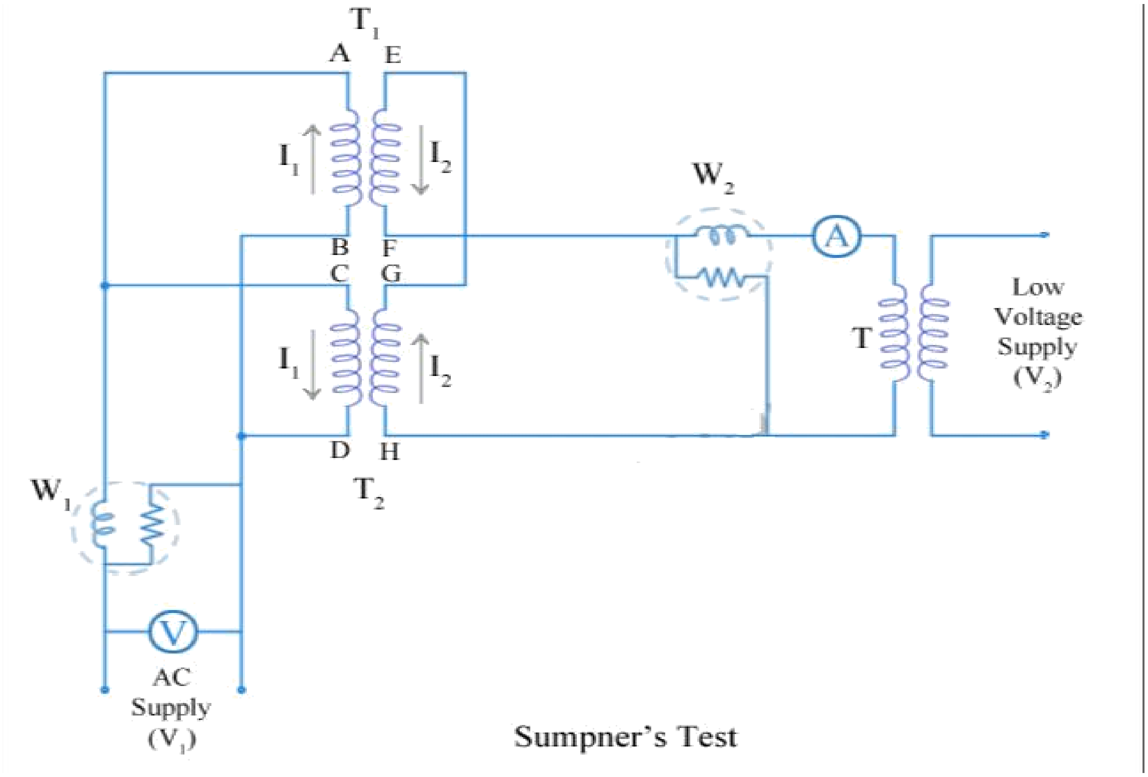
= -1.8015%

Sumpner's Test Or Back-To-Back Test On Transformer

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they cannot help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test give more accurate results of regulation and efficiency than O.C. and S.C. tests.

Sumpner's Test

Sumpner's test or back to back test can be employed only when two identical transformers are available. Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical transformers are connected in parallel across a supply. Secondaries are connected in series such that emf's of them are opposite to each other. Another low voltage supply is connected in series with secondaries to get the readings, as shown in the circuit diagram shown below.



Sumpner's Test

In above diagram, T_1 and T_2 are identical transformers. Secondaries of them are connected in voltage opposition, i.e. E_{EF} and E_{GH}. Both the emf's cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated. The current drawn from V_1 is $2I_0$, where I_0 is equal to no load current of each transformer. Thus input power measured by wattmeter W_1 is equal to iron losses of both transformers.
i.e. iron loss per transformer $P_i = W_1/2$.

Now, a small voltage V_2 is injected into secondary with the help of a low voltage transformer. The voltage V_2 is adjusted so that, the rated current I_2 flows through the secondary. In this case, both primaries and secondaries carry rated current. Thus short circuit test is simulated and wattmeter W_2 shows total full load copper losses of both transformers.
i.e. copper loss per transformer $P_{Cu} = W_2/2$.

From above test results, the **full load efficiency of each transformer** can be given as –

$$\text{\% full load efficiency of each transformer} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

Predetermination of Voltage Regulation

Modern power systems operate at some standard voltages. The equipments working on these systems are therefore given input voltages at these standard values, within certain agreed tolerance limits. In many applications this voltage itself may not be good enough for obtaining the best operating condition for the loads. A transformer is interposed in between the load and the supply terminals in such cases. There are additional drops inside the transformer due to the load currents. While input voltage is the responsibility of the supply provider, the voltage at the load is the one which the user has to worry about.

If undue voltage drop is permitted to occur inside the transformer the load voltage becomes too low and affects its performance. It is therefore necessary to quantify the drop that takes place inside a transformer when certain load current, at any power factor, is drawn from its output leads. This drop is termed as the voltage regulation and is expressed as a ratio of the terminal voltage (the absolute value per se is not too important).

The voltage regulation can be defined in two ways - Regulation Down and Regulation up. These two definitions differ only in the reference voltage as can be seen below. Regulation down: This is defined as ‖ the change in terminal voltage when a load current at any power factor is applied, expressed as a fraction of the no-load terminal voltage.

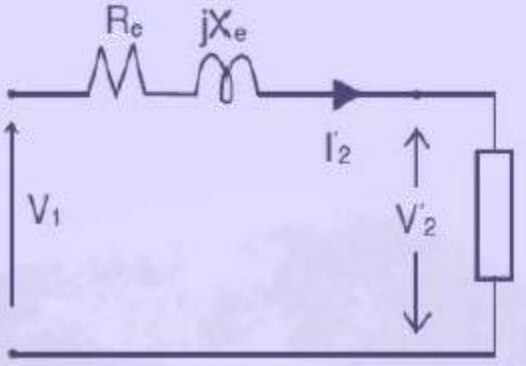
Expressed in symbolic form we have,

$$Regulation = \frac{|V_{nl}| - |V_l|}{|V_l|}$$

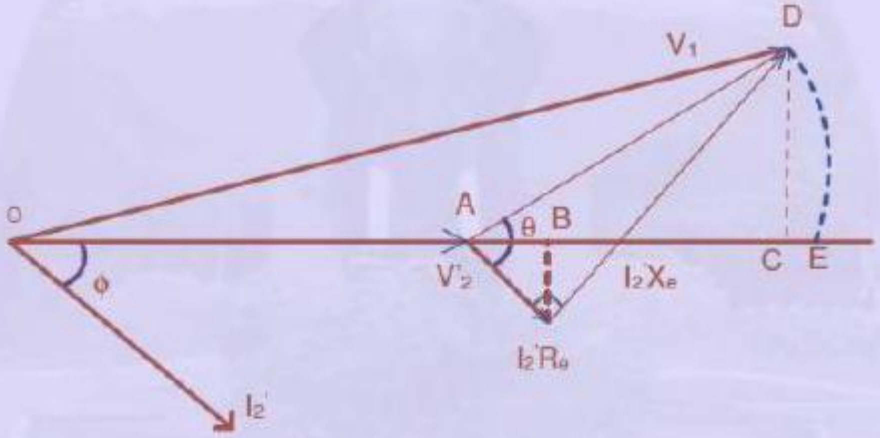
Where,
Vnl is the no-load terminal voltage.
Vl is load voltage.
Normally full load regulation is of interest as the part load regulation is going to be lower.

This definition is more commonly used in the case of alternators and power systems as the user-end voltage is guaranteed by the power supply provider. He has to generate proper no-load voltage at the generating station to provide the user the voltage he has asked for. In the expressions for the regulation, only the numerical differences of the voltages are taken and not vector differences.

In the case of transformers both definitions result in more or less the same value for the regulation as the transformer impedance is very low and the power factor of operation is quite high. The power factor of the load is defined with respect to the terminal voltage on load. Hence a convenient starting point is the load voltage. Also the full load output voltage is taken from the name plate. Hence regulation up has some advantage when it comes to its application. Fig. 23 shows the phasor diagram of operation of the transformer under loaded condition. The no-load current I0 is neglected in view of the large magnitude of I‘2.



(a) Equivalent Circuit



(b)Phasor Diagram

Fig. Regulation of Transformer

$I_1 = I'_2$.

$$V_1 = I'_2(R_e + jX_e) + V'_2$$

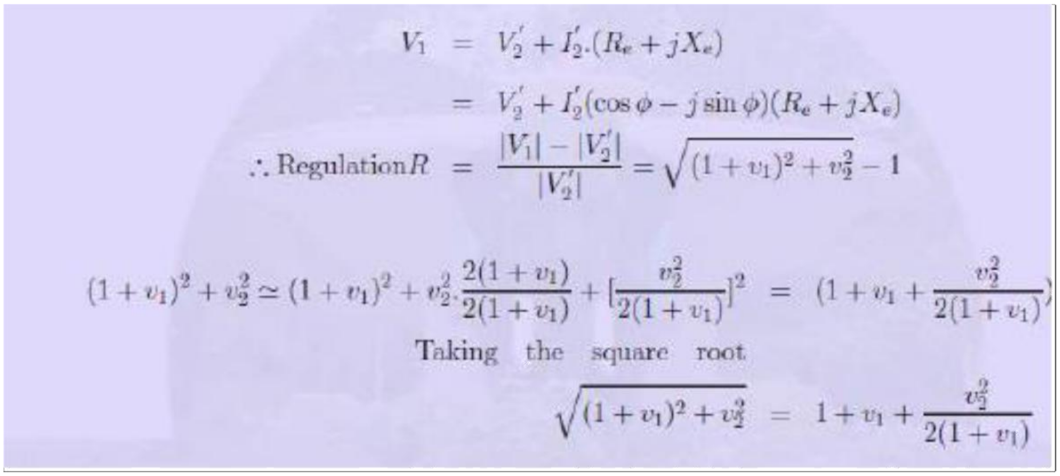
$$OD = V_1 = \sqrt{[OA + AB + BC]^2 + [CD]^2}$$

$$= \sqrt{[V'_2 + I'_2 R_e \cos\phi + I'_2 X_e \sin\phi]^2 + [I'_2 X_e \cos\phi - I'_2 R_e \sin\phi]^2}$$

ϕ - power factor angle,

θ- internal impedance angle=$\tan^{-1}\frac{X_e}{R_e}$

Also,

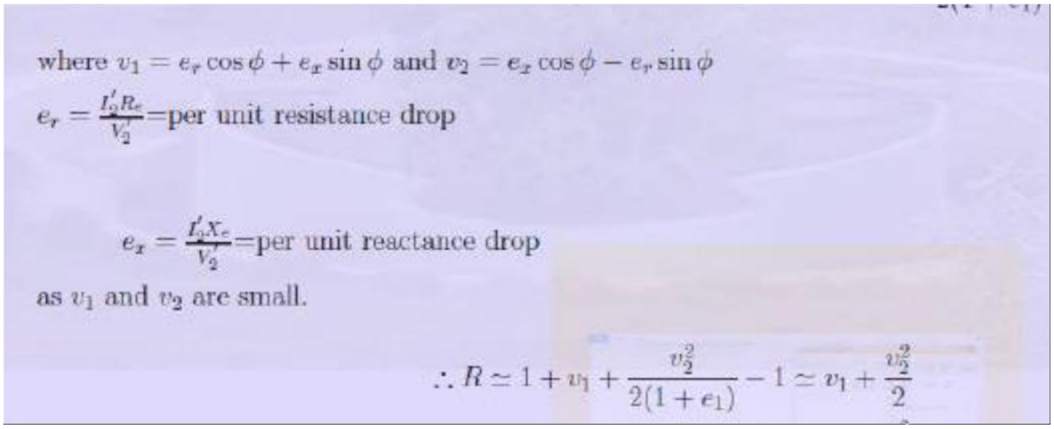


$$\begin{aligned} V_1 &= V_2' + I_2'.(R_e + jX_e) \\ &= V_2' + I_2'(\cos\phi - j\sin\phi)(R_e + jX_e) \\ \therefore \text{Regulation}R &= \frac{|V_1| - |V_2'|}{|V_2'|} = \sqrt{(1+v_1)^2 + v_2^2} - 1 \end{aligned}$$

$$(1+v_1)^2 + v_2^2 \simeq (1+v_1)^2 + v_2^2.\frac{2(1+v_1)}{2(1+v_1)} + [\frac{v_2^2}{2(1+v_1)}]^2 = (1 + v_1 + \frac{v_2^2}{2(1+v_1)})$$

