DC MACHINES & TRANSFORMERS (20A02302T)

LECTURE NOTES

II-B.Tech I-Semester

Prepared by

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VEMU INSTITUTE OF TECHNOLOGY

(Approved By AICTE, New Delhi and Affiliated to JNTUA, Ananthapuramu)

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JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR
(Established by Govt. of A.P., ACT No.30 of 2008)
ANANTHAPURAMU – 515 002 (A.P) INDIA

ELECTRICAL AND ELECTRONICS ENGINEERING

Course Code	DC MACHINES & TRANSFORMERS		L	T	P	C
20A02302T			3	0	0	3
Pre-requisite	Fundamentals of Electrical circuits and Magnetic circuits	Semester	III			

Course Objectives:

Student will be able to

- Study magnetic materials, electromechanical energy conversions, principle and operation of DC machines and transformers and starters.
- understand the constructional details of DC machines and Transformers
- Analyze the performance characteristics of DC machines and transformer
- Evaluate efficiency, regulation and load sharing of DC machines and transformers Design Equivalent circuit of transformer

Course Outcomes (CO):

At the end of this course, students will demonstrate the ability to

- Understand the concepts of magnetic circuits, principle and operations of DC machines, starters and single and three phase transformers
- Analyze armature reaction, parallel operation, speed control and characteristics of DC machines. Alsoanalyze the performance characteristics with the help of OC and SC tests of transformer
- Evaluate generated emf, back emf, speed, efficiency and regulations of DC machines and efficiency and regulation of transformer also load sharing of parallel connected transformers
- Design winding diagrams of DC machines and equivalent circuit of transformer.

UNIT - I	**Magnetic Material Properties and Applications:**	10 Hrs

Introduction, Magnetic materials and their properties, magnetically induced emf and force, AC operation of magnetic circuits, hysteresis and eddy current losses, permanent magnets, and applications of permanent magnet materials.

Principles of electromechanical energy conversion:

Energy in magnetic system, field energy and mechanical force, multiply-excited magnetic field systems, forces/torques in systems with permanent magnets, energy conversion via electric field, dynamical equations of electro mechanical systems

UNIT - II	**DC Generators**	9Hrs

Constructional details of DC machine, principle of operation of DC generator, armature windings and its types, emf equation, armature reaction, effect of brush lead, demagnetizing and cross magnetizing ampere turns, compensating windings, commutation, emf induced in a coil undergoing commutation, methods of improving commutation, OCC and load characteristics of different types of generators. Parallel operation of DC Generators: DC shunt and series generators in parallel, equalizing connections

UNIT - III	**DC Motors**	10 Hrs

Force on conductor carrying current, back emf, Torque and power developed by armature, speed control of DC motors (Armature control and Flux control methods), Necessity of starters, constructional details of 3-point and 4-point starters, characteristics of DC motors, Losses in DC machines, condition for maximum efficiency

Testing of DC machines:

Brake test, Swinburne’s test, Hopkinson's test, Fields test, Retardation test.

UNIT - IV	**Single Phase Transformers**	10 Hrs

Principle, construction and operation of single-phase transformers, equivalent circuit, phasor diagrams (no load and on load), Magnetizing current, effect of nonlinear B-H curve of magnetic core material, harmonics in magnetization current, losses and efficiency Testing - open circuit and short circuit tests, voltage regulation, Sumpner's test, separation of hysteresis and eddy current losses. Parallel operation of single-phase transformers, Autotransformers - construction, principle, applications and comparison with two winding transformer.

UNIT - V	**Three Phase Transformers**	9 Hrs

Three-phase transformer – construction, types of connection and their comparative features, Phase conversion - Scott connection, Tap-changing transformers - No-load and on-load tap changing of transformers, Three-winding transformers- Cooling of transformers.

Textbooks:

1. P. S. Bimbhra, "Electrical Machinery", Khanna Publishers, 2011.
2. I. J. Nagrath and D. P. Kothari, "Electric Machines", McGraw Hill Education,2010.

Reference Books:

1. A. E. Fitzgerald and C. Kingsley, "Electric Machinery", New York, McGraw Hill Education, 2013.
2. A. E. Clayton and N. N. Hancock, "Performance and design of DC machines", CBS Publishers, 2004.
3. M. G. Say, "Performance and design of AC machines", CBS Publishers, 2002.

Online Learning Resources:

- https://onlinecourses.nptel.ac.in/noc21_ee71/preview
- https://onlinecourses.nptel.ac.in/noc21_ee24/preview

DC MACHINES & TRANSFORMERS (20A02302T)

UNIT-I

Magnetic Material Properties and Applications

LECTURE NOTES

UNIT - I

MAGNETIC MATERIAL PROPERTIES AND APPLICATIONS

PRINCIPLES OF ELECTROMECHANICAL ENERGY CONVERSION

MAGNETICALLY INDUCED EMF

It can be defined as the generation of a potential difference in a coil due to the changes in the magnetic flux through it. In simpler words, electromotive force or EMF is said to be induced when the flux linking with a conductor or coil changes.

MAGNETIC FORCE

The magnetic force is a consequence of the electromagnetic force, one of the four fundamental forces of nature, and is caused by the motion of charges. Two objects containing charge with the same direction of motion have a magnetic attraction force between them. Similarly, objects with charge moving in opposite directions have a repulsive force between them.

What is permeability of the material?

In electromagnetism, the measure of the resistance of a material against the formation of a magnetic field is called permeability.

What is magnetic susceptibility?

The measure of the magnetisation of the material is called magnetic susceptibility.

MAGNETIC PROPERTIES OF MATERIALS

Property 1: Intensity of magnetisation (I)

The electrons circulating around the nucleus have a magnetic moment. When the material is not magnetised the magnetic dipole moment sum up to zero. When the material is kept in an external magnetic field, the magnetic moments are aligned in a particular direction and the material gets a net non-zero dipole moment. The net dipole moment per unit volume is defined as magnetization or intensity of magnetisation.

Property 2: Magnetic Field (H) or Magnetic intensity

The magnetic field produced only by the electric current flowing in a solenoid is called the magnetic intensity. It is the external magnetic field that induces magnetic property in a material.

Property 3: Magnetic susceptibility

When a material is placed in an external magnetic field, the material gets magnetised. For a small magnetising field, the intensity of magnetisation (I) acquired by the material is directly proportional to the magnetic field (H).

$I \propto H$

$I = \chi_m H$, χ_m is the susceptibility of the material.

Property 4: Retentivity

The ability of a material to retain or resist magnetization is called retentivity.

Property 5: Coercivity

The coercivity of a material is the ability to withstand the external magnetic field without becoming demagnetized.

Faraday's Laws of Electromagnetic Induction

Faraday's First Law of Electromagnetic Induction

Whenever a conductor is placed in a varying magnetic field, an electromotive force is induced. If the conductor circuit is closed, a current is induced, which is called induced current.

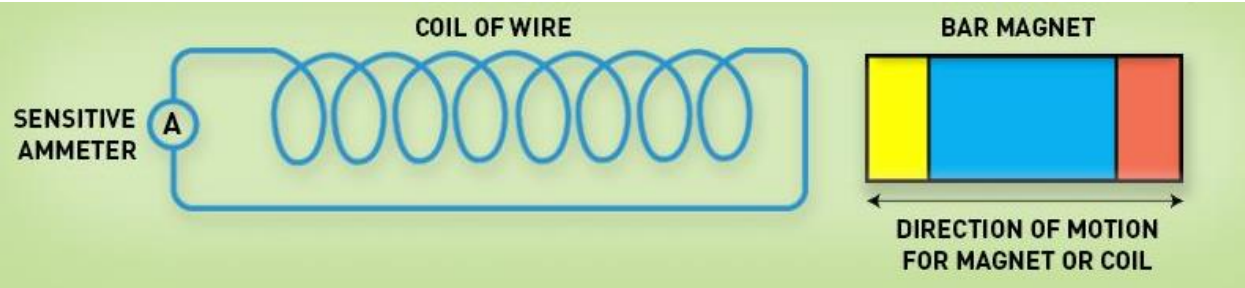


Fig: Changing the Magnetic Field Intensity in a Closed Loop

Mentioned here are a few ways to change the magnetic field intensity in a closed loop:

- By rotating the coil relative to the magnet.
- By moving the coil into or out of the magnetic field.
- By changing the area of a coil placed in the magnetic field.
- By moving a magnet towards or away from the coil.

Faraday's Second Law of Electromagnetic Induction

Faraday's second law of electromagnetic induction states that The induced emf in a coil is equal to the rate of change of flux linkage.

TYPES OF MAGNETIC MATERIALS

1. Paramagnetic Materials
2. Diamagnetic Material
3. Ferromagnetic Materials
4. Antiferromagnetic Materials
5. Ferrimagnetic Materials

1. Paramagnetic Materials

Paramagnetic substances are those which are attracted by magnets and when placed in a magnetic field move from weaker to stronger parts of the field.

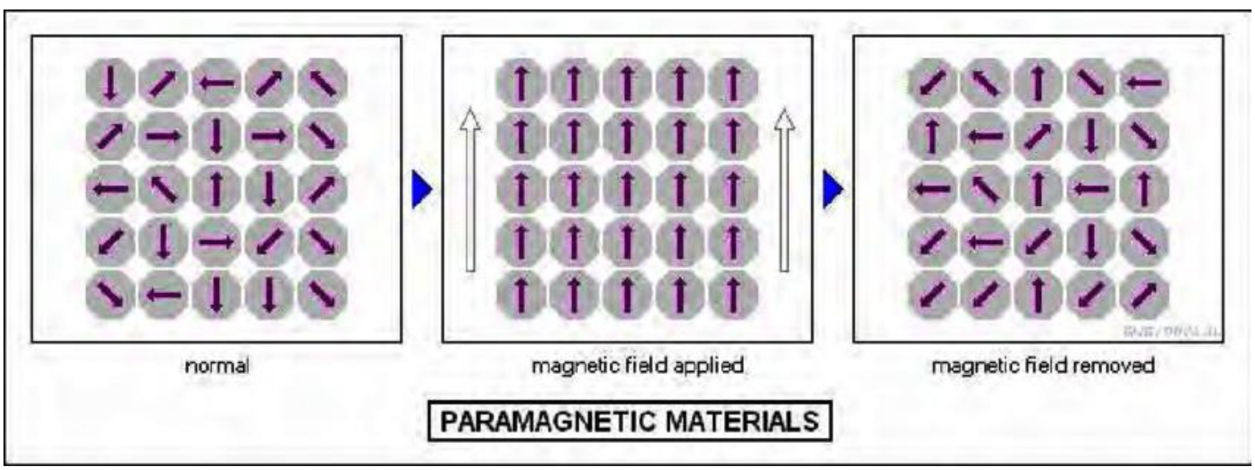


Fig: A schematic diagram of spin structure in paramagnetic materials.

Paramagnetic materials examples

Familiar examples are:

- aluminum
- manganese

- platinum,
- crown glass
- the solution of salts of iron and oxygen

Properties of paramagnetic materials

- If a bar of paramagnetic material is suspended in between the pole pieces of an electromagnet, it sets itself parallel to the lines of force.
- When a bar of paramagnetic material is placed in a magnetic field the lines of force tend to accumulate in it.
- If a paramagnetic liquid is placed in a watch glass resting on the pole pieces of an electromagnet then it accumulates in the middle. It is because in the central region the field is the strongest. If the pole pieces are not close together the field is strongest near the poles and the liquid moves away from the center giving an almost opposite effect.
- If one end of a narrow u-tube containing a paramagnetic liquid is placed within the pole pieces of an electromagnet in such a manner that the level of the liquid is in the lie with the field, then on applying the field the level of the liquid rises. The rises in proportional to the susceptibility of the liquid.
- When a paramagnetic gas is allowed to ascend between the poles pieces of an electromagnet it spreads along the direction of the field.

2. Diamagnetic Materials

Diamagnetic substances are those which are repelled by magnets and when placed in a magnetic field move from the stronger to the weaker part of the field.