Taking the square root

$$\sqrt{(1+v_1)^2 + v_2^2} = 1 + v_1 + \frac{v_2^2}{2(1+v_1)}$$



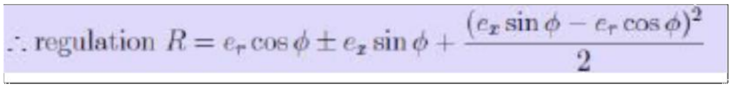
where $v_1 = e_r\cos\phi + e_x\sin\phi$ and $v_2 = e_x\cos\phi - e_r\sin\phi$

$e_r = \frac{I_2'R_e}{V_2'}$=per unit resistance drop

$e_x = \frac{I_2'X_e}{V_2'}$=per unit reactance drop

as v_1 and v_2 are small.

$$\therefore R \simeq 1 + v_1 + \frac{v_2^2}{2(1+e_1)} - 1 \simeq v_1 + \frac{v_2^2}{2}$$



$$\therefore \text{regulation } R = e_r\cos\phi \pm e_x\sin\phi + \frac{(e_x\sin\phi - e_r\cos\phi)^2}{2}$$

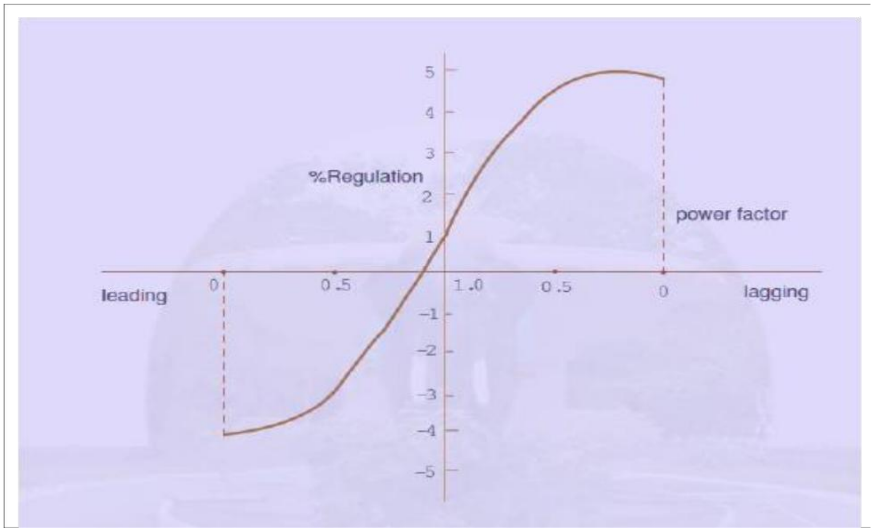
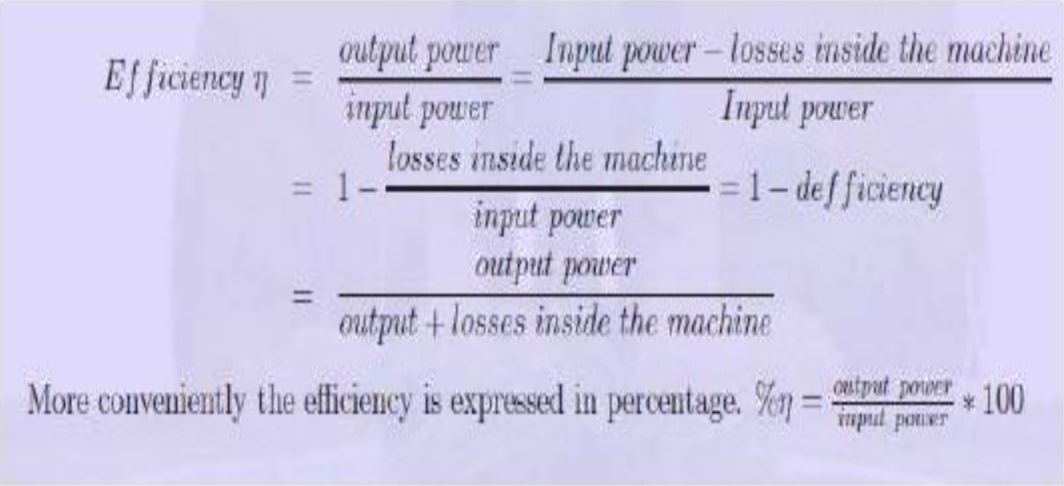


Fig. Variation of full load regulation with power factor

Predetermination of Efficiency

Transformers which are connected to the power supplies and loads and are in operation are required to handle load current and power as per the requirements of the load. An unloaded transformer draws only the magnetization current on the primary side, the secondary current being zero. As the load is increased the primary and secondary currents increase as per the load requirements. The volt amperes and wattage handled by the transformer also increases. Due to the presence of no load losses and I2R losses in the windings certain amount of electrical energy gets dissipated as heat inside the transformer. This gives rise to the concept of efficiency.

Efficiency of power equipment is defined at any load as the ratio of the power output to the power input. Putting in the form of an expression,



$$Efficiency\ \eta = \frac{output\ power}{input\ power} = \frac{Input\ power - losses\ inside\ the\ machine}{Input\ power}$$

$$= 1 - \frac{losses\ inside\ the\ machine}{input\ power} = 1 - defficiency$$

$$= \frac{output\ power}{output + losses\ inside\ the\ machine}$$

More conveniently the efficiency is expressed in percentage. $\%\eta = \frac{output\ power}{input\ power} * 100$

While the efficiency tells us the fraction of the input power delivered to the load, the deficiency focuses our attention on losses taking place inside transformer. As a matter of fact the losses heat up machine. The temperature rise decides the rating of the equipment.

The temperature rise of the machine is a function of heat generated the structural configuration, method of cooling and type of loading (or duty cycle of load). The peak temperature attained directly affects the life of the insulations of the machine for any class of insulation.

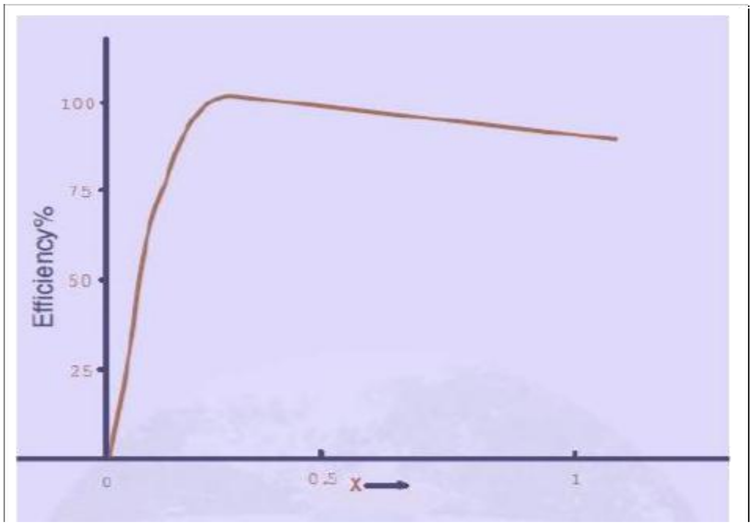


Fig. Efficiency

A typical curve for the variation of efficiency as a function of output is given in Fig. The losses that take place inside the machine expressed as a fraction of the input is sometimes termed as deficiency. Except in the case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handling the power. Thus the value for the efficiency is always less than one. In the case of a.c. machines the rating is expressed in terms of apparent power. It is nothing but the product of the applied voltage and the current drawn. The actual power delivered is a function of the power factor at which this current is drawn. As the reactive power shuttles between the source and the load and has a zero average value over a cycle of the supply wave it does not have any direct effect on the efficiency. The reactive power however increases the current handled by the machine and the losses resulting from it. Therefore the losses that take place inside a transformer at any given load play a vital role in determining the efficiency. The losses taking place inside a transformer can be enumerated as below:

1. Primary copper loss
2. Secondary copper loss
3. Iron loss
4. Dielectric loss
5. Stray load loss

These are explained in sequence below.

Primary and secondary copper losses take place in the respective winding resistances due to the flow of the current in them

$$P_c = I_1^2 r_1 + I_2^2 r_2 = I_2'^2 R_e$$

The primary and secondary resistances differ from their d.c. values due to skin effect and the temperature rise of the windings. While the average temperature rise can be approximately used, the skin effect is harder to get analytically. The short circuit test gives the value of Re taking into account the skin effect.

The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is a function of the material used for the core.

$$P_h = K_h B^{1.6} f$$

For constant voltage and constant frequency operation this can be taken to be constant. The eddy current loss in the core arises because of the induced emf in the steel lamination sheets and the eddies of current formed due to it. This again produces a power loss Pe in the lamination.

$$P_e = K_e B^2 f^2 t^2$$

where t is the thickness of the steel lamination used. As the lamination thickness is much smaller than the depth of penetration of the field, the eddy current loss can be reduced by reducing the thickness of the lamination. Present day laminations are of 0.25 mm thickness and are capable of operation at 2 Tesla. These reduce the eddy current losses in the core. This loss also remains constant due to constant voltage and frequency of operation. The sum of hysteresis and eddy current losses can be obtained by the open circuit test.

The dielectric losses take place in the insulation of the transformer due to the large electric stress. In the case of low voltage transformers this can be neglected. For constant voltage operation this can be assumed to be a constant.

The stray load losses arise out of the leakage fluxes of the transformer. These leakage fluxes link the metallic structural parts, tank etc. and produce eddy current losses in them. Thus they take place ‘all round‘ the transformer instead of a definite place , hence the name ‘stray‘. Also the leakage flux is directly proportional to the load current unlike the mutual flux which is proportional to the applied voltage. Hence this loss is called ‘stray load‘ loss. This can also be estimated experimentally. It can be modeled by another resistance in the series branch in the equivalent circuit. The stray load losses are very low in air-cored transformers due to the absence of the metallic tank

Thus, the different losses fall in to two categories Constant losses (mainly voltage dependant) and Variable losses (current dependant). The expression for the efficiency of the transformer operating at a fractional load x of its rating, at a load power factor of Θ2, can be written as

$$\eta = \frac{xS\cos\theta_2}{xS\cos\theta_2 + P_{const} + x^2 P_{var}}$$

Here S in the volt ampere rating of the transformer (V‘2 I‘2 at full load), Pconst being constant losses and Pvar the variable losses at full load.

UNIT-IV

3-PHASE INDUCTION MOTORS

4.1. Three Phase Induction Motor

The most common type of AC motor being used throughout the work today is the "Induction Motor". Applications of three-phase induction motors of size varying from half a kilowatt to thousands of kilowatts are numerous. They are found everywhere from a small workshop to a large manufacturing industry.

The advantages of three-phase AC induction motor are listed below:

- Simple design
- Rugged construction
- Reliable operation
- Low initial cost
- Easy operation and simple maintenance
- Simple control gear for starting and speed control
- High efficiency.

Induction motor is originated in the year 1891 with crude construction (The induction machine principle was invented by *NIKOLA TESLA* in 1888.). Then an improved construction with distributed stator windings and a cage rotor was built.

The slip ring rotor was developed after a decade or so. Since then a lot of improvement has taken place on the design of these two types of induction motors. Lot of research work has been carried out to improve its power factor and to achieve suitable methods of speed control.

4.2 Types and Construction of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

1. Squirrel cage Induction Motors
2. Slip ring Induction Motors

4.2.1 Squirrel cage Induction Motors

(a) Stator Construction

The induction motor stator resembles the stator of a revolving field, three phase alternator. The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in Fig: 4.1(a).

The phase windings are placed 120 electrical degrees apart and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor.When the stator is energized from a three phase voltage it will produce a rotating magnetic field in the stator core.

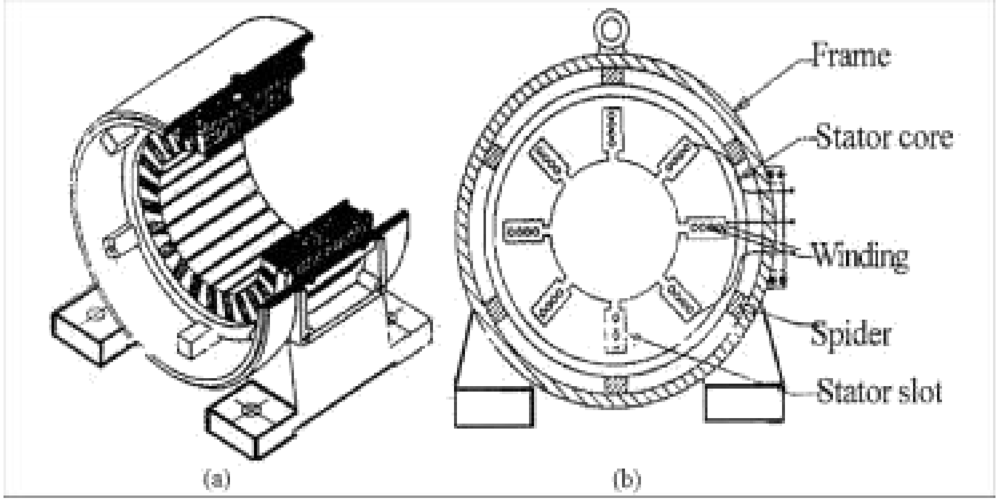


Fig.4.1.

(b) Rotor Construction

The rotor of the squirrel cage motor shown in Fig: 4.1(b) contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core.

These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings shown in Fig: 4.1(b).In small machines the conductor bars and end rings are sometimes made of aluminium with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived.

The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used.

The rotor bars are not insulated from the rotor core because they are made of metals having less Resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.

(c) End Shields

The function of the two end shields is to support the rotor shaft. They are fitted with bearings and Attached to the stator frame with the help of studs or bolts attention.

4.2.2 Slip ring Induction Motors

(a) Stator Construction

The construction of the slip ring induction motor is exactly similar to the construction of squirrel cage induction motor. There is no difference between squirrel cage and slip ring motors.

(b) Rotor Construction

- The rotor of the slip ring induction motor is also cylindrical or constructed of lamination.
- Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star.
- The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig.4.2.

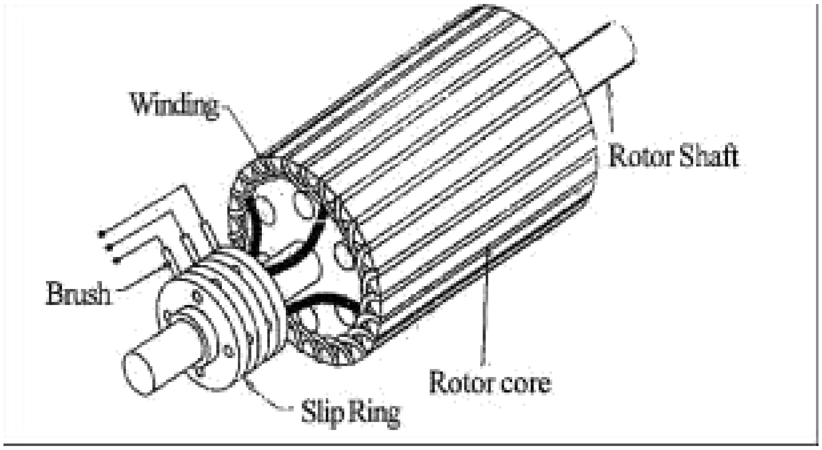


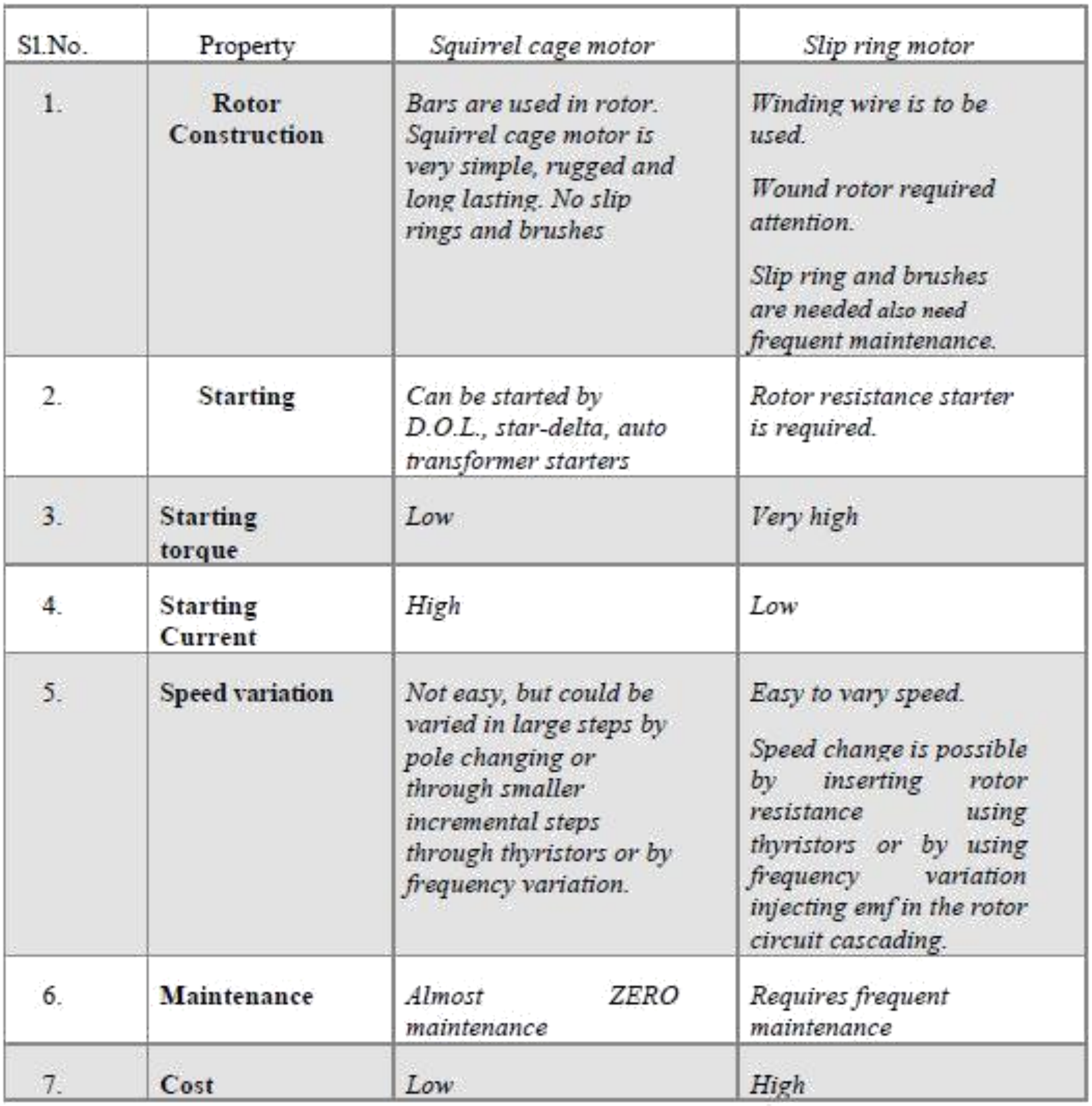
Fig.4.2

The Advantages of the Slipring Motor

- It has susceptibility to speed control by regulating rotor resistance.
- High starting torque of 200 to 250% of full load value.
- Low starting current of the order of 250 to 350% of the full load current.

Hence slip ring motors are used where one or more of the above requirements are to be met.

4.2.3 Comparison of Squirrel Cage and Slip Ring Motor



Sl.No.	Property	*Squirrel cage motor*	*Slip ring motor*
1.	**Rotor Construction**	*Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes*	*Winding wire is to be used.* *Wound rotor required attention.* *Slip ring and brushes are needed also need frequent maintenance.*
2.	**Starting**	*Can be started by D.O.L., star-delta, auto transformer starters*	*Rotor resistance starter is required.*
3.	**Starting torque**	*Low*	*Very high*
4.	**Starting Current**	*High*	*Low*
5.	**Speed variation**	*Not easy, but could be varied in large steps by pole changing or through smaller incremental steps through thyristors or by frequency variation.*	*Easy to vary speed.* *Speed change is possible by inserting rotor resistance using thyristors or by using frequency variation injecting emf in the rotor circuit cascading.*
6.	**Maintenance**	*Almost ZERO maintenance*	*Requires frequent maintenance*
7.	**Cost**	*Low*	*High*

4.3 Principle of Operation

The operation of a 3-phase induction motor is based upon the application of Faraday Law and the Lorentz force on a conductor. The behaviour can readily be understood by means of the following example.

Consider a series of conductors of length l, whose extremities are short-circuited by two bars A and B (Fig.3.3 a). A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed v, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place.

1. A voltage E = Blv is induced in each conductor while it is being cut by the flux (Faraday law).
2. The induced voltage immediately produces a current I, which flows down the conductor underneath the pole face, through the end-bars, and back through the other conductors.
3. Because the current carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force).
4. The force always acts in a direction to drag the conductor along with the magnetic field. If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently, the force acting on the conductors wilt also decreases. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.

In an induction motor the ladder is closed upon itself to form a squirrel-cage (Fig.3.3b) and the moving magnet is replaced by a rotating field. The field is produced by the 3-phase currents that flow in the stator windings.