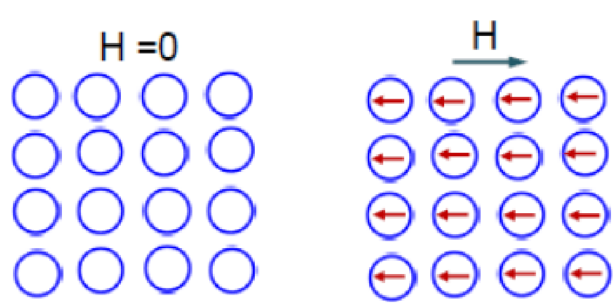


Fig: Diamagnetic Materials

Diamagnetic materials examples

Familiar examples of these are:

- bismuth

- phosphorus
- antimony
- copper
- water
- alcohol
- hydrogen

Properties of Diamagnetic materials

- When a diamagnetic substance is placed in a magnetic field it sets itself at right angles to the direction of the lines of force.
- When diamagnetic material is placed within a magnetic field the lines of force tend to go away from the material.
- When a diamagnetic substance is placed in a watch glass on the pole pieces of a magnet the liquid accumulates on the sides causing a depression at the center which is the strongest part of the field. When the distance between the pole pieces is larger, the effect is reversed.
- A diamagnetic liquid in a u-tube placed in a magnetic field shows as depression.
- When a diamagnetic gas is allowed to ascend between, the poles piece of an electromagnet it spreads across the field.

3. Ferromagnetic Materials

Ferromagnetic substances are those which are attracted by the magnets and can also be magnetized.

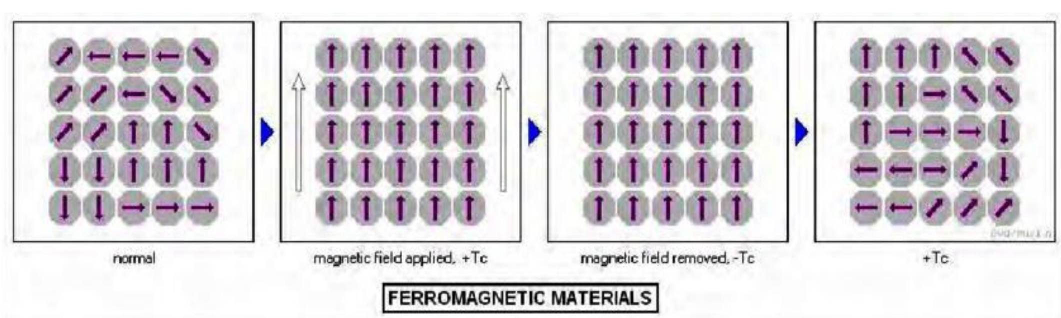


Fig: Schematic diagram of spin-ordering in ferromagnetic materials.

Ferromagnetic materials examples

Familiar examples are:

- iron
- nickel
- cobalt and their alloys

Properties of Ferromagnetic Substances

- The ferromagnetic substance shows the properties of the paramagnetic substance to a much greater degree.
- The susceptibility has a positive value and the permeability is also very large.
- The intensity of magnetization I is proportional to the magnetizing field H for a small value

4. Antiferromagnetic Materials

Antiferromagnetic Materials defined as equal magnitude of magnetic moment associated with unpaired electrons are aligned in opposite directions, the net magnetic moment is zero.

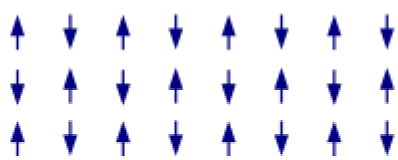


Fig: Antiferromagnetic material

Antiferromagnetic materials examples

Manganese oxide, (MnO),

Chromium oxide, (Cr2O3),

Ferrous oxide (FeO) etc.

Properties of Antiferromagnetic Materials

- When any material is placed in an applied magnetic field, it experiences the field and thus induces a magnetic property in it.
- These magnetic properties are induced on the macroscopic level based on the interaction between the individual dipole moments of an atom with the applied magnetic fields.
- The one that shows the commonly known property that the material is attracted to the magnetic field wholly, is known as the ferromagnet. In this, the magnetic moments of each atom are all aligned in the same direction.

- In the case of antiferromagnets, the magnetic moments of each atom are arranged in such a way that every second moment is in the opposite direction to the first.
- In simple words, in a pair of atoms, the moments are arranged in such a way that they cancel out each other. That is if one is upwards the other will be downwards.
- Thus, in anti-ferromagnets, the net magnetic moment of the substance is zero as the alternate orientations of moment cancel out each other. This indicates that they do not produce any magnetic field of their own.
- The anti-ferromagnetic nature can be destroyed by heating at higher temperatures.

5. Ferrimagnetic Materials

A ferrimagnetic material is one that has populations of atoms with opposing magnetic moments. The opposing moments are unequal and a spontaneous magnetization remains. This happens when the populations consist of different materials or ions (such as Fe2+ and Fe3+).

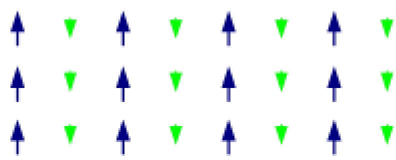


Fig: Ferrimagnetic Material

Ferrimagnetic Materials examples

Ferrimagnetism is exhibited by ferrites and magnetic garnets. Example: magnetite (iron(II,III) oxide; Fe3O4) and yttrium iron garnet are ferrimagnet.

Properties of Ferrimagnetic Materials

- Ferrimagnetic materials have high resistivity and have anisotropic properties.
- The anisotropy is actually induced by an external applied field. When this applied field aligns with the magnetic dipoles, it causes a net magnetic dipole moment and causes the magnetic dipoles to precess at a frequency controlled by the applied field, called Larmor or precession frequency.
- As a particular example, a microwave signal circularly polarized in the same direction as this precession strongly interacts with the magnetic dipole moments; when it is polarized in the opposite direction, the interaction is very low.

- When the interaction is strong, the microwave signal can pass through the material. This directional property is used in the construction of microwave devices like isolators, circulators, and gyrators.
- Ferrimagnetic materials are also used to produce optical isolators and circulators.
- Ferrimagnetic minerals in various rock types are used to study ancient geomagnetic properties of Earth and other planets.
- That field of study is known as paleomagnetism. In addition, it has been shown that ferrimagnets such as magnetite can be used for thermal energy storage.

Eddy Current Loss

When a magnetic material is subjected to a changing magnetic field, a voltage is induced in the material according to Faraday's law of electromagnetic induction. Since the material is conducting, the induced voltage circulates currents within the body of the magnetic material. These circulating currents are known as *eddy currents*. These eddy currents causes I2RI2R loss in the material, known as *eddy current loss*. The eddy current loss also results in the increase in temperature of the material.

Eddy current power loss, $P_e = K_e B^2_{max} f^2 t^2 V$ Watts

Where,

Ke = Eddy current coefficient,

Bmax = Maximum flux density,

f = frequency of magnetization or flux,

t = thickness of lamination, and

V = Volume of magnetic material.

The eddy current loss can be reduced as follows –

- By using thin sheets, called *laminations* which are insulated from each other by a thin coating of varnish, instead of using a solid block of magnetic material.
- Using a magnetic material of high resistivity (e.g. silicon steel).

Hysteresis Loss

When a magnetic material is subjected to cycle of magnetization (i.e. it is magnetised first in one direction and then in the other), a power loss occurs due to molecular friction in the material i.e. the magnetic domains of the material resist being turned first in one direction and then in the other. Therefore, energy is required in the material to overcome this opposition. This loss being in the form of heat and is termed as *hysteresis loss.* The effect of hysteresis loss is the rise of temperature of the machine.

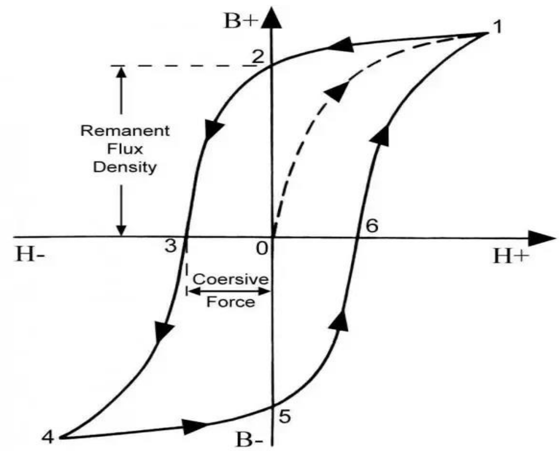


Fig: Hysteresis Loop

The formula for the calculation of hysteresis loss is devised by *Steinmetz,* known as *Steinmetz hysteresis law.* He found that the area of hysteresis loop of a magnetic material is directly proportional to 1.6th1.6th power of the maximum flux density.

Area of hysteresis loop$\propto$ $B^{1.6}$max

Hysteresis energy loss=η $B^{1.6}$max

Where, η is a proportionality constant called as *hysteresis coefficient*. Its value depends upon the nature of magnetic material i.e. the smaller the value of hysteresis coefficient of a material, the lesser is the hysteresis loss.

If f is the frequency of magnetisation and V is the volume of the magnetic material in m^3, then,

Hysteresis power loss, Ph=η$B^{1.6}$max f V Watts

The hysteresis loss can be reduced by using silicon steel to make the core of electric machines.

PERMANENT MAGNETS

- Permanent magnets are materials where the magnetic field is generated by the internal structure of the material itself.
- Inside atoms and crystals you have both electrons and the nucleus of the atom. Both the nucleus and the electrons themselves act like little magnets, like little spinning chunks of

electric charge, and they have magnetic fields inherent in the particles themselves. There's also a magnetic field that's generated by the orbits of the electrons as they move about the nucleus. So the magnetic fields of permanent magnets are the sums of the nuclear spins, the electron spins and the orbits of the electrons themselves.

- In many materials, the magnetic fields are pointing in all sorts of random directions and cancel each other out and there's no permanent magnetism. But in certain materials, called ferromagnets, all the spins and the orbits of the electrons will line up, causing the materials to become magnetic. This would be your normal iron, cobalt, nickel.
- Permanent magnets are limited by the structure of the material. And the strongest magnetic field of a permanent magnet is about 8,000 gauss. The strongest magnets here at the Magnet Lab are 450,000 gauss, which would be almost 50 times stronger than that.

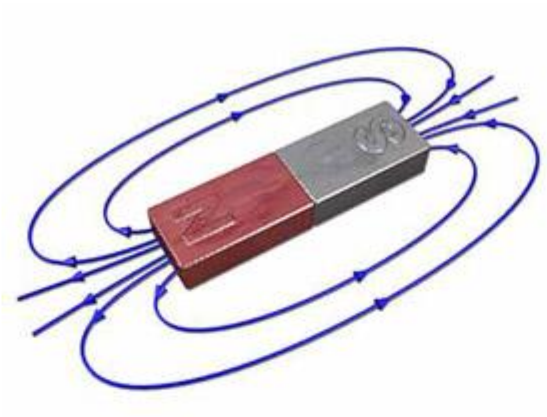


Fig: Field lines of a permanent magnet go from north to south.

Common Applications for Permanent Magnets

- Holding Systems Requring Very High Forces.
- Sensors.
- Reed switches.
- Hard Disc Drives.
- Audio Equipment.
- Acoustic Pick-Ups.
- Headphones & Loudspeakers.
- MRI Scanners.

Principles of Electromechanical Energy Conversion

→ In daily life we come across various devices which convert energy from one form to other. The structure of these devices will differ depending upon their application.

→ Some devices are used for continuous energy conversion such as motors and generators.

→ A Hydro electric plant converts hydro energy into electrical energy.

* An Electromechanical energy conversion device is one which converts mechanical energy into electrical energy or electrical energy into mechanical energy.

* Motors and Generators come under high energy converting devices.

Principle of Energy Conversion:-

→ According to this principle energy can neither be created nor destroyed, but it can only be changed from one form to the other.

→ The principle of Energy Conversion is used for estimation of forces.

→ The Fig.1 shows typical electromechanical energy conversion system.

It mainly consists of three essential parts
(1) An Electrical system
(2) Coupling field system
(3) Mechanical system.

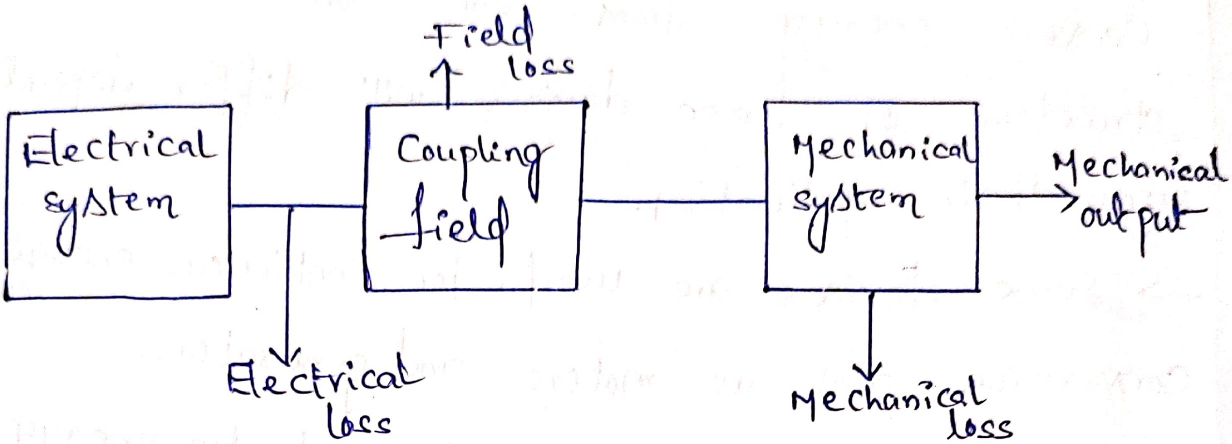


Fig. 1 Electromechanical Energy Conversion System.

* The Energy transfer equation is given by

Electrical energy i/p from source	=	Total Energy Losses	+	Increase in stored energy in the coupling field system	+	Mechanical energy output to the load → (1)

* The total energy losses in the system consists of ohmic losses (i^2R losses) in the resistance of the winding of electrical system, core loss in the field due to changing magnetic field in the core and the mechanical loss in the form of friction and windage losses due to motion of mechanical system. The total losses components in the mechanical system are converted into heat
* Now the energy balance equation can be written as

Electrical energy input from source − ohmic losses	=	Increase in stored energy in the field	+	Core losses	+	friction & windage losses + Mechanical energy output → (2)

Now considering a small interval of time 'dt'.

let the electrical input to the system (excluding ohmic loss) be We

dW_f be the energy supplied (either stored or lost)

dW_m be the energy converted into mechanical form (either useful or lost)

The expression (2) can be written as

$$dW_e = dW_f + dW_m$$

In the above expression in a limiting case dW_f represents change in energy stored in the field neglecting the Core losses which is generally small.

dW_m represents mechanical energy output when mechanical losses such as friction and windage losses are neglected.

Energy Balance :-

* Since for all practical purposes, the mass of the materials used in the construction of an electrical machine remains const. under operating conditions, the principle of conservation of energy can be applied in the analysis of the energy conservation.

The input energy must, therefore be equal to the summation of the useful output energy, heat and increase in the energy stored in the magnetic field

Thus energy balance eqn can be written as

For Motor action:

Energy input from electric source	=	Mechanical energy o/p	+	Increase in energy stored in the magnetic field + Energy converted into heat → (1)

Eqn (1) is applicable to all conversion devices.

→ For motor action the electrical and mechanical energy terms have positive values

→ The eqn (1) applies equally to generator action but simply have negative values.

For generator action:

Total mechanical energy input	=	Electrical energy o/p	+	Increase in energy stored in the magnetic field	+	energy converted into heat. → (2)

By considering the losses the energy balance equ can be written as

Electrical energy i/p from source − ohmic losses = Increase in stored energy in coupling field system + Core losses + friction and windage losses + mechanical energy o/p. → (3)

For example consider a simple energy conversion device shown in fig 3.

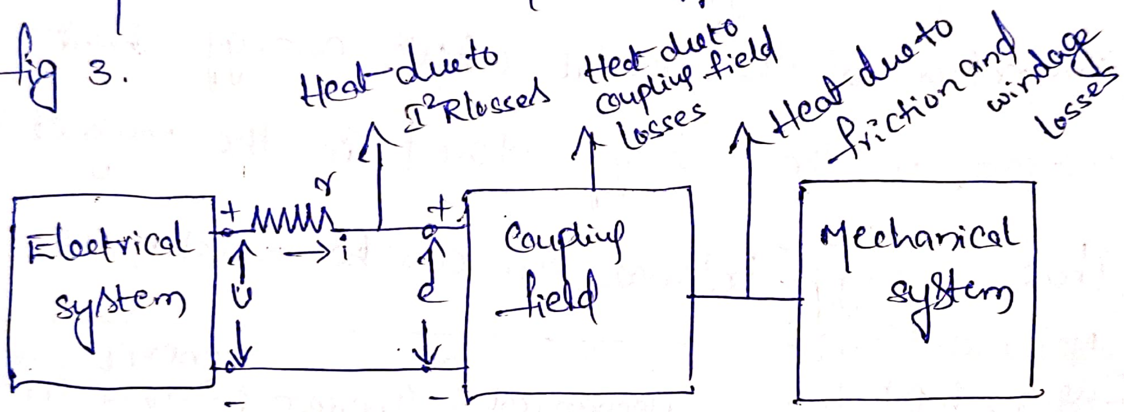


Fig.1. General representation of Electromechanical Energy Conversion device

→ The differential energy input from the electrical source in time dt is vidt, and ohmic loss is $i^2r\,dt$

Hence the left hand side of equ (3) becomes

$$dW_{elec} = vidt - i^2r\,dt \quad \rightarrow (4)$$

$$= (v - ir)\,i\,dt$$

where dW_{elec} = net electrical energy i/p.

⇒ For coupling field system

$$\text{emf } e = v - ir \quad \rightarrow (5)$$

$$(4) \Rightarrow \quad dW_{elec} = e\,i\,dt \quad \rightarrow (6)$$

In differential form, the eqn of energy conversion system is written as

$$dw_{ele} = eidt = dw_{field} + dw_{mech} \rightarrow (7)$$

dw_{field} = differential energy absorbed by the coupling field

dw_{mech} = differential energy converted into mechanical losses.

Force and Torque in Magnetic Field system:-

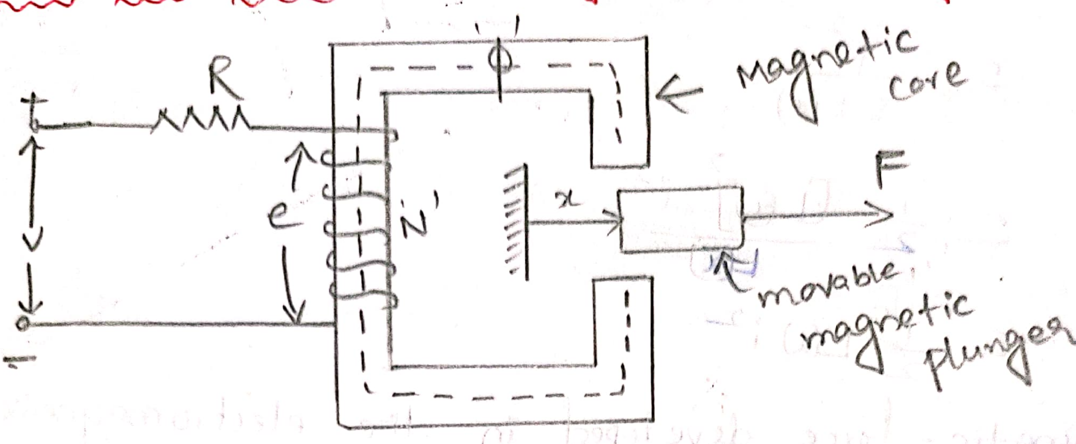


Fig: Force producing device.

→ In An Electromagnetic system, the ψ-i characteristics are said to be linear when the magnetic non linearity is absent in the system (where ψ is the flux linkage and 'i' is the current.

→ This happens when the reluctance of the magnetic path is neglected.

→ Therefore, for deriving the magnetic force developed (or) the electromagnetic torque developed in a linear electromagnetic system, neglecting the reluctance of the magnetic path.

→ The inductance of electromagnetic system depends upon the airgap.

→ Therefore the inductance of the system is given by

$$L(x) = \frac{\psi}{i} \Rightarrow \psi = L(x)\, i$$

→ The energy in the field is given by

$$W_{field} = \int i \, d\psi \, *$$

$$= \int_0^{\psi} \frac{\psi}{L(x)} \, d\psi$$

$$= \frac{\psi^2}{2L(x)}$$

$$= \frac{1}{2} \frac{[L(x)]^2 i^2}{L(x)}$$

$$= \frac{1}{2} L(x) i^2$$

* The magnetic force developed in the electromagnetic system can be obtained by differentiating the above expression as follows.

$$F_M = \frac{-d}{dx} [W_{field}],$$

$$= \frac{-d}{dx} \cdot \frac{1}{2} L(x) i^2$$

$$\boxed{F_M = -\frac{1}{2} i^2 \frac{dL(x)}{dx}} \longrightarrow (1)$$

Both the energies ie energy in the field and the co-energy should be equal for the system to be linear

ie $W_{field} = W'_{field}$

$$= \frac{1}{2} L(x) i^2$$

Hence by using the co energy, the magnetic force developed is given by

$$F_M = \frac{d}{dx} [W'_{field}]$$

$$= \frac{d}{dx} \left[\frac{1}{2} L(x) i^2\right]$$

$$\boxed{F_M = \frac{1}{2} i^2 \frac{d}{dx} L(x)} \longrightarrow (2)$$

It can be observed that the magnetic force developed either by using energy [equ (1)] or by using co energy [equ 2] are Same in magnitude.

→ As the reluctance of the magnetic path is neglected for linear electro magnetic path, the entire mmf drop will be present in the air path only.

* The total Amp-turns supplied is given by,

$$N \cdot i = (H_a l_a) \times 2$$

$$= 2 H_a l_a$$

where H_a = magnetic field intensity

l_a = length of the air gap.

* The energy in the field can also be given by

W_{field} = Energy density × volume of air gap.

$$= \frac{B_a^2}{2\mu_0} \times (A l_a) \times 2$$

$$= \frac{B_a^2}{\mu_0} \times A l_a$$

where A = cross sectional area of the core material

B_a = magnetic flux density

μ_0 = permeability of the material

Therefore by using the above energy in the field, the expression for the force developed due to magnetic field in an electromagnetic linear system is given by

$$F_M = \frac{d}{d l_a}\left(\frac{B_a^2}{\mu_0} A l_a\right) = \frac{B_a^2 A}{\mu_0}$$

* The magnetic force developed per unit area is given by

$$\frac{F_M}{A} = \frac{B_a^2}{\mu_0} \frac{A}{A} \; N/m^2$$

$$\boxed{F_m/A = \frac{B_a^2}{\mu_0} \; N/m^2}$$

* In order to obtain the expression for the torque developed in an electromagnetic linear system, we need to Consider a rotational electromagnetic Linear system.

* Here the force is replaced by torque while the linear displacement dx is replaced by angular displacement $d\theta$.

* Therefore when Coenergy is Consider, the expression for electromagnetic torque developed in an electromagnetic linear system is given by,

$$\boxed{T_M = \frac{\partial W'_{field}(i, \theta)}{\partial \theta}}$$

And when the energy in field Considered the the electromagnetic torque in the linear electromagnetic system is given by

$$\boxed{T_M = \frac{-\partial W_{field}(i, \theta)}{\partial \theta}}$$

~~The energy stored in the field is given by~~

~~$W_f = \int_0^{\psi} i\,d\psi = W_{fc} V_c + W_{fg} V_g$.~~

Co Energy :-

→ The flux linkage - current characteristic of an electromagnetic system depends very much upon the magnetic materials used in the system and also on the air gap length.

→ The ψ - i characteristics of the system shown in fig 2 for different air gap lengths are shown in fig 3(a)

→ with increase of air gap length, the characteristics become more and more Linear.