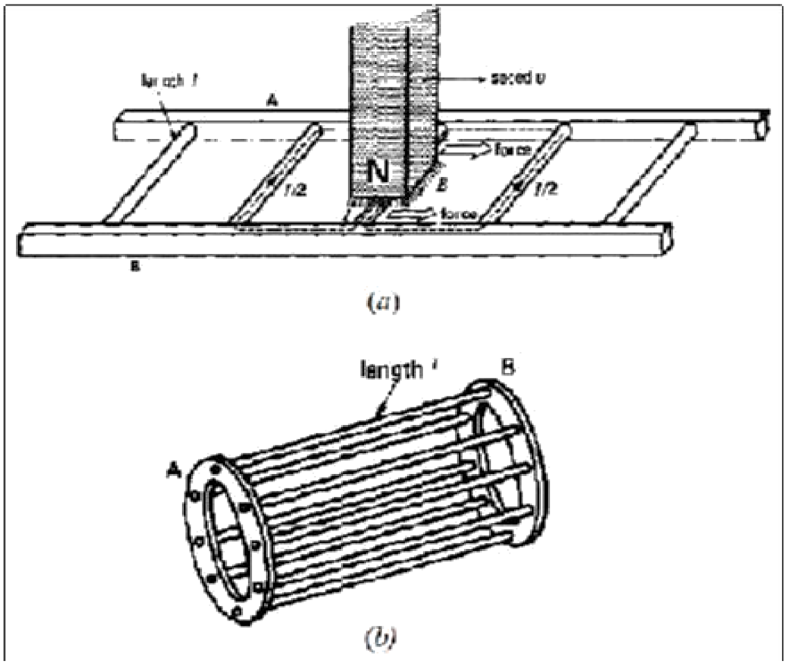
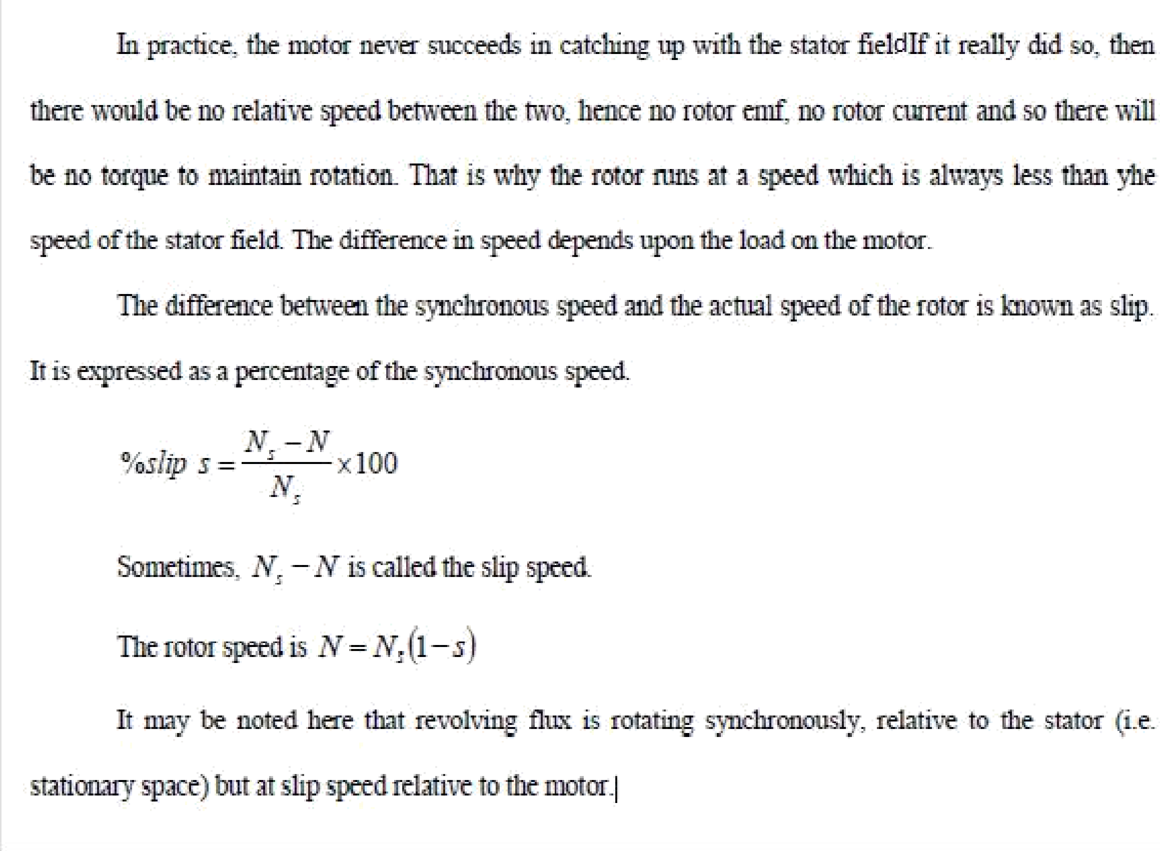


Fig.4.3

SLIP



In practice, the motor never succeeds in catching up with the stator fieldIf it really did so, then there would be no relative speed between the two, hence no rotor emf, no rotor current and so there will be no torque to maintain rotation. That is why the rotor runs at a speed which is always less than yhe speed of the stator field. The difference in speed depends upon the load on the motor.

The difference between the synchronous speed and the actual speed of the rotor is known as slip. It is expressed as a percentage of the synchronous speed.

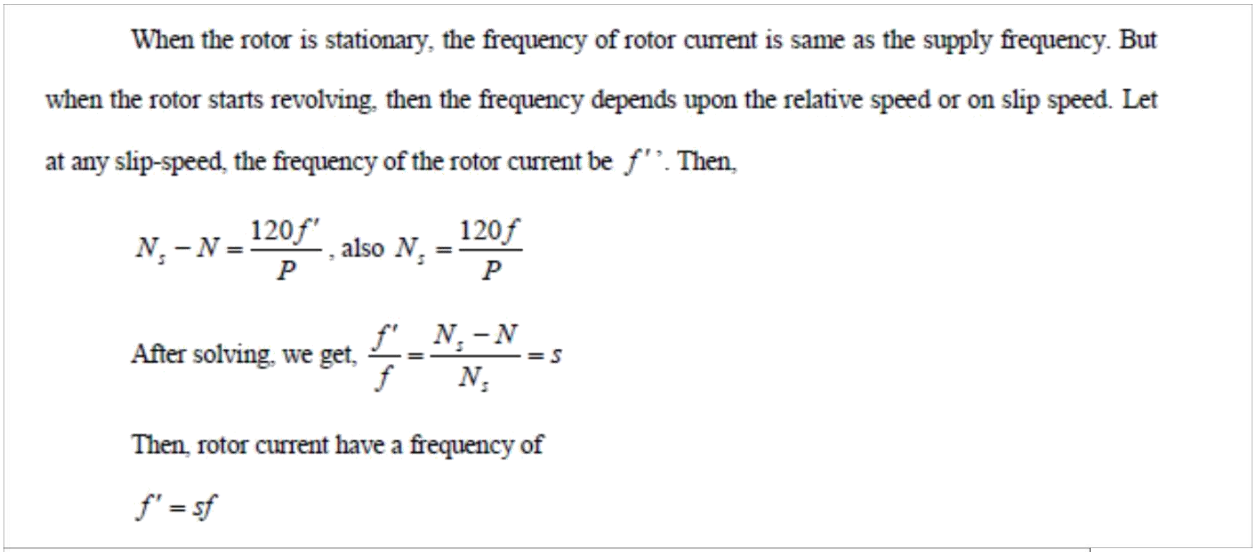
$$\%slip\ s = \frac{N_s - N}{N_s} \times 100$$

Sometimes, $N_s - N$ is called the slip speed.

The rotor speed is $N = N_s(1-s)$

It may be noted here that revolving flux is rotating synchronously, relative to the stator (i.e. stationary space) but at slip speed relative to the motor.

Frequency of rotor current



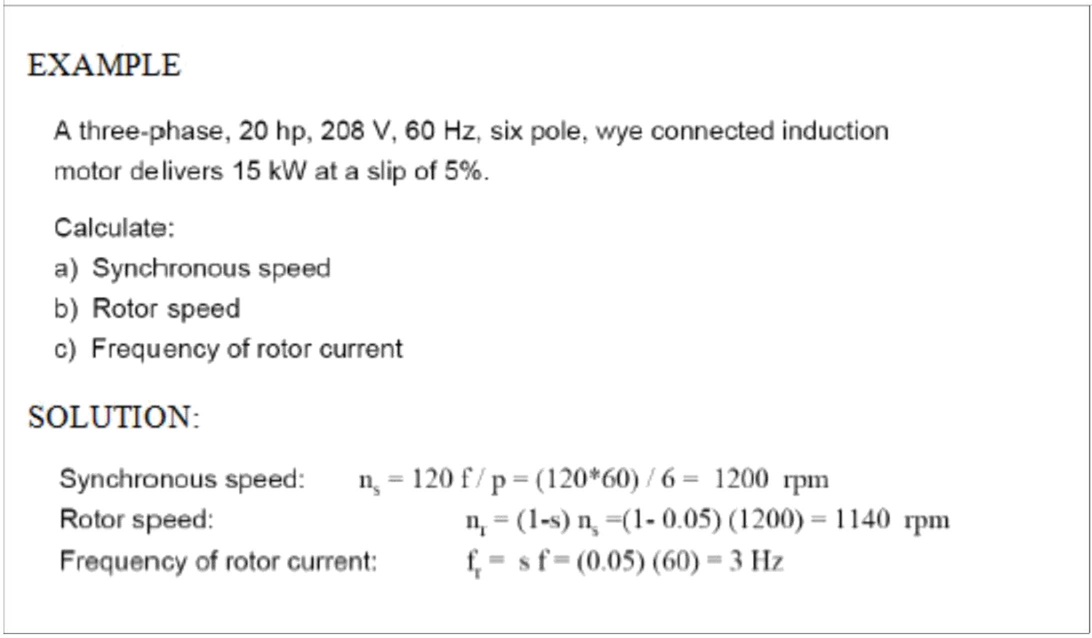
When the rotor is stationary, the frequency of rotor current is same as the supply frequency. But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip speed. Let at any slip-speed, the frequency of the rotor current be f'. Then,

$$N_s - N = \frac{120f'}{P}, \text{ also } N_s = \frac{120f}{P}$$

After solving, we get, $\frac{f'}{f} = \frac{N_s - N}{N_s} = s$

Then, rotor current have a frequency of

$f' = sf$



EXAMPLE

A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%.

Calculate:

a) Synchronous speed

b) Rotor speed

c) Frequency of rotor current

SOLUTION:

Synchronous speed: $n_s = 120\ f / p = (120*60) / 6 = 1200$ rpm

Rotor speed: $n_r = (1\text{-}s)\ n_s = (1\text{-}\ 0.05)\ (1200) = 1140$ rpm

Frequency of rotor current: $f_r = s\ f = (0.05)\ (60) = 3$ Hz

Example

A 3-phase, 460 V, 100 hp, 60 Hz, four-pole

induction machine delivers rated output power at a slip of 0.05.

Determine the:

(a) Synchronous speed and motor speed.

(b) Speed of the rotating air gap field.

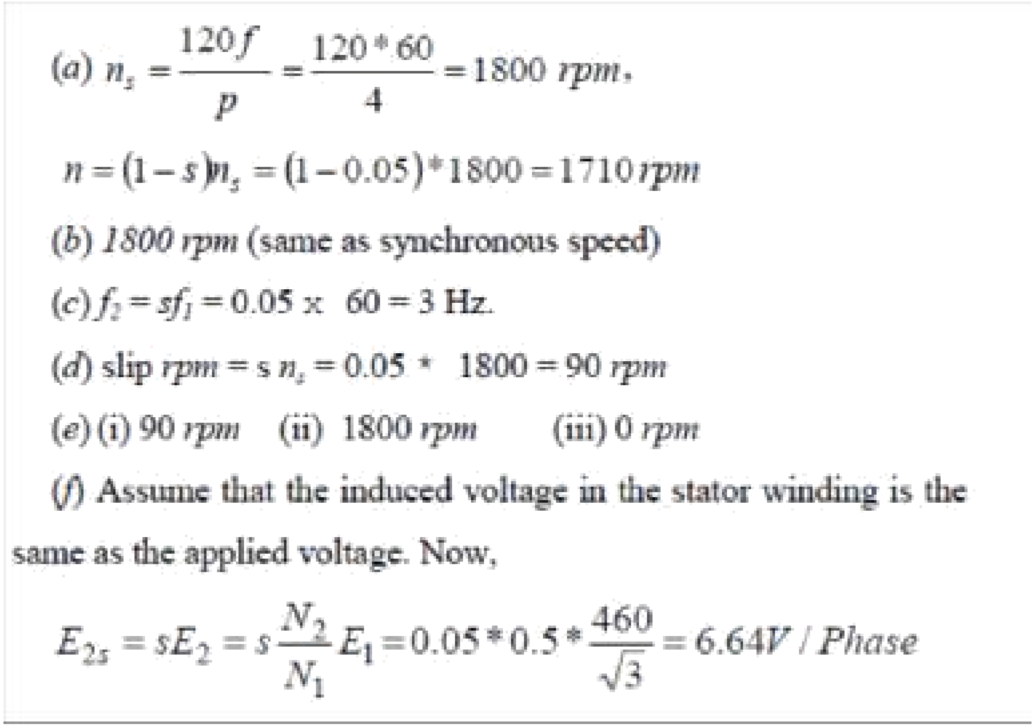
(c) Frequency of the rotor circuit.

(d) Slip rpm.

(e) Speed of the rotor field relative to the (i) rotor structure. (ii) Stator structure. (iii) Stator rotating field.

(f) Rotor induced voltage at the operating speed, if the stator-to-rotor turns ratio is 1 : 0.5.

Solution



(a) $n_s = \frac{120f}{p} = \frac{120*60}{4} = 1800\ rpm.$

$n = (1-s)n_s = (1-0.05)*1800 = 1710\,rpm$

(b) *1800 rpm* (same as synchronous speed)

(c) $f_2 = sf_1 = 0.05 \times 60 = 3$ Hz.