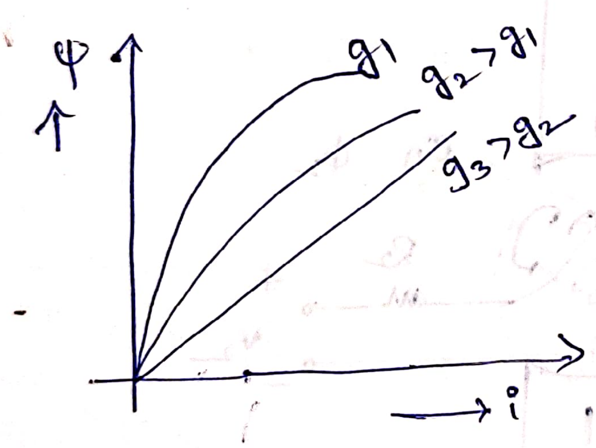


Fig 3(a)

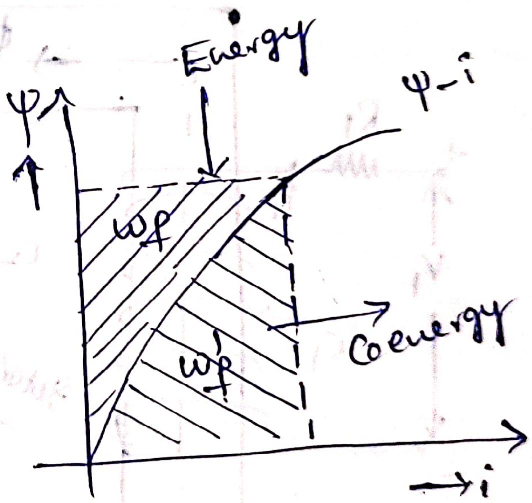


fig.3(b)

→ Fig 3(b) represents ψ-i characteristics for a given gap length. The energy stored in the magnetic field 'W_f' represented by the hatched portion between λ-axis and ψ-i characteristic.

* The other area below λ-i characteristic represented by W_f' is known as 'Co energy'

and is given by

$$W_f' = \int_0^{\psi} \psi \, di \rightarrow (1)$$

So $W_f + W_f' = \psi i$

Co energy is more than energy in the magnetic field where the electromechanical system is non linear.

But for linear systems

$$\boxed{W_f = W_f'}$$

Multi excited Magnetic field system :-

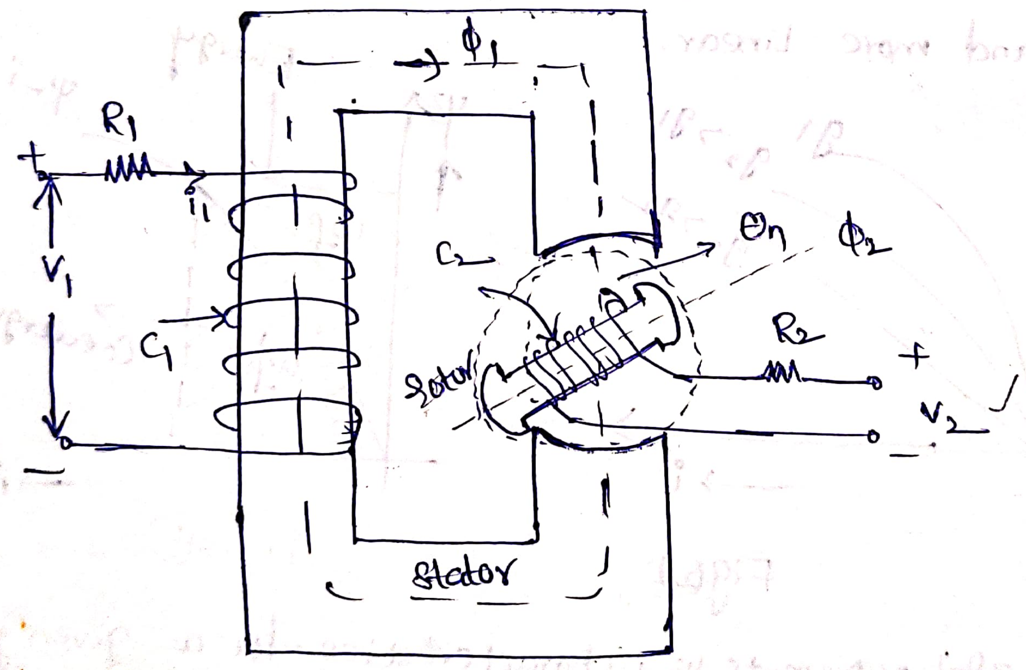


Fig 1. Doubly excited Rotating system.

Fig 1. shows double excited system. The stator and rotor are seperately magnetised by two seperate sources called doubly excited. When C_1 and C_2 coils excited, the following take place.

→ The flux ϕ_1 produced by C_1 links with its own coil C_1 and the secondary coil C_2 ✓

i.e $\psi_1 = L_1 i_1 + M i_2 \rightarrow (1)$

→ The flux ϕ_2 produced by C_2 links with its own coil C_2 and the secondary coil C_1 ✓

i.e $\psi_2 = L_2 i_2 + M i_1 \rightarrow (2)$

→ The voltage equations according to KVL

$$V_1 = R_1 i_1 + e_1$$

$$V_1 = R_1 i_1 + \frac{d\psi_1}{dt} \rightarrow (3)$$

$$V_2 = R_2 i_2 + e_2$$

$$V_2 = R_2 i_2 + \frac{d\psi_2}{dt} \rightarrow (4)$$

Substituting ψ value in equ (3)

$$V_1 = R_1 i_1 + \frac{d}{dt}(L_1 i_1 + M i_2)$$

$$V_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + i_1 \frac{dL_1}{dt} + M \frac{di_2}{dt} + i_2 \frac{dM}{dt} \rightarrow (5)$$

Multiplying on both side by i_1

$$V_1 i_1 = R_1 i_1^2 + L_1 i_1 \frac{di_1}{dt} + i_1^2 \frac{dL_1}{dt} + i_1 M \frac{di_2}{dt} + i_1 i_2 \frac{dM}{dt} \rightarrow (6)$$

$$V_2 i_2 = R_2 i_2^2 + L_2 i_2 \frac{di_2}{dt} + i_2^2 \frac{dL_2}{dt} + i_2 M \frac{di_1}{dt} + i_1 i_2 \frac{dM}{dt} \rightarrow (7)$$

Add equ (6) and equ (7), to get the total energy

$$(V_1 i_1 + V_2 i_2)dt = (R_1 i_1^2 + R_2 i_2^2)dt + L_1 i_1 di_1 + L_2 i_2 di_2 + i_1^2 dL_1 + i_2^2 dL_2 + i_1 M di_2 + i_2 M di_1 + 2 i_1 i_2 dM \rightarrow (8)$$

Integrate on both sides

$$\int (v_1 i_1 + v_2 i_2)\,dt = \int (R_1 i_1^2 + R_2 i_2^2)\,dt + \int (L_1 i_1 di_1 + L_2 i_2 di_2 + i_1 M di_2 + i_2 M di_1 + i_1^2 dL_1 + i_2^2 dL_2 + 2 i_1 i_2 dM) \rightarrow (8)$$

Equ (8) shows

Electrical energy input	=	Electrical Energy loss	+	Electrical energy stored in the magnetic field system.

$W_e = W_{loss} + W_{fe}$

* As the system is under steady state mechanical output is zero, the total electrical energy is stored in the system in magnetic field.
* under this condition the terms dL_1, dL_2 and dM become zero.

Total stored energy in magnetic field :-

$$W_{fe} = \int (L_1 i_1 di_1 + L_2 i_2 di_2 + i_1 M di_2 + i_2 M di_1) + 0$$

$$= \int_0^{i_1} L_1 i_1 di_1 + \int_0^{i_2} L_2 i_2 di_2 + \int_0^{i_1 i_2} (i_1 M di_2 + i_2 M di_1)$$

$$W_{fe} = \frac{1}{2} L_1 i_1^2 + \frac{1}{2} L_2 i_2^2 + i_1 i_2 M \rightarrow (9)$$

$\int (x\,dy + y\,dx) = xy$

Electro Magnetic Torque :-

Differentiating the above equation (9) with respect to θ_m we get

$$T = \frac{d}{d\theta_m} W_{fe} = \frac{1}{2} i_1^2 \frac{dL_1}{d\theta_m} + \frac{1}{2} i_2^2 \frac{dL_2}{d\theta_m} + i_1 i_2 \frac{dM}{d\theta_m} \rightarrow (10)$$

Singly Excited Magnetic field systems:-

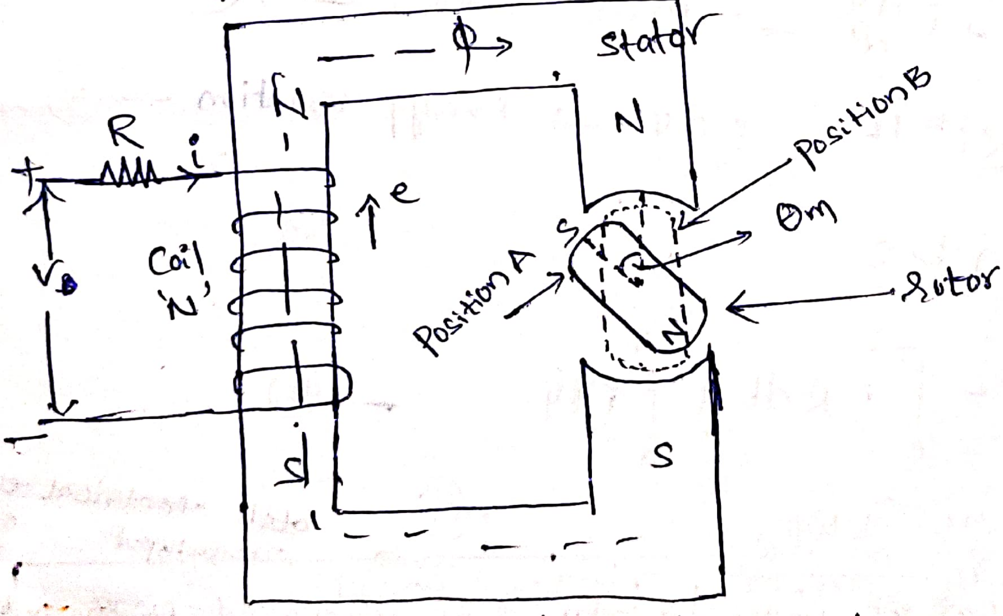


Fig: Singly Excited Rotating system.

* Fig shows. singly excited rotating system. The rotor is a simple iron piece.
* Let us take the rotor in the position A. when stator is magnetized, the rotor also magnetized with opposite polarity by induction principle.
* Then a force of attraction takes place b/n rotor and stator poles. The rotor rotates to the position B where there is a less reluctance. Then it stops rotating.
* Reluctance is the cause for its deflection.
* Hence it is called "reluctance torque"

The instantaneous voltage equation for the coil

By KVL

$$v = Ri + e$$

$$= Ri + N\frac{d\phi}{dt}$$

$$= Ri + \frac{d}{dt}N\phi$$

$$v = Ri + \frac{d\psi}{dt} \longrightarrow \text{Voltage relation} \longrightarrow (1)$$

$$vi = Ri^2 + i\frac{d\psi}{dt} \longrightarrow \text{power relation} \longrightarrow (2)$$

$$vi\,dt = Ri^2 dt + i\,d\psi \rightarrow \text{Energy equation} \rightarrow (3)$$

Integrating on b.s.

$$\int_0^T vi\,dt = \int_0^T i^2 R\,dt + \int_0^\psi i\,d\psi \longrightarrow (4)$$

$$W_e = W_{loss} + W_f \longrightarrow (5)$$

total electrical energy input = electrical loss + Electrical energy converted to magnetic energy.

$$W_f = \int_0^{\psi} i \, d\psi = W_{fe} + W_{me}$$

where W_{fe} = energy stored in magnetic field

W_{me} = mechanical energy output

Static energy Equation :-

when the rotor is in steady state $W_{me} = 0$

$$W_{fe} = \int_0^{\psi} i \, d\psi$$

flux linkages $\psi = Li$

$\psi = N\phi$

$$= \int_0^{\psi} \frac{\psi}{L} \, d\psi$$

$$= \frac{\psi^2}{2L}$$

$$= \frac{[Li]^2}{2L}$$

$$= \frac{1}{2} Li^2$$

Torque Equation :

In order to obtain the expression for the torque developed, differentiate the energy stored in magnetic field with respect to θ_m.

$$T = \frac{d}{d\theta_m} W_{fe} = \frac{d}{d\theta_m} \frac{1}{2} Li^2$$

$$\boxed{T = \frac{i^2}{2} \frac{dL}{d\theta_m}}$$

Field Energy and Co-energy:-

→ In both motor and Generator the field energy is Converted into electric (or) mechanical energy.