(d) slip $rpm = s\,n_s = 0.05 * 1800 = 90\ rpm$

(e) (i) 90 *rpm* (ii) 1800 *rpm* (iii) 0 *rpm*

(f) Assume that the induced voltage in the stator winding is the same as the applied voltage. Now,

$$E_{2s} = sE_2 = s\frac{N_2}{N_1}E_1 = 0.05*0.5*\frac{460}{\sqrt{3}} = 6.64V\,/\,Phase$$

4.4 Rotating Magnetic Field and Induced Voltages

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig.4.4). Coils that are diametrically opposite are connected in series by means of three jumpers that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

The three sets of windings are connected in wye, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line to neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

For a two-pole machine, rotating in the air gap, the magnetic field (i.e., flux density) being sinusoidally distributed with the peak along the centre of the magnetic poles. The result is illustrated in Fig.4.5. The rotating field will induce voltages in the phase coils aa', bb', and cc'. Expressions for the induced voltages can be obtained by using Faraday laws of induction.

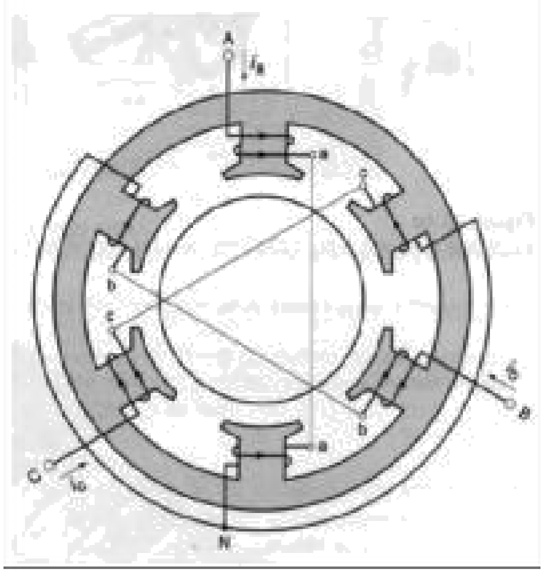


Fig: 4.4 Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

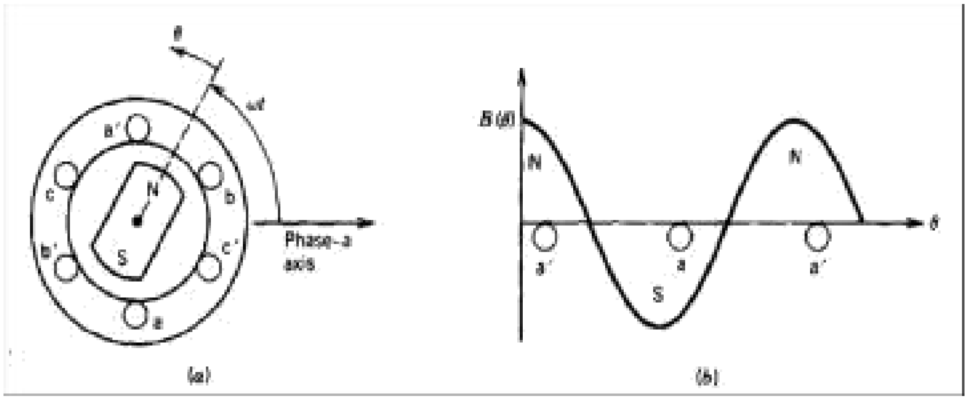
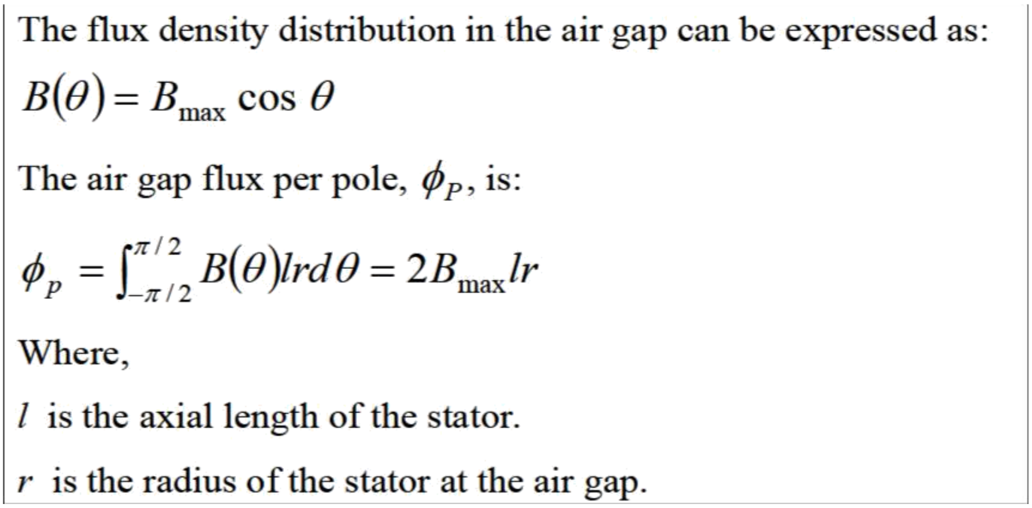


Fig: 4.5 Air gap flux density distribution.



The flux density distribution in the air gap can be expressed as:

$$B(\theta) = B_{\max} \cos \theta$$

The air gap flux per pole, ϕ_P, is:

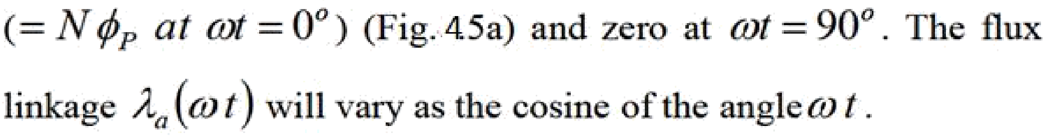
$$\phi_p = \int_{-\pi/2}^{\pi/2} B(\theta) lr d\theta = 2B_{\max} lr$$

Where,

l is the axial length of the stator.

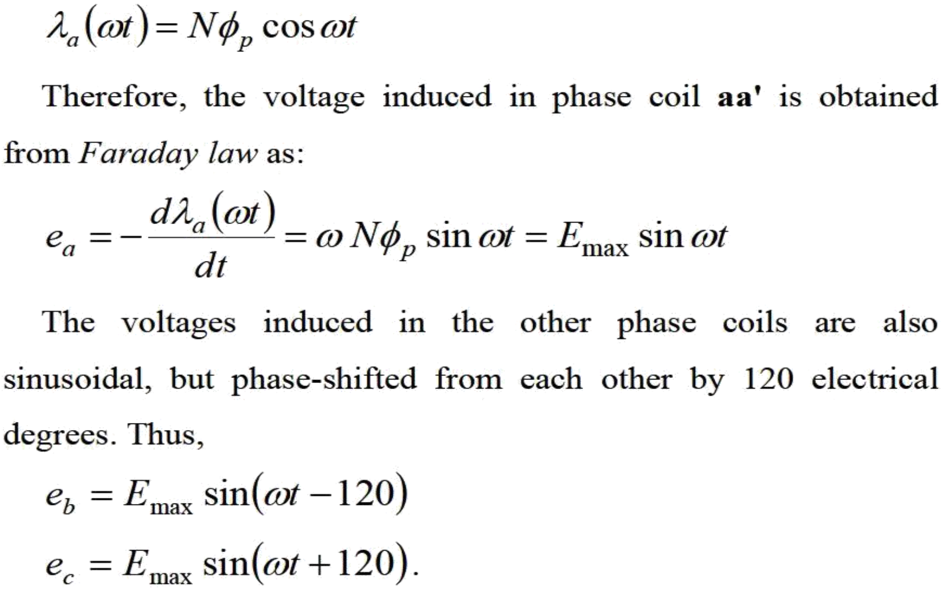
r is the radius of the stator at the air gap.

Let us consider that the phase coils are full-pitch coils of N turns (the coil sides of each phase are 180 electrical degrees apart as shown in Fig.4.5). It is obvious that as the rotating field moves (or the magnetic poles rotate) the flux linkage of a coil will vary. The flux linkage for coil aa' will be maximum.



$(= N\phi_P \ at \ \omega t = 0^o)$ (Fig. 45a) and zero at $\omega t = 90^o$. The flux linkage $\lambda_a(\omega t)$ will vary as the cosine of the angle ωt.

Hence,



$$\lambda_a(\omega t) = N\phi_p \cos \omega t$$

Therefore, the voltage induced in phase coil **aa'** is obtained from *Faraday law* as:

$$e_a = -\frac{d\lambda_a(\omega t)}{dt} = \omega N\phi_p \sin \omega t = E_{\max} \sin \omega t$$

The voltages induced in the other phase coils are also sinusoidal, but phase-shifted from each other by 120 electrical degrees. Thus,

$$e_b = E_{\max} \sin(\omega t - 120)$$

$$e_c = E_{\max} \sin(\omega t + 120).$$

the *rms* value of the induced voltage is:

$$E_{rms} = \frac{\omega N \phi_p}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} N\phi_p = 4.44 fN\phi_p$$

Where f is the frequency in hertz. Above equation has the same form as that for the induced voltage in transformers. However, $Ø_P$ represents the flux per pole of the machine.

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full-pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor K_W, called the winding factor, must therefore be applied. For most three-phase machine windings K_W is about 0.85 to 0.95.

Therefore, for a distributed phase winding, the rms voltage per phase is

$$Erms = 4.44fN_{ph}\varphi_p K_W$$

Where N_{ph} is the number of turns in series per phase.

TORQUE EQUATION

As we know, the torque T_a is proportional to the product of armature current and flux per pole.

$$T_a \alpha \phi I_a$$

In induction motor, $T \alpha \phi I_2 \cos\phi_2$

Hence, $T = K\phi I_2 \cos\phi_2$

Where, I_2 = rotor current at standstill

ϕ_2 = angle between rotor emf and rotor current

K = a constant

Denoting rotor emf at standstill by E_2, we have that

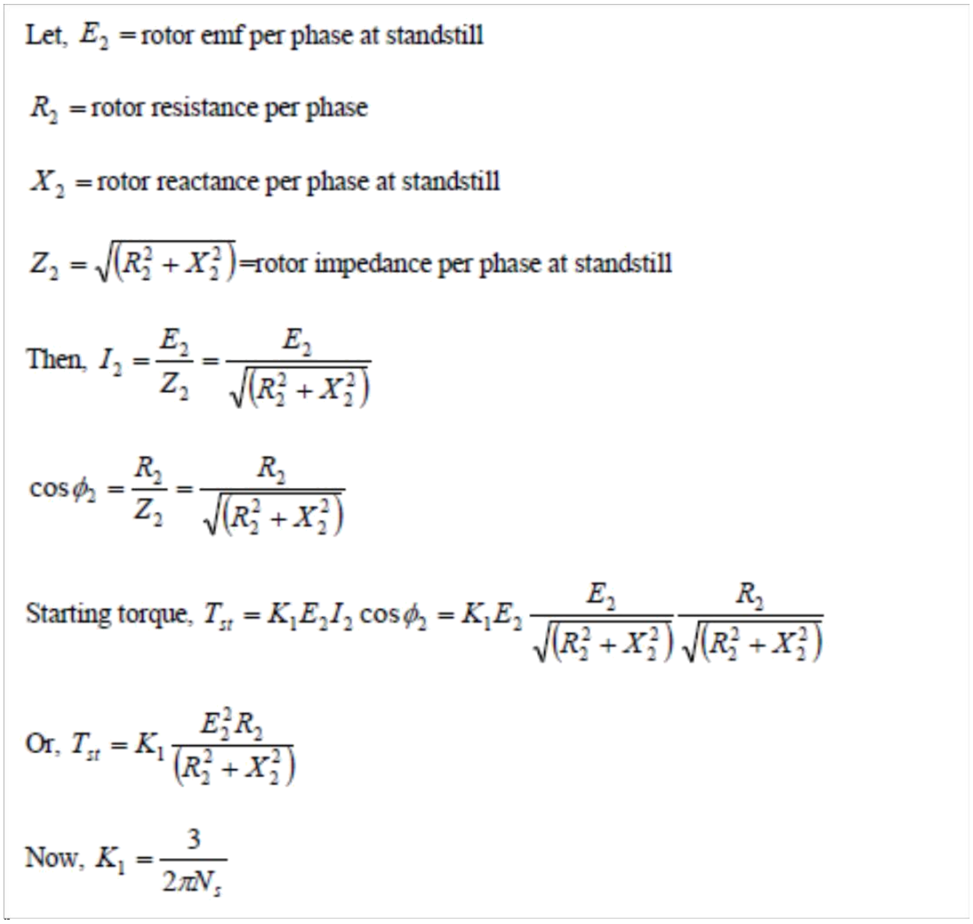
$$E_2 \alpha \phi$$

Hence, $T \alpha E_2 I_2 \cos\phi_2$ or $T = E_2 I_2 \cos\phi_2$

Where, K_1 is another constant.