→ We can express the magnetic flux as the flux linkage $\psi = N\phi$.

where N = Number of winding turns

ϕ = Magnetic flux.

→ In case of a real magnetic circuit the ψ-i curve is not linear due to saturation of the iron core.

→ For the linear magnetic circuit the ψ-i characteristic is a straight line shown in fig(b). This straight line is described by the equation

$$\psi = Li$$

where L = coefficient known as winding inductance.

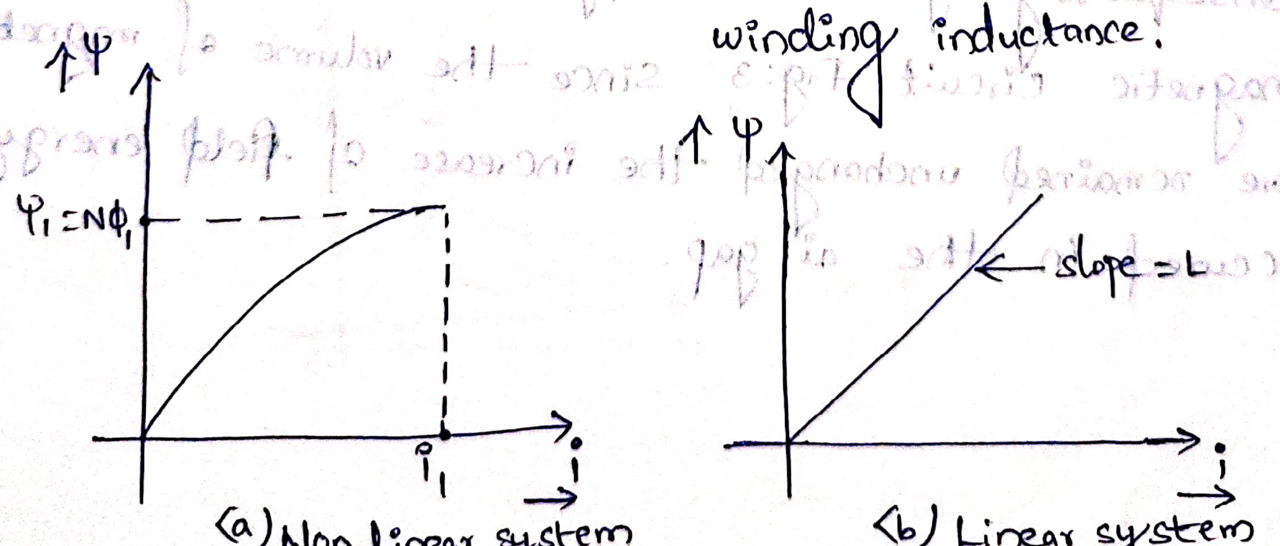
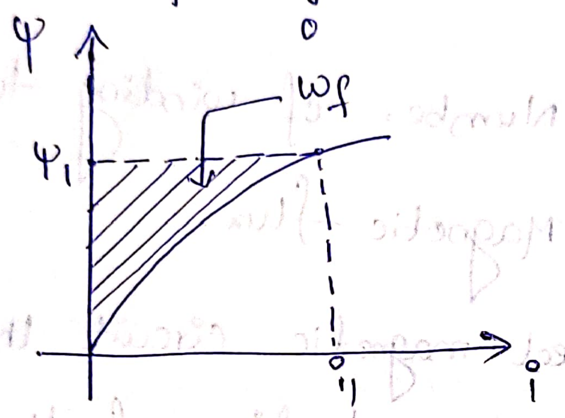


Fig: Flux linkage - current characteristic

→ when the flux linkage is increased from 0 to ψ_1 by means of increase of current from 0 to i_1.

The energy stored in the field is

$$W_f = \int_0^{\psi_1} i \, d\psi$$



Field energy on ψ–i characteristic

* Suppose the air gap of the system increases. The ψ–i characteristic will become more flat and straight. Fig: 2. To maintain the same flux linkage (magnetic flux) greater current should flow in the winding and Consequently greater energy is stored in the magnetic circuit Fig: 3. Since the volume of magnetic core remained unchanged the increase of field energy occured in the air gap.

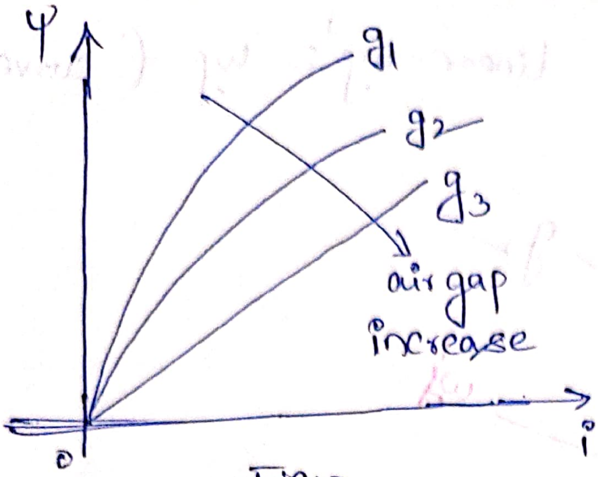


Fig: 2

ψ-i characteristics for various air gaps in the machine

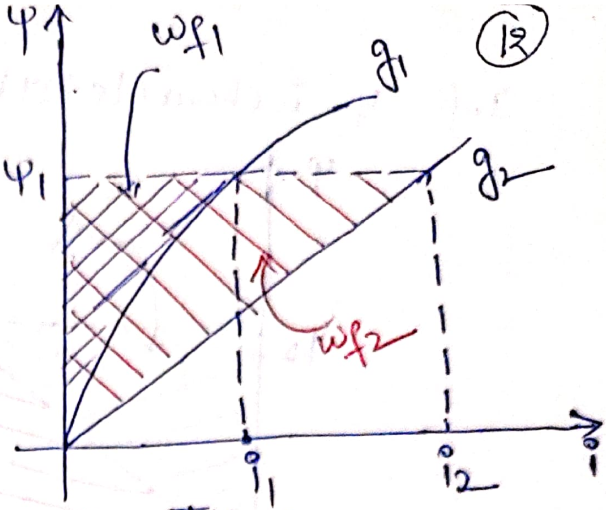


Fig: 3

Field energy in the machine with different air gap.

Co energy :-

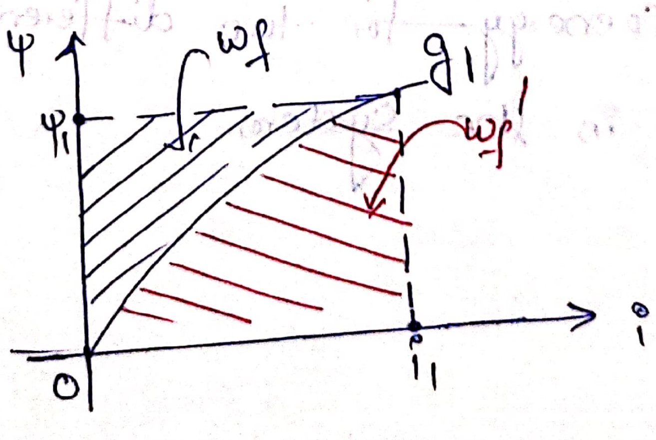
It is defined as

$$w_f' = \int_0^{i_1} \psi \, di$$

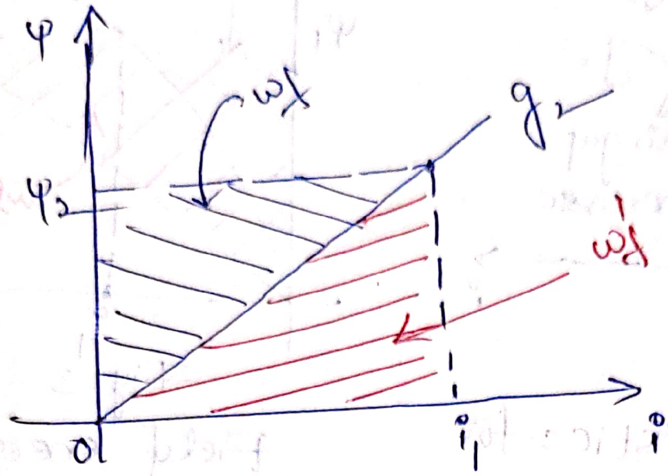
It does not have any physical significance. Coenergy and energy of the system is shown in Fig below.

$$w_f' + w_f = \psi i$$

If ψ-i characteristic is non linear $w_f' > w_f$ (curve g_1)



If $\varphi - i$ characteristic is linear $w_f' = w_f$ (curve g_2)



If the air gap increases from g_1 to g_2 and the current remains unchanged the co energy will decrease. as shown in below figure:

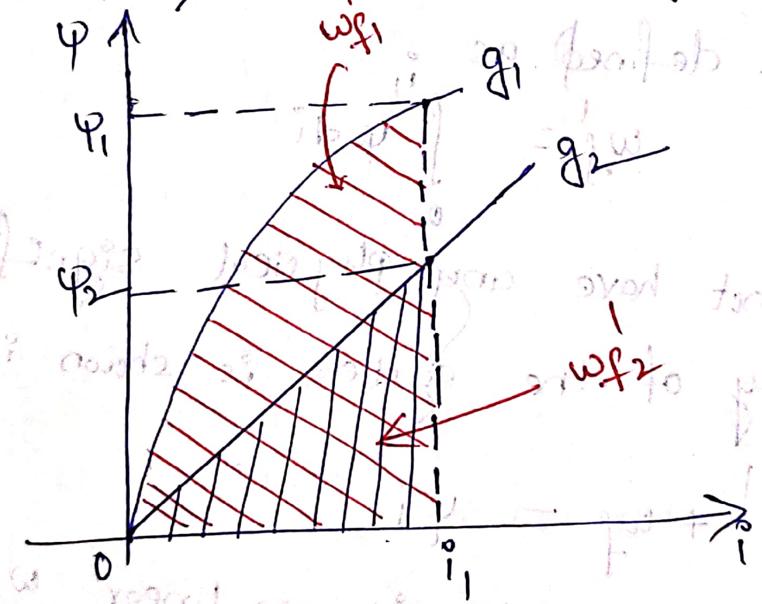


Fig: Field co energy for two different values of air gap in the system.

DC MACHINES & TRANSFORMERS (20A02302T)

UNIT-II

DC GENERATORS

LECTURE NOTES

1. Course Objectives

The objectives of this course is to

1. The constructional features of DC machines and different types of windings employed in DC machines.
2. Characteristics of generators and parallel operation of generators.
3. Methods for speed control of DC motors and application of DC machines.
4. The Constructional Features of transformers, Predetermination of regulation and efficiency of transformers.
5. Various tests on single phase and three phase transformers and parallel operation of transformers.

2. Prerequisites

Students should have knowledge on

1. Engineering Physics
2. Basic Electrical Circuits

3. Syllabus

UNIT 2

DC Generators

Constructional details of DC machine, principle of operation of DC generator, armature windings and its types, emf equation, armature reaction, effect of brush lead, demagnetizing and cross magnetizing ampere turns, compensating windings, commutation, emf induced in a coil undergoing commutation, methods of improving commutation, OCC and load characteristics of different types of generators.

Parallel operation of DC Generators: DC shunt and series generators in parallel, equalizing connections

4. Course outcomes

1. **Apply** the knowledge of magnetic material properties and fundamentals of energy conversion principles.
2. **Identify** the working principle of Dc machines & Transformers with mechanism and various operations performed
3. **Illustrate** the characteristics of various DC machines & Transformers with various operational conditions to determine efficiency & regulation.
4. **Evaluate** the performance & losses of Machines with help of various testing methods like OCC, speed control and OC & SC test.
5. **Explain** & **analyse** the parallel operation of DC machines & Transformers, Scott connections and phase conversions of transformers.

5. Lecture Notes

1.1 INTRODUCTION

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 laws, when a 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 a 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.

Figure 1.1: Block diagram of Generator

1.2 CONSTRUCTIONAL FEATURES

Mainly it consists of Stator, Rotor core, Rotor windings;

Stator: It is the fixed and main part of the DC generator. The function of the stator is to supply the magnetic fields where the coils rotate. Stator consists of permanent magnets (two of them with opposite poles facing) which is placed to fit around the rotor.

Rotor (Armature Core): It is the next main part of the DC generator. It consists of slotted iron laminations which are stacked so as to form a cylindrical armature core. The laminations are usually provided to reduce the loss due to eddy current.

Armature Windings:

The slots of the armature core are used to hold the armature windings. It is in the form of a closed circuit winding connected in series –parallel to increase the amount of current generated.

A DC generator has the following parts

1. Yoke
2. Field Poles Include Pole shoe & Pole Core
3. Field winding
4. Armature core & Armature winding
5. Commutator
6. Brushes
7. Bearing

The construction of dc motor and generator is nearly same. A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus, a DC generator or a DC motor can be broadly termed as a DC machine. These basic constructional details are also valid for the construction of a DC motor.

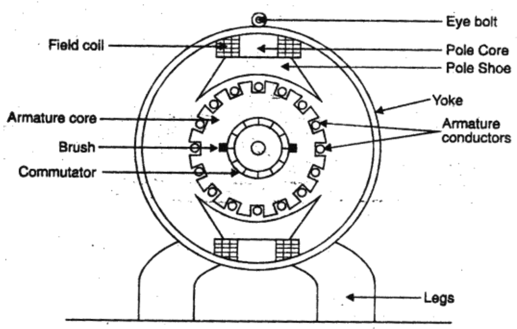


Fig 1.2. Front View of DC Generator

1. **Yoke:** The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding. Yoke of DC generator serves two purposes; It holds the

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

2. **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.
3. **Field winding:** They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.
4. **Armature core:** Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.
5. **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding.

   Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.

6. **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors.

   A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft.

Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

7. **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.

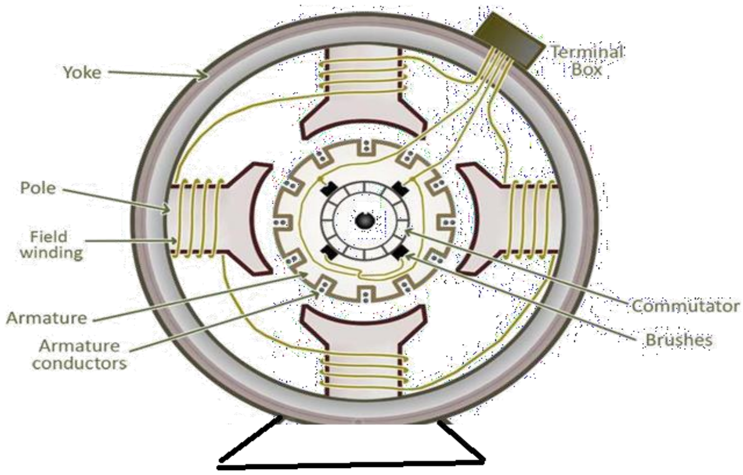


Fig 1.3 Front View of DC Generator

1.2.1Additional details:

FIELD SYSTEM:

- The function of the field system is to produce uniform magnetic field within which the armature rotates.
- It consists of a number of salient poles (of course, even number) bolted to the inside of circular frame (generally called yoke).
- Yoke is usually made of solid cast steel whereas the pole pieces are composed of stacked laminations.
- Field coils are mounted on the poles and carry the d.c. exciting current.
- The field coils are connected in such a way that adjacent poles have opposite polarity.
- The m.m.f. developed by the field coils produces a magnetic flux that passes through the pole pieces, the air gap, the armature and the frame.

ARMATURE CORE:

- The armature core is keyed to the machine shaft (fig.1.4) and rotates between the field poles. It consists of slotted soft-iron laminations that are stacked to form a cylindrical core.
- The laminations are individually coated with a thin insulating film so that they do not come in electrical contact with each other. The purpose of laminating the core is to reduce the eddy current loss.

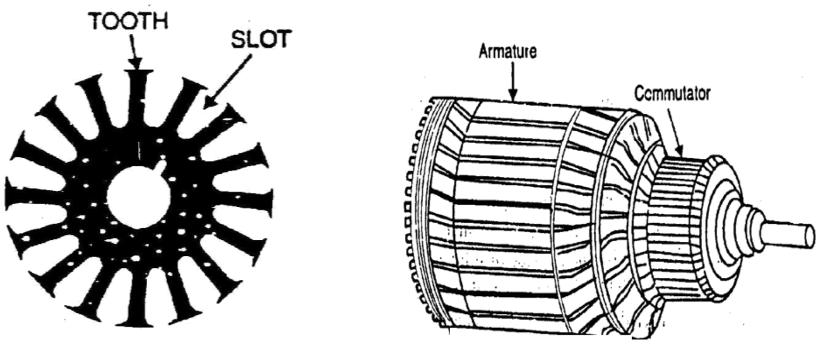


Fig 1.4 Front View of rotor lamination and final rotor cylindrical structure

ARMATURE WINDING:

- The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding.
- This is the winding in which "Working e.m.f. "is induced.
- A d.c. machine (generator or motor) generally employs windings distributed in slots over the circumference of the armature core.
- The Fig 1.5 i show a single-turn coil. It has two conductors or coil sides connected at the back of the armature.
- The fig 1.6 ii shows a 4-turn coil which has 8 conductors or coil sides.

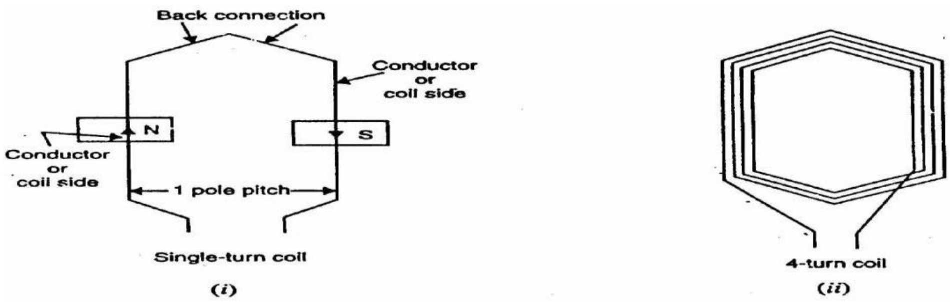


Fig 1.5 single & Multiple coil rotor winding

1.3 PRINCIPLE OF OPERATION OF DC GENERATORS

1.3.1 PRINCIPLE OF DC GENERATOR

An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that **whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed**.

1.3.2 SIMPLE LOOP GENERATOR

The direction of induced e.m.f. (and hence current) is given by Fleming's right hand rule.

Therefore, the essential components of generator are…

(a) A magnetic field

(b) Conductor or a group of conductors

(c) Motion of conductor w.r.to. Magnetic field

- Consider a loop, say, ABCD. Assume it is rotating in clockwise direction in a uniform magnetic field with a constant speed.
- When the loop ABCD starts rotating, flux linked to the coil to the sides CD and AB will start changing. Now the emf induced to the sides of the coil also starts changing.
- In actual, the emf induced on one of the coil side will add to the emf induced to the other coil.

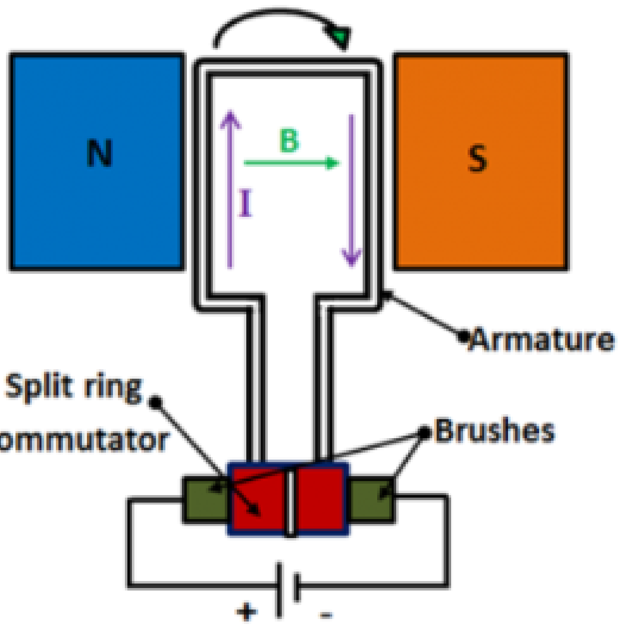


FIG. 1.6 TYPICALLY ILLUSTRATES THE BASIC PRINCIPLE OF DC GENERATOR.

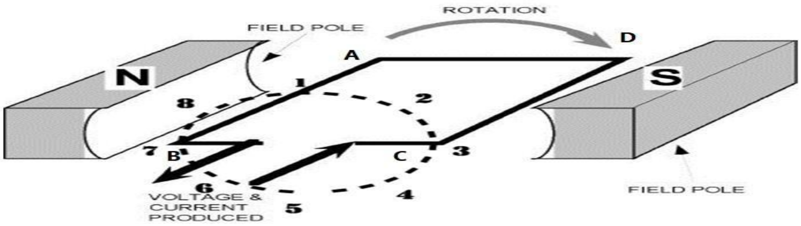


FIG. 1.7 Simple loop GENERATOR

Case1: At position 1

- Here the emf is zero.
- This is because the magnetic flux lines are moving parallel.

Case2: At position 2

- Here a low emf is induced.
- The coil sides are at an angle w.r.t the flux.

Case3: At position 3

- Here the emf generated is maximum.
- The coil sides are at right angles with the flux.

Case4: At position 4

- The emf generated is low.
- The coil sides are at an angle w.r.t the flux.

Case5: At position 5

- No magnetic lines are cut.
- The emf induced is zero.

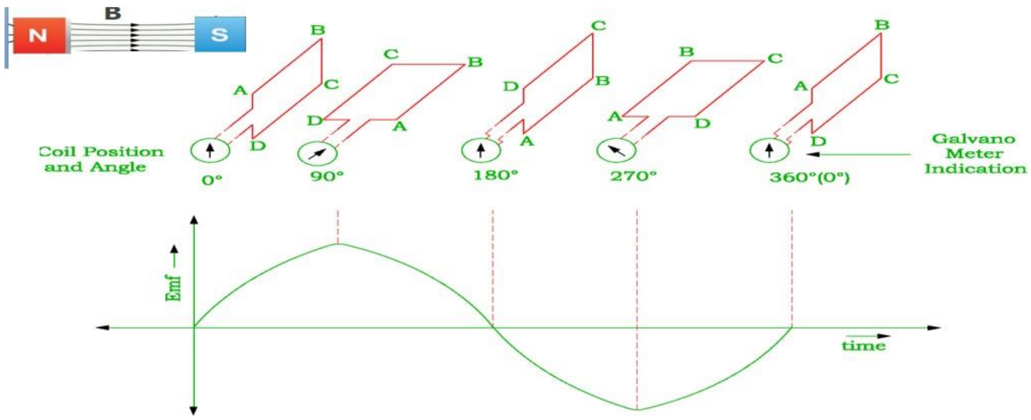
Case 6: At position 6

- The direction of emf generated is reversed.
- Coil sides move under a pole of opposite polarity.

Case 7: At position 7 Maximum emf is generated here.

The cycle will then repeat. Here the emf generated is an alternating one.

- This alternating voltage is then converted into dc voltage by a device known as the commutator. Commutator is a **mechanical rectifier.**
- The purpose of brushes is simply to collect current from the rotating loop or winding to the external stationary load.



1.4 EMF EQUATION FOR DC GENERATOR

1.4.1 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,

$$e = d\Phi/dt = \text{total flux}/\text{total time taken}$$

Induced emf of one conductor is

$$e = \frac{\Phi P}{60/N} = \frac{\Phi P N}{60}$$

1.4.2 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.

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

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

1.4.3 Solved Example Problems:

1.A6 pole lap wound DC generator has 720 conductors and a flux of 80 mili Weber per pole is driven at 1000 RPM. Find the generated EMF?

Solution:

No. of poles P=6 ; For a Lap wound generator,

No.of parallel paths are A=P=6

No.of Conductors are Z= 720;

Flux per pole φ = 80 m.Webers =0.080 Webers

Speed of rotor N=1000rpm

Eg= (φ ZN/60) *(P/A) = ((0.080 *720*1000/60)(6/6) = 960V

2. A 4 pole DC generator has 51 slots and each contains 20 conductors. Flux per pole is 7 mili Weber and runs at 1500 RPM. Find the produced EMF of the machine if its armature is wave wounded.