Starting torque

The torque developed by the motor at the instant of starting is called starting torque.



Let, E_2 = rotor emf per phase at standstill

R_2 = rotor resistance per phase

X_2 = rotor reactance per phase at standstill

$Z_2 = \sqrt{(R_2^2 + X_2^2)}$ = rotor impedance per phase at standstill

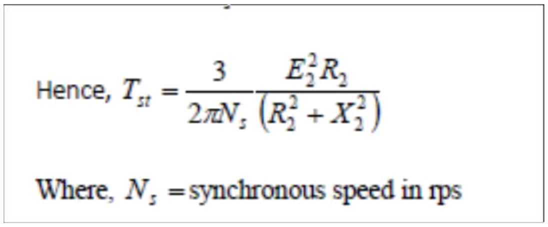
Then, $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}}$

$$\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$$

Starting torque, $T_{st} = K_1 E_2 I_2 \cos\phi_2 = K_1 E_2 \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$

Or, $T_{st} = K_1 \frac{E_2^2 R_2}{(R_2^2 + X_2^2)}$

Now, $K_1 = \frac{3}{2\pi N_s}$



Hence, $T_{st} = \frac{3}{2\pi N_s} \frac{E_2^2 R_2}{(R_2^2 + X_2^2)}$

Where, N_s = synchronous speed in rps

Condition for maximum torque

If supply voltage V is constant, then the flux ϕ and hence, E_2 both are constant

$$T_{st} = K_2 \frac{R_2}{\left(R_2^2 + X_2^2\right)}$$

Differentiate both side with respect to R_2, we have

$$\frac{dT_{st}}{dR_2} = K_2\left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2 . 2R_2}{\left(R_2^2 + X_2^2\right)}\right] = 0$$

$$\Rightarrow R_2 = X_2$$

The starting torque will be maximum if $R_2 = X_2$.

Torque under running condition

Let, E_2 = rotor emf per phase at standstill

R_2 = rotor resistance per phase

f_2 = frequency of rotor current at standstill

Under running condition, $E_r = sE_2$

The frequency of the induced emf will likewise become

$f_r = sf_2$

Due to decrease in frequency of the rotor emf, the rotor reactance will also decrease.

Hence, $X_r = sX_2$

Where, E_r and X_r are emf and reactance under running conditions.

Now, the torque under running conditions

$$T \alpha \phi I_r \cos\phi_2$$

Now, $E_r = sE_2$ and $I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

Also, $\cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$

$$T_r \alpha E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Or, $T_{st} = K\frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$

Where, K is a constant. Its value can be proved to be equal to $\frac{3}{2\pi N_s}$. Hence, in that case, expression for torque becomes

$$T_r = \frac{3}{2\pi N_s}\frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

Condition for maximum torque under running condition

The torque of a rotor under running conditions is,

$$T_r = K\frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The condition for maximum torque may be obtained by differentiating the above expression with respect to slip and then putting equal to zero, and solved we get

$$R_2 = sX_2$$

Hence, torque under running condition is maximum when at that the slip which makes rotor reactance per phase equal to rotor resistance per phase.

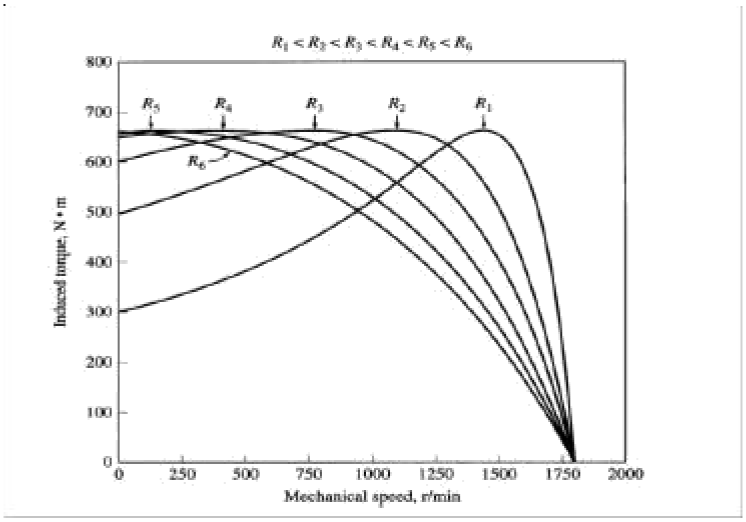


Fig. Effect of rotor resistance on torque-speed characteristic

TORQUE – SPEED CHARACTERISTICS

For small values of slip *s*, the torque is directly proportional to *s*.

For large values of slip *s*, the torque is inversely proportional to *s*.

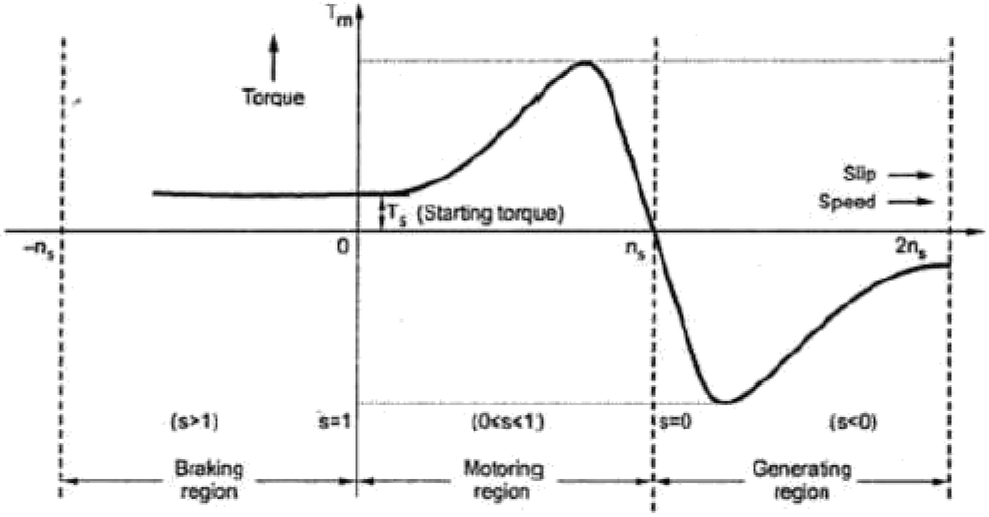


Fig. Complete torque-speed characteristic of a three phase induction machine

UNIT-V

SYNCHRONOUS MACHINES

Synchronous machines

The synchronous motor and induction motor are the most widely used types of AC motor. The difference between the two types is that the synchronous motor rotates in exact synchronism with the line frequency. The synchronous motor does not rely on current induction to produce the rotor's magnetic field. By contrast, the induction motor requires "*slip*", the rotor must rotate slightly slower than the AC current alternations, to induce current in the rotor winding. Small synchronous motors are used in timing applications such as in synchronous clocks, timers in appliances, tape recorders and precision servomechanisms in which the motor must operate at a precise speed; speed accuracy is that of the power line frequency, which is carefully controlled in large interconnected grid systems.

These machines are commonly used in analog electric clocks, timers and other devices where correct time is required. In high-horsepower industrial sizes, the synchronous motor provides two important functions. First, it is a highly efficient means of converting AC energy to work. Second, it can operate at leading or unity power factor and thereby provide power-factor correction.

Synchronous motors fall under the more general category of *synchronous machines* which also includes the synchronous generator. Generator action will be observed if the field poles are "driven ahead of the resultant air-gap flux by the forward motion of the prime mover". Motor action will be observed if the field poles are "dragged behind the resultant air-gap flux by the retarding torque of a shaft load".

There are mainly two types of rotor used in **construction of alternator**,

1. Salient pole type.
2. Cylindrical rotor type.

CONSTRUCTION OF SALIENT POLE ROTOR MACHINES

The construction of a synchronous motor(with salient pole rotor) is as shown in the figure at left. Just like any other motor, it consists of a stator and a rotor. The stator core is constructed with thin silicon lamination and insulated by a surface coating, to minimize the eddy current and hysteresis losses. The stator has axial slots inside, in which three phase stator winding is placed.

The stator is wound with a three phase winding for a specific number of poles equal to the rotor poles.

The rotor in synchronous motors is mostly of salient pole type. DC supply is given to the rotor winding via slip-rings. The direct current excites the rotor winding and creates electromagnetic poles. In some cases permanent magnets can also be used. The figure above illustrates the construction of a synchronous motor very briefly.

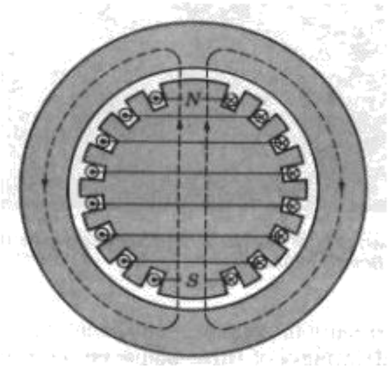
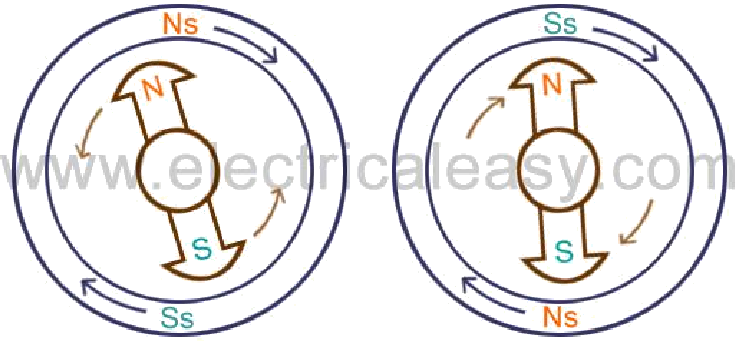


Fig. Salient pole synchronous machinr

Working principle of salient pole synchronous machine

The stator is wound for the similar number of poles as that of rotor, and fed with three phase AC supply. The 3 phase AC supply produces rotating magnetic field in stator. The rotor winding is fed with DC supply which magnetizes the rotor. Consider a two pole **synchronous machine** as shown in figure below.



- Now, the stator poles are revolving with synchronous speed (lets say clockwise). If the rotor position is such that, N pole of the rotor is near the N pole of the stator (as shown in first schematic of above figure), then the poles of the stator and rotor will repel each other, and the *torque produced will be anticlockwise*.
- The stator poles are rotating with synchronous speed, and they rotate around very fast and interchange their position. But at this very soon, rotor can not rotate with the same angle (due to inertia), and the next position will be likely the second schematic in above figure. In this case, poles of the stator will attract the poles of rotor, and *the torque produced will be clockwise.*

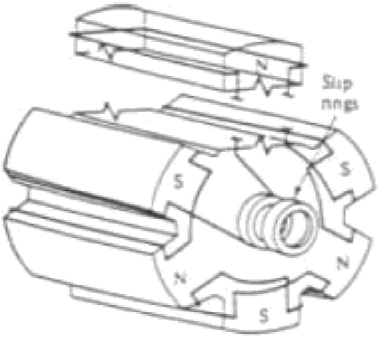


Fig. Salient pole rotoe

- Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start.

But, if the rotor is rotated upto the synchronous speed of the stator by means of an external force (in the direction of revolving field of the stator), and the rotor field is excited near the synchronous speed, the poles of stator will keep attracting the opposite poles of the rotor (as the rotor is also, now, rotating with it and the position of the poles will be similar throughout the cycle). Now, the rotor will undergo unidirectional torque. The opposite poles of the stator and rotor will get locked with each other, and the rotor will rotate at the synchronous speed.