Solution:

Given data

Poles P= 4

Armature core slots are = 51

No. of conductors in one slot = 20

Total no. of conductors (Z) = 51*20 =1020

Flux per pole φ = 0.007 Weber's

Speed N= 1500 rpm

For wave wounded windings, No. of parallel paths are A=2

Eg= (φ ZN/60) (P/A) =((0.007*1020*1500)/60) (4/2) =357 V

3. A 6 pole machine has an armature with 90 slots and 8 conductors per slot and runs at 1000 RPM. Flux per pole is 0.05wb. Determine the Induced EMF if winding is lap and wave.

Solution: Poles No. P =6

No. of slots=90

Conductors per slot =8

Total no. Of conductors(Z) =90*8=720

N=1000rpm

φ = 0.05 wb

i) LAP winding (A=P):::: Eg= (φ ZN/60) (P/A) = 600V

ii) WAVE winding (A=2):::: Eg= (φ ZN/60) (P/A) =1800V

4. A lap wound DC shunt generator having 80 slots with 10 conductors per slot generates no load EMF of 400 V when running at 1000 RPM. At what speed should It be rotated to generate a voltage of 220 V on open circuit.

Solution:

LAP winding, No. of parallel paths A=P ; No.of slots are =80 ;

No.of. Conductors per slot =10 ; Total no. of conductors = 10*80 =800 ;

No-load EMF Eg = 400V; Speed of machine N= 1000 rpm ;

N1 = ? To generate voltage of Eg 1=220V

We know that Eg = (φ Z N/60) (P/A) ....(Eg Directly propositional to N)

Eg/N = Eg1/N1 >>>>> 400/1000 = 220/N1 >>>>> N1 =550rpm

5. An 8 Pole DC generator has 500 armature conductors and has a useful flux per Pole of 0.065 wb. What will be the EMF generated if it is lap connected and runs at 1000 RPM. What must be the speed at which it is to be driven to produce the same EMF if it is wave wound?

Solution:

Given data P =8 ; Z=500 ; φ = 0.065 Wb ; For LAP winding A=P=8

N (speed) =1000rpm;

i) E_g= (φ ZN/60) (P/A) =((0.065*500*1000)/60) (8/8) =541.67 V

ii) For Wave wound A=2 ; N_1 = ? E_g=541.67V

We know ; E_g = (φ ZN/60) (P/A)

N_1 = (E_g*A*60)/ (φ*Z*P)

= (541.67*2*60)/(0.065*500*8)

= 250rpm

6. **A four pole generator having wave-wound armature winding has 51 slots, each slot containing 20 conductors. What will be the voltage generated in the machine when driven at 1500 rpm assuming the flux per pole to be 7.0 mWb ?**

Solution:

For a simplex wave wound generator,A=2

No.of conductors Z=No.of slots* Conductors per slot=51*20=1020

Speed N=1500rpm and No.of poles P=2

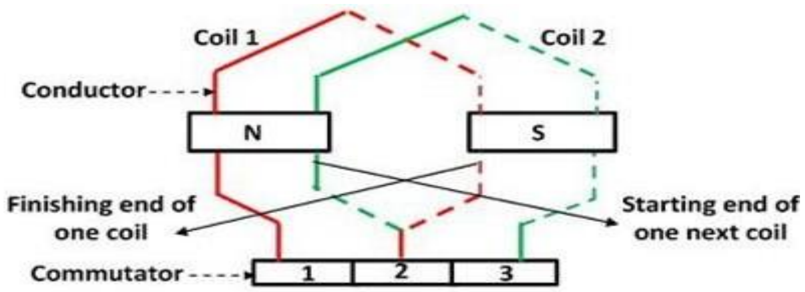
EMF Generated/path = φZN P/60A

= $(7*10^{-3})$ * 51*20*1500*2 /(60*2)

=178.5V

1.5 TYPES OF ARMATURE WINDING CONNECTIONS: LAP & WAVE WINDINGS

LAP WINDING (PARALLEL) WINDING :



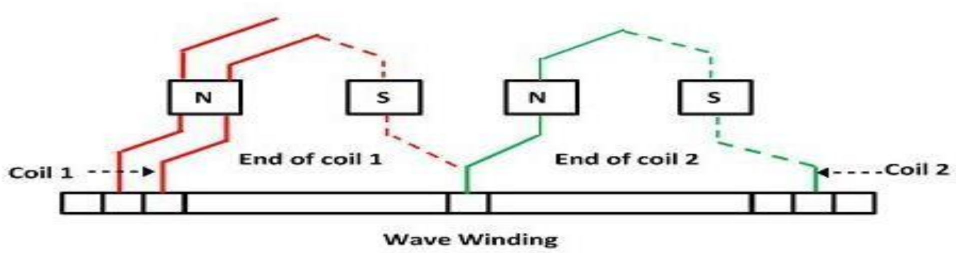
Lap Winding

- In lap winding, the consecutive coils overlap each other. The first end of the winding is connected to the one segment of the commutator, and the starting end of the other coil is placed under the same pole and join with the same segment of the com The conductors are connected in such a way that the number of parallel paths equals to the number of poles.

- Consider the machine has P poles and Z armature conductors, then there will be P parallel paths, and each path will have Z/P conductors in series.
- The number of brushes is equivalent to the number of parallel paths.

WAVE WINDING (SERIES WINDING):

- The one end of the coil is connected to the starting end of the other coil.
- The coils are connected in the wave shape and hence it is called the wave winding.
- The conductor of the wave winding are split into two parallel paths, and each path had Z/2 conductors in series.
- The number of brushes is equal to 2, i.e., the number of parallel paths.



LAP WINDING	WAVE WINDING
1. The number of parallel path in lap winding is equal to the number of poles.	1. The number of parallel path is always equal to 2.
2. The number of carbon brush in lap winding is equal to the number of poles.	2. The number of carbon brush in wave winding is 2.
3. Lap winding are used for low voltage and high current rating machines.	3. Wave connected winding is required for high voltage but low current rating machines.
4. emf generated in lap winding is independent of number of poles.	4. the emf generated depends on the number of poles.
5. It is more costly due to requirement of equalizer ring and more carbon brushes.	5. It is comparatively cheap.

1.6. TYPES or CLASSIFICATION OF GENERATORS

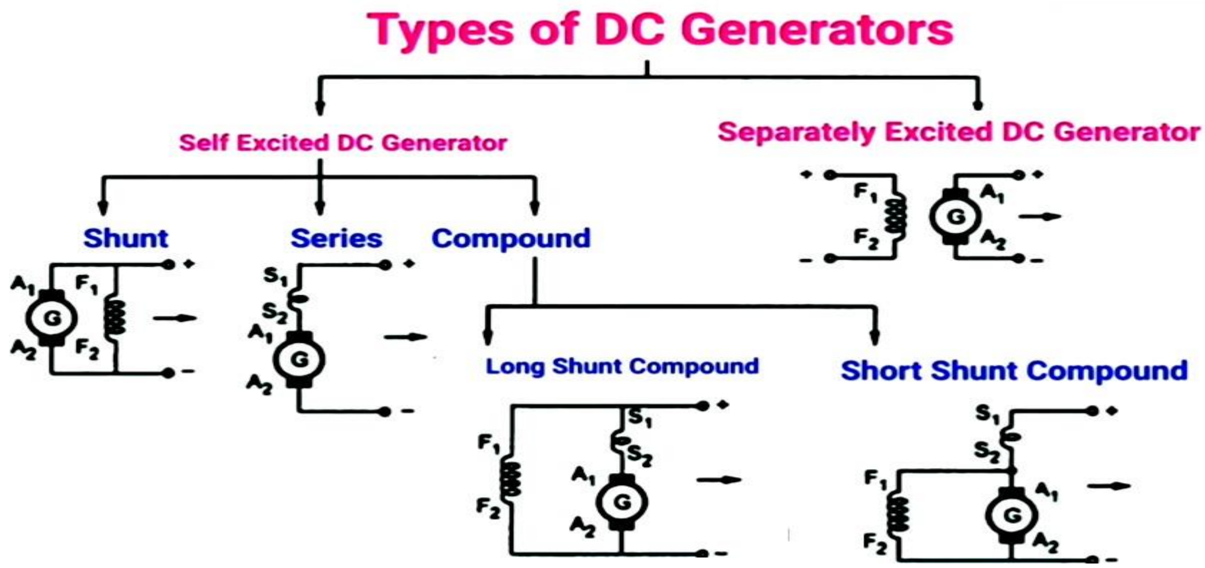


Fig 1.8 Types of generators

1.6.1 SEPARATELY EXCITED GENERATOR:

- A DC generator whose field winding or coil is energized by a separate or external DC source is called a separately excited DC Generator.
- The flux produced by the poles depends upon the field current with the unsaturated region of magnetic material of the poles. i.e. flux is directly proportional to the field current. But in the saturated region, the flux remains constant.
- The figure of separately -excited DC Generator is shown below:

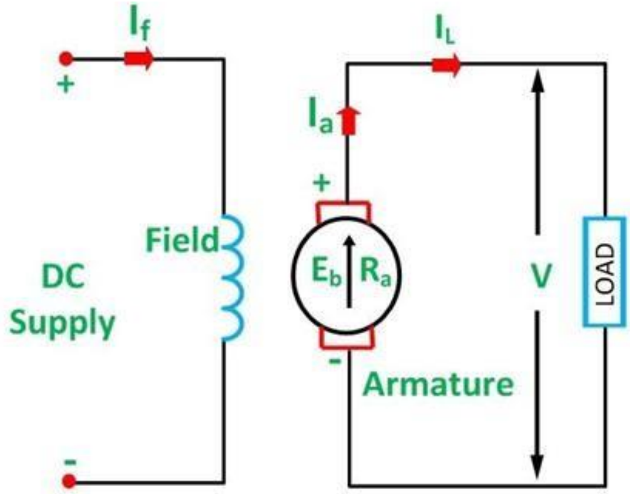


Fig 1.8 Equivalent circuit of separately excited generator

Here,

$I_a = I_L$ where I_a is the armature current and I_L is the line current.

Terminal voltage is given as $V = E_g - I_a R_a$

If the contact brush drop is known, then the equation (1) is written as:

$$V=E_g-I_a R_a -2V_b$$

The power developed is given by the equation shown below:

Power developed = $E_g I_a$

Power output = $V I_L = VI_a$

1.6.2 SELF EXCITED GENERATOR: I) Series II) Shunt III) Compound

1.6.2.1 SERIES EXCITED GENERATOR:

- The field winding and armature winding is connected in series.
- This 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.

$I_a = I_L = I_{se}$;

$V_t = V = E_g - I_a.R_a - 2V_b$

Power output = $V I_a = V I_L$

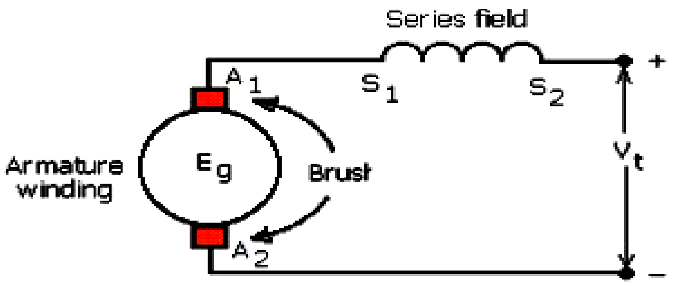


Fig 1.9 Equivalent circuit of series excited generator

1.6.2.2 SHUNT GENERATOR

In a shunt generator, the field winding is connected in parallel with the armature winding, so that terminal voltage of the generator is applied across it.