The salient features of pole field structure has the following special feature-

1. They have a large horizontal diameter compared to a shorter axial length.
2. The pole shoes covers only about $^{2}/_{3}$rd of pole pitch.

3. Poles are laminated to reduce eddy current loss.
4. The salient pole type motor is generally used for low speed operations of around 100 to 400 rpm, and they are used in power stations with hydraulic turbines or diesel engines.

Construction of round (or) cylindrical rotor synchronous machine

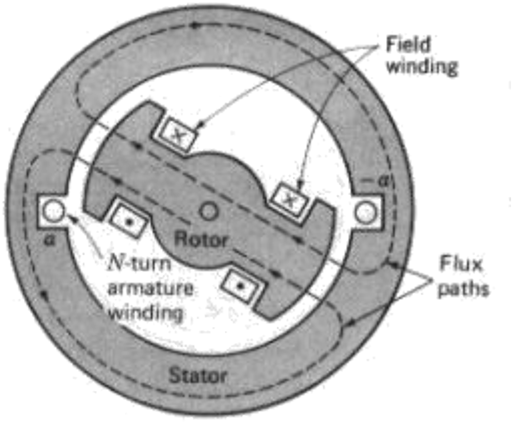


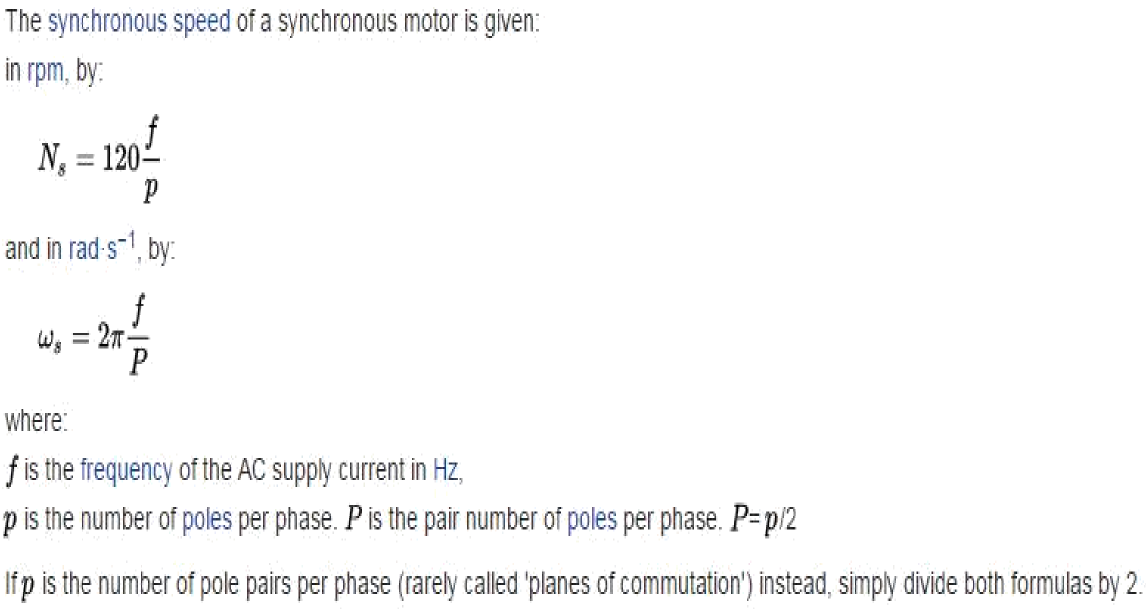
Fig. Round (or) cylindrical rotor

The cylindrical rotor is generally used for very high speed operation and are employed in steam turbine driven alternators like turbo generators. The cylindrical rotor type machine has uniform length in all directions, giving a cylindrical shape to the rotor thus providing uniform flux cutting in all directions. The rotor in this case consists of a smooth solid steel cylinder, having a number of slots along its outer periphery for hosing the field coils.

The cylindrical rotor alternators are generally designed for 2-pole type giving very high speed of $N_s = (120 \times f)/P = (120 \times 50) / 2 = 3000$ rpm. Or 4-pole type running at a speed of $N_s = (120 \times f) / P = (120 \times 50) / 4 = 1500$ rpm. Where f is the frequency of 50 Hz.

The a cylindrical rotor synchronous generator does not have any projections coming out from the surface of the rotor, rather central polar area are provided with slots for housing the field windings as we can see from the diagram above. The field coils are so arranged around these poles that flux density is maximum on the polar central line and gradually falls away as we move out towards the periphery. The cylindrical rotor type machine gives better balance and quieter-operation along with lesser windage losses.

Synchronous speed



The synchronous speed of a synchronous motor is given:

in rpm, by:

$$N_s = 120\frac{f}{p}$$

and in rad·s^{-1}, by:

$$\omega_s = 2\pi\frac{f}{P}$$

where:

f is the frequency of the AC supply current in Hz,

p is the number of poles per phase. P is the pair number of poles per phase. $P=p/2$

If p is the number of pole pairs per phase (rarely called 'planes of commutation') instead, simply divide both formulas by 2.

Example

A 3-phase, 12-pole (6-pole-pair) synchronous motor is operating at an AC supply frequency of 50 Hz. The number of poles per phase is 12/3 = 4, so the synchronous speed is:

$$N_s = 120 \times \frac{50}{4} = 1500 \text{ rpm}$$

EMF Equation

Consider following

Φ= flux per pole in wb

P = Number of poles

Ns = Synchronous speed in rpm

f = frequency of induced emf in Hz

Z = total number of stator conductors

Zph = conductors per phase connected in series

Tph = Number of turns per phase

Assuming concentrated winding, considering one conductor placed in a slot

According to Faraday's Law electromagnetic induction,

The average value of emf induced per conductor in one revolution

$e_{avg} = d\Phi / dt$

e_{avg} = Change of Flux in one revolution/ Time taken for one revolution

Change of Flux in one revolution = p x Φ

Time taken for one revolution = 60/Ns seconds.

Hence $e_{avg} = (p \times \Phi) / (60/Ns) = p \times \Phi \times Ns / 60$

We know f = PNs /120

hence PNs /60 = 2f

Hence $e_{avg} = 2 \Phi f$ volts

Hence average emf per turn = 2 x 2 Φ f volts = 4Φf volts

If there are Tph, number of turns per phase connected in series, then average emf induced in Tph turns is

Eph,avg = Tph x eavg = 4 f Φ Tph volts

Hence RMS value of emf induced E = 1.11 x Eph, avg

= 1.11 x 4 Φ f Tph volts

= 4.44 f Φ Tph volts

Eph,avg= 4.44 f Φ Tph volts

This is the general emf equation for the machine having concentrated and full pitched winding.In practice, alternators will have short pitched winding and hence coil span will not be 180^{O}(degrees), but on or two slots short than the full pitch.

If we assume effect of

Kd= Distribution factor

Kc or KP = Cos α/2

Eph,avg= $4.44 K_c K_d f \Phi$ Tph volts

This is the actual available voltage equation of an alternator per phase.If alternator or AC Generator is Star Connected as usually the case, then the Line Voltage is √3 times the phase voltage.

Voltage regulation by synchronous impedance method

This method is also called E.M.F. method of determining the regulation. The method requires following data to calculate the regulation.

1. The armature resistance per phase (R_a).

2. Open circuit characteristics which is the graph of open circuit voltage against the field current. This is possible by conducting open circuit test on the alternator.

3. Short circuit characteristics which is the graph of short circuit current against field current. This is possible by conducting short circuit test on the alternator.

Let us see, the circuit diagram to perform open circuit as well as short circuit test on the alternator. The alternator is coupled to a prime mover capable of driving the alternator at its synchronous speed. The armature is connected to the terminals of a switch. The other terminals of the switch are short circuited through an ammeter. The voltmeter is connected across the lines to measure the open circuit voltage of the alternator.

The field winding is connected to a suitable d.c. supply with rheostat connected in series. The field excitation i.e. field current can be varied with the help of this rheostat. The circuit diagram is shown in the Fig.

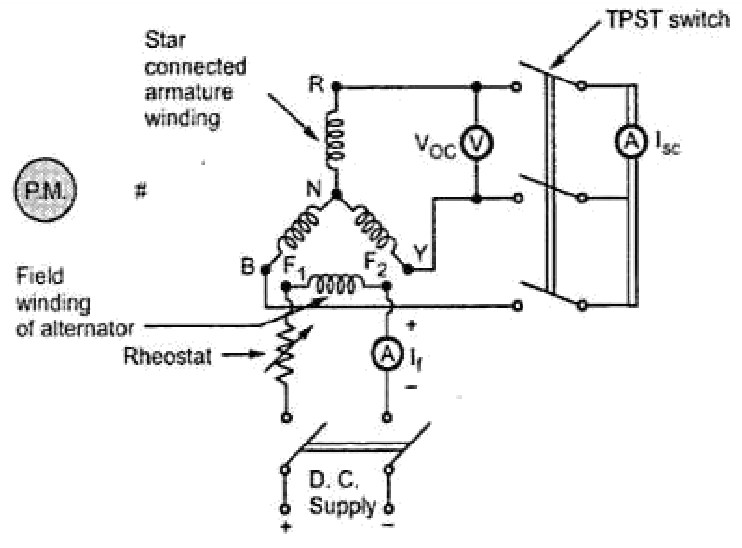


Fig. Circuit diagram for open circuit and short circuit test on alternator

Open Circuit Test

Procedure to conduct this test is as follows :

i) Start the prime mover and adjust the speed to the synchronous speed of the alternator.

ii) Keeping rheostat in the field circuit maximum, switch on the d.c. supply.

iii) The T.P.S.T switch in the armature circuit is kept open.

iv) With the help of rheostat, field current is varied from its minimum value to the rated value. Due to this, flux increasing the induced e.m.f. Hence voltmeter reading, which is measuring line value of open circuit voltage increases. For various values of field current, voltmeter readings are observed.

Note : This is called open circuit characteristics of the alternator, called O.C.C. This is shown in the Fig.

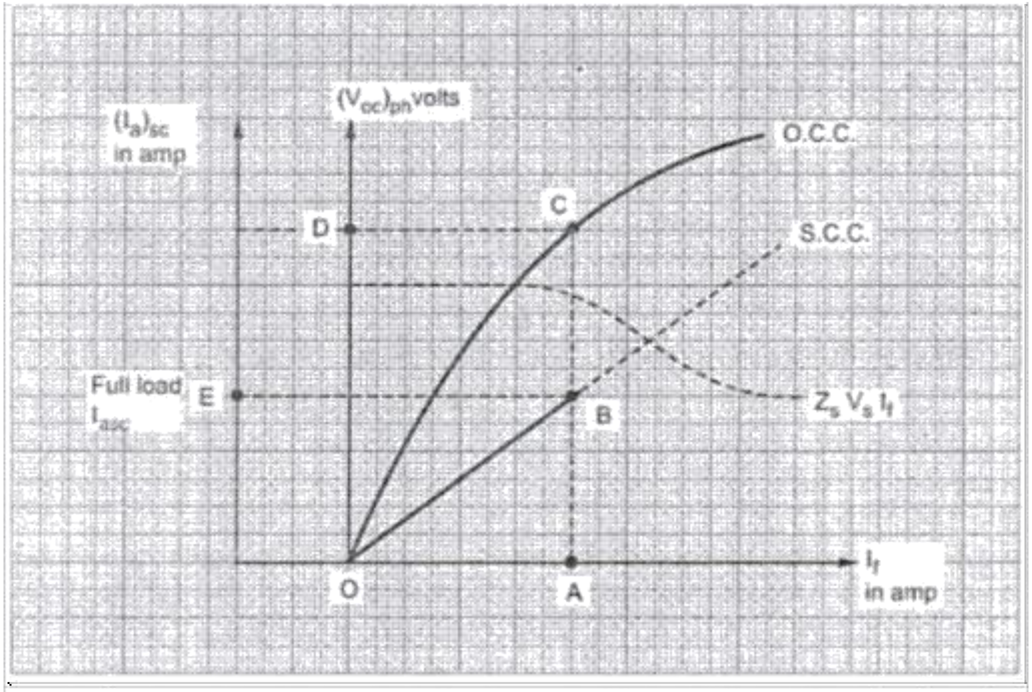


Fig. O.C.C. and S.C.C. of an alternator

Short Circuit Test

After completing the open circuit test observation, the field rheostat is brought to maximum position, reducing field current to a minimum value. The T.P.S.T switch is closed. As ammeter has negligible resistance, the armature gets short circuited. Then the field excitation is gradually increased till full load current is obtained through armature winding. This can be observed on the ammeter connected in the armature circuit. The graph of short circuit armature current against field current is plotted from the observation table of short circuit test. This graph is called short circuit characteristics, S.C.C. This is also shown in the Fig.

The S.C.C. is a straight line graph passing through the origin while O.C.C. resembles B-H curve of a magnetic material.

Note : As S.C.C. is straight line graph, only one reading corresponding to full load armature current along with the origin is sufficient to draw the straight line.

Determination of From O.C.C. and S.C.C.

The synchronous impedance of the alternator changes as load condition changes. O.C.C. and S.C.C. can be used to determine Z_s for any load and load p.f. conditions.

In short circuit test, external load impedance is zero. The short circuit armature current is circulated against the impedance of the armature winding which is Z_s. The voltage responsible for driving this short circuit current is internally induced e.m.f. This can be shown in the equivalent circuit drawn in the Fig. 5.3.

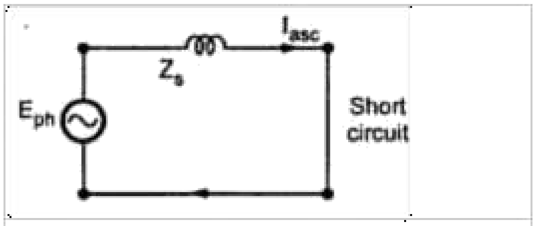


Fig. Equivalent circuit on short circuit

From the equivalent circuit we can write,

$Z_s = E_{ph}/ I_{asc}$

Now value of I_{asc} is known, which can observed on the alternator. But internally induced e.m.f. can not be observed under short circuit condition. The voltmeter connected will read zero which is voltage across short circuit. To determine Z_s it is necessary to determine value of E which is driving I_{asc} against Z_s.

Now internally induced e.m.f. is proportional to the flux i.e. field current I_f.

$E_{ph}\ \alpha\ \Phi\ \alpha\ I_f$ ...... from e.m.f. equation

So if the terminal of the alternator are opened without disturbing I_f which was present at the time of short circuited condition, internally induced e.m.f. will remain same as E_{ph}. But now current will be zero. Under this condition equivalent circuit will become as shown in the Fig.

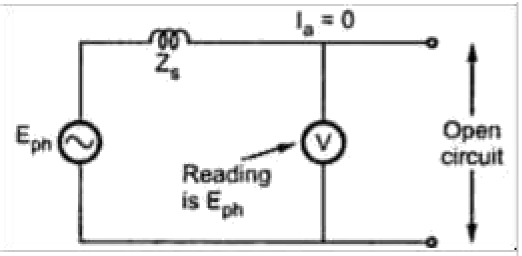


Fig.

It is clear now from the equivalent circuit that as $I_a = 0$ the voltmeter reading $(V_{oc})_{ph}$ will be equal to internally induced e.m.f. (E_{ph}).

$$\therefore \qquad \boxed{E_{ph} = (V_{oc})_{ph} \text{ on open circuit}}$$

This is what we are interested in obtaining to calculate value of Z_s. So expression for Z_s can be modified as,

$$Z_s = \left.\frac{(V_{oc})_{ph}}{(I_{asc})_{ph}}\right|_{\text{for same } I_f}$$

$$\text{Thus in general,} \qquad \boxed{Z_s = \left.\frac{\text{Phase e.m.f. on open circuit}}{\text{Phase current on short circuit}}\right|_{\text{For same excitation current}}}$$

So O.C.C. and S.C.C. can be effectively to calculate Z_s.

The value of Z_s is different for different values of I_f as the graph of O.C.C. is non linear in nature.

So suppose Z_s at full load is required then,

I_{asc} = full load current.

From S.C.C. determine I_f required to drive this full load short circuit I_a. This is equal to 'OA', as shown in the Fig.2.

Now for this value of I_f, $(V_{oc})_{ph}$ can be obtained from O.C.C. Extend kine from point A, till it meets O.C.C. at point C. The corresponding $(V_{oc})_{ph}$ value is available at point D.

$(V_{oc})_{ph} = OD$

While $(I_{asc})_{ph} = OE$

$$\therefore \quad Z_s \text{ at full load} = \left.\frac{(V_{oc})_{ph}}{\text{Full load } (I_{asc})_{ph}}\right|_{\text{same } I_f \text{ (same excitation)}}$$

$$= \left.\frac{OD}{OE}\right|_{\text{same } I_f = OA}$$

at full load

General steps to determine Z_s at any load condition are :

i) Determine the value of $(I_{asc})_{ph}$ for corresponding load condition. This can be determined from known full load current of the alternator. For half load, it is half of the full load value and so on.

ii) S.C.C. gives relation between $(I_{asc})_{ph}$ and I_f. So for $(I_{asc})_{ph}$ required, determine the corresponding value of I_f from S.C.C.

iii) Now for this same value of I_f, extend the line on O.C.C. to get the value of $(V_{oc})_{ph}$. This is $(V_{oc})_{ph}$ for same I_f, required to drive the selected $(I_{asc})_{ph}$.

iv) The ratio of $(V_{oc})_{ph}$ and $(I_{asc})_{ph}$, for the same excitation gives the value of Z_s at any load conditions.

The graph of synchronous impedance against excitation current is also shown in the Fig. 2.

Regulation Calculations

From O.C.C. and S.C.C., Z_s can be determined for any load condition.

The armature resistance per phase (R_a) can be measured by different methods. One of the method is applying d.c. known voltage across the two terminals and measuring current. So value of R_a per phase is known.

$$\text{Now} \qquad Z_s = \sqrt{(R_a)^2 + (X_s)^2}$$

$$\therefore \qquad \boxed{X_s = \sqrt{(Z_s)^2 - (R_a)^2} \ \Omega/\text{ph}}$$

So synchronous reactance per phase can be determined.

No load induced e.m.f. per phase, E_{ph} can be determined by the mathematical expression derived earlier.

$$\boxed{E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi \pm I_a X_s)^2}}$$

where V_{ph} = Phase value of rated voltage

I_a = Phase value of current depending on the load

condition cosΦ = p.f. of load

Positive sign for lagging power factor while negative sign for leading power factor, R_a and X_s values are known from the various tests performed.

The regulation then can be determined by using formula,

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

Advantages and Limitations of Synchronous Impedance Method

The main advantages of this method is the value of synchronous impedance $Z_s$for any load condition can be calculated. Hence regulation of the alternator at any load condition and load power factor can be determined. Actual load need not be connected to the alternator and hence method can be used for very high capacity alternators.

The main limitation of this method is that the method gives large values of synchronous reactance. This leads to high values of percentage regulation than the actual results. Hence this method is called pessimistic method.

Theory of operation of synchronous motor

Electrical motor in general is an electro-mechanical device that converts energy from electrical domain to mechanical domain. Based on the type of input we have classified it into single phase and 3 phase motors. Among 3 phase induction motors and synchronous motors are more widely used. When a 3 phase electric conductors are placed in a certain geometrical positions (In certain angle from one another) there is an electrical field generate. Now the rotating magnetic field rotates at a certain speed, that speed is called synchronous speed. Now if an electromagnet is present in this rotating magnetic field, the electromagnet is magnetically locked with this rotating magnetic field and rotates with same speed of rotating field.

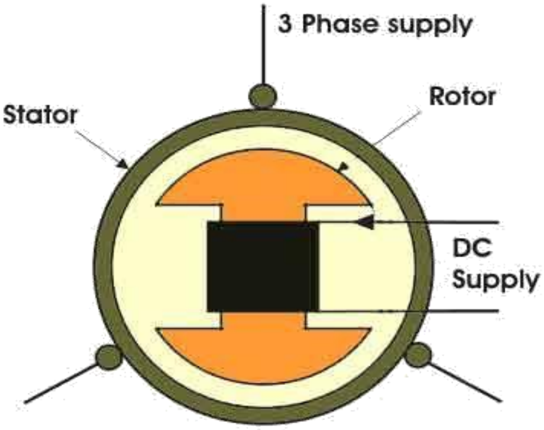
Synchronous motors is called so because the speed of the rotor of this motor is same as the rotating magnetic field. It is basically a fixed speed motor because it has only one speed, which is synchronous speed and therefore no intermediate speed is there or in other words it’s in synchronism with the supply frequency. Synchronous speed is given by

$$N_s = \frac{120f}{p}$$

Construction of Synchronous Motor

Normally it's construction is almost similar to that of a 3 phase induction motor, except the fact that the rotor is given dc supply, the reason of which is explained later. Now, let us first go through the basic construction of this type of motor.

From the above picture, it is clear that how this type of motors are designed. The stator is given is given three phase supply and the rotor is given dc supply.



Synchronous Motor

Main Features of Synchronous Motors

1. Synchronous motors are inherently not self starting. They require some external means to bring their speed close to synchronous speed to before they are synchronized.
2. The speed of operation of is in synchronism with the supply frequency and hence for constant supply frequency they behave as constant speed motor irrespective of load condition
3. This motor has the unique characteristics of operating under any electrical power factor. This makes it being used in electrical power factor improvement.

Principle of Operation Synchronous Motor

Synchronous motor is a doubly excited machine i.e two electrical inputs are provided to it. It’s stator winding which consists of a 3 phase winding is provided with 3 phase supply and rotor is provided with DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux. The rotor carrying DC supply also produces a constant flux. Considering the frequency to be 50 Hz, from the above relation we can see that the 3 phase rotating flux rotates about 3000 revolution in 1 min or 50 revolutions in 1 sec. At a particular instant rotor and stator poles might be of same polarity (N-N or S-S) causing repulsive force on rotor and the very next second it will be N-S causing attractive force. But due to inertia of the rotor, it is unable to rotate in any direction due to attractive or repulsive force and remain in standstill condition. Hence it is not self starting. To overcome this inertia, rotor is initially fed some mechanical input which rotates it in same direction as magnetic field to a speed very close to synchronous speed. After some time magnetic locking occurs and the synchronous motor rotates in synchronism with the frequency.

Methods of Starting of Synchronous Motor

1. Synchronous motors are mechanically coupled with another motor. It could be either 3 phase induction motor or DC shunt motor. DC excitation is not fed initially. It is rotated at speed very close to its synchronous speed and after that DC excitation is given. After some time when magnetic locking takes place supply to the external motor is cut off.
2. **Damper winding :** In case, synchronous motor is of salient pole type, additional winding is placed in rotor pole face. Initially when rotor is standstill, relative speed between damper winding and rotating air gap flux in large and an emf is induced in it which produces the required starting torque. As speed approaches synchronous speed , emf and torque is reduced and finally when magnetic locking takes place, torque also reduces to zero. Hence in this case synchronous is first run as three phase induction motor using additional winding and finally it is synchronized with the frequency.

Applications of synchronous motors

Synchronous motors are especially useful in applications requiring precise speed and/or position control.

- Speed is independent of the load over the operating range of the motor.
- Speed and position may be accurately controlled using open loop controls, e.g. stepper motors.
- Low-power applications include positioning machines, where high precision is required, and robot actuators.
- They will hold their position when a DC current is applied to both the stator and the rotor windings.
- A clock driven by a synchronous motor is in principle as accurate as the line frequency of its power source. (Although small frequency drifts will occur over any given several hours, grid operators actively adjust line frequency in later periods to compensate, thereby keeping motor-driven clocks accurate (see *Utility frequency#Stability*).)
- Record player turntables
- Increased efficiency in low-speed applications (e.g. ball mills)