Shunt field current, $I_{sh} = V/R_{sh}$

Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V=E_g-I_a R_a$

Power developed in armature $=E_g I_a$

Power delivered to load $=VI_L$

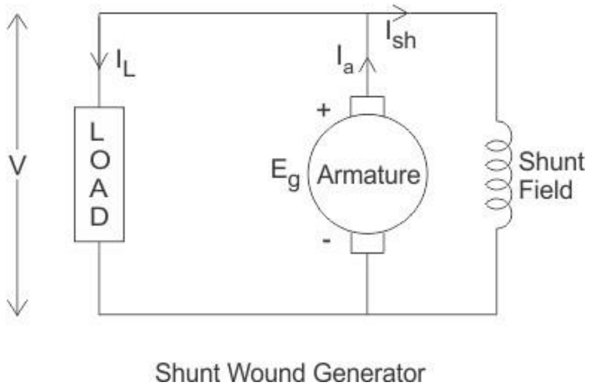


Fig 1.10 Equivalent circuit of shunt generator

1.6.2.3 COMPOUND GENERATOR

- The generator which has both shunt and a series field is called the compound wound generators.
- If the magnetic flux produced by the series winding assists the flux produced by the shunt winding, then the machine is said to be cumulative compounded. If the series field flux opposes the shunt field flux, then the machine is called the differentially compounded.
- It is connected in two ways. One is a long shunt compound generator, and another is a short shunt compound generator.
- If the shunt field is connected in parallel with the armature alone then the machine is called the short compound generator. In long shunt compound generator, the shunt field is connected in series with the armature.

1.6.2.3. a LONG SHUNT COMPOUND WOUND GENERATOR

- In a **long shunt-wound generator,** the shunt field winding is parallel with both armature and series field winding.
- The connection diagram of the long shunt-wound generator is shown below:

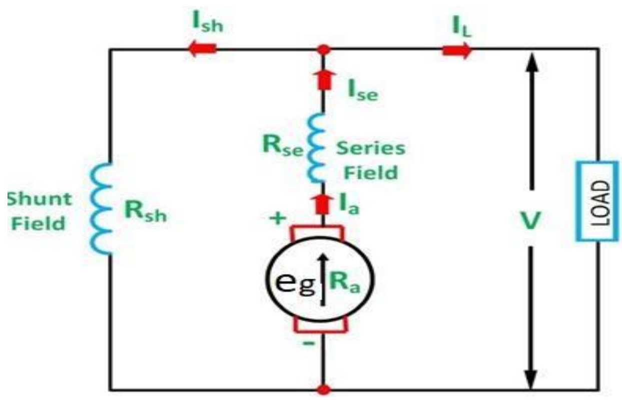


Fig 1.11 Equivalent circuit of long shunt dc compound generator

The shunt field current is given as: $I_{sh} = V/R_{sh}$

Series field current is given as: $I_{se} = I_a = I_L + I_{sh}$

Terminal voltage is given as: $V = E_g - I_a R_a - I_{se} R_{se} = E_g - I (R_a + R_{se})$

If the brush contact drop is included, the terminal voltage equation is written as: $V = E_g - I(R_a + R_{se}) - 2V_b$

Power developed in armature $= E_g I_a$

Power delivered to load $= V I_L$

1.6.2.3.b SHORT SHUNT COMPOUND WOUND GENERATOR

- In **a Short Shunt Compound Wound** Generator, the shunt field winding is connected in parallel with the armature winding only.
- The connection diagram of a short shunt-wound generator is shown below.

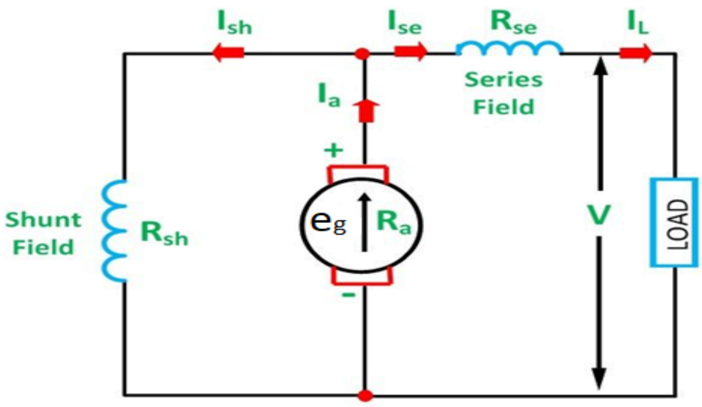


Fig 1.12 Equivalent circuit of short shunt dc compound generator

The shunt field current is given as $I_{sh} = (V + I_L R_{se}) / R_{sh} = (E_g - I_a R_a)/R_{sh}$

Armature current; $I_a = I_L + I_{sh}$

Series field current is given as $I_{se} = I_L$

Terminal voltage is given as: $V = E_g - I_a R_a - I_L R_{se}$

If the brush contact drop is included, the terminal voltage equation is written as:

$V = E_g - I R_a - I_L R_{se} - 2V_b$

Power developed in armature $= E_g I_a$

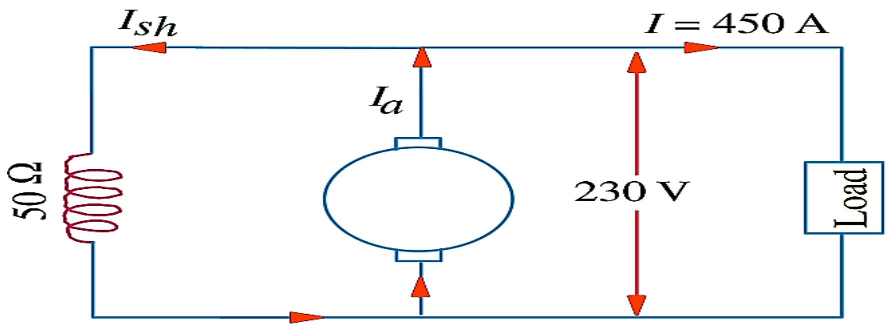
Power delivered to load $= V I_L$

1.6.3. Solved Example Problems:

1. **A shunt generator delivers 450 A at 230 V and the resistance of the shunt field and armature are 50 Ω and 0.03 Ω respectively. Calculate the generated e.m.f?**

Solution:

The Generator Circuit is as shown in the figure,



Current through shunt field winding is Ish =230/50 =4.6 A

Load current, I =450A

Armature current I_a=I + I_{sh} =450+4.6 =454.6 A

Armature voltage drop = I_a*R_a =454.6*0.03 =13.6V

Generated EMF , E_g =V + I_a*R_a =230 +13.6 =243.6V

2. **A 4 Pole lap connected shunt generator has 300 armature conductors and a flux/pole of 0.1 Wb. It runs at 1000 rpm. The armature and field resistances are 0.2Ω and 125 Ω respectively. Calculate the terminal voltage when it is loaded to take a load current of 90A.**

Solution:

Poles P=4, Conductors total Z=300, φ=0.1 Wb, N=1000 rpm ;

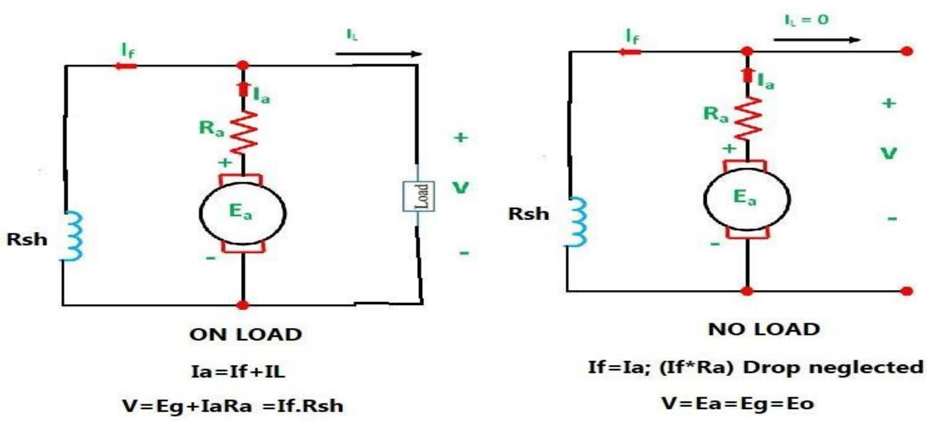
R_a=0.2Ω R_{sh}=125Ω ;; I_L=90A

$V=E_g-I_aR_a$ = ?

E_g= (0.1x300x1000)(4)/(60x4) = 500V

$I_a=I_{sh}+I_L$ =4+90=94A and I_{sh} = E_g/R_{sh}= 500/125 =4A

V= 500-94x0.2 =481.2V



3. **A 30KW,300V Dc shunt generator has armature and field resistances of 0.05 Ω and 100 Ω respectively. Calculate the total power developed in the armature when it delivers full load.**

Solution:

POWER OUTPUT (P) =30KW; Terminal voltage V=300 volts

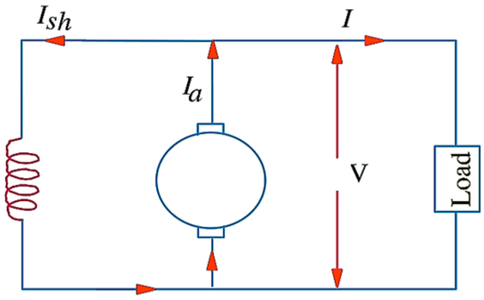
R_a = 0.05 Ω R_{Sh}=100 Ω ; load current, I_L = P/V =30000/300=100A (;; P=VI)

I_{sh}= V/R_{sh} = 300/100 =3A

I_a=I_{sh}+I_L =3+100=103A

E_g = V+I_a R_a =300+103x0.05=305.15V (;;Eg-Ia Ra=V)

Power at armature = E_g*I_a =305.15*103 =31430.45=31.43KW



4. **A DC shunt generator has an induced voltage on open circuit of 127V.When the machine is on load, the terminal voltage is 120V. Find the load current if the field circuit resistance is 15Ω and the armature resistance is 0.02Ω**

Solution:

Terminal voltage V=120volts;

Open circuit voltage (Induced voltage) E_g =127 Volts;

R_a =0.02 Ω ;; R_{sh} =15 Ω

I_L =I=??? I =Ia-I_{sh} ;;

I_{sh}=V/R_{sh}= 120/15 =8A E_g=V + I_a R_a >>>> I_a =(E_g-V)/Ra =(127-120)/0.0.2

=350A

I =350-8 =342 A

5. **A 4 pole dc shunt generator with lap connected armature has field and armature resistances of 50 Ω and 0.1 Ω respectively. It supplies power to sixty numbers of 100V, 40W lamps. Calculate the armature current and the generated emf. Allow a contact drop of 1V/brush and interpole and compensating winding drops of 1V/pole and 0.25V/pole respectively.**

Solution:

Poles P =4 ; As winding is Lap connected ;A=P=4;

Field winding resistance R_{sh}= 50 Ω ; Armature winding resistance R_a=0.1Ω

LOAD::: No.of Lamps =60

Wattage of each Lamp=40W.

Voltage of each lamp V=100Volts

Total Load power P = 60x40 =2400 Watts

Terminal Voltage V = 100 Volts

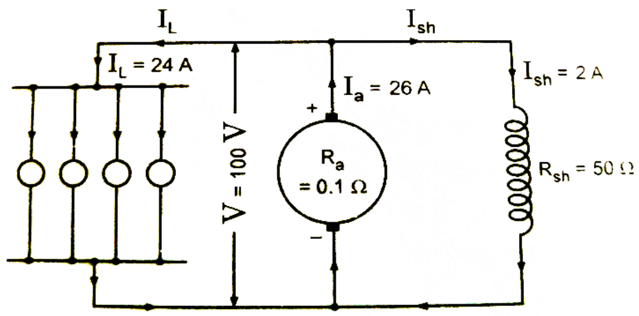
Load current I = P/V =2400/100 =24A

I_{sh}=V/R_{sh} = 100/50 =2A

I_a =I_{sh}+I =2+24A=26A

E_g=V+IaRa+brush voltage drop+ interpole & compensating Winding drops

E_g=100+(26x0.1)+2x1+4x1+4x0.25 =109.6V



6.Ashort shunt compound wound dc generator delivers 100A to a load at 250V. The generator has shunt field, series field and armature resistances of 130Ω,0.1 Ω and 0.1 Ω respectively. Calculate the voltage generated in the armature winding. Assume 1V voltage drop per brush.

Solution: Given SHORT SHUNT DC Generator

Load current = 100A, Terminal voltage =250V

R_a=0.1 Ω R_{sh}=130Ω R_{se}=0.1Ω Brush contact voltage drop is = 1V/brush

I_{se}= IL =100A

V_{sh}= V +I_{se}*R_{se} =250+100*0.1 =260V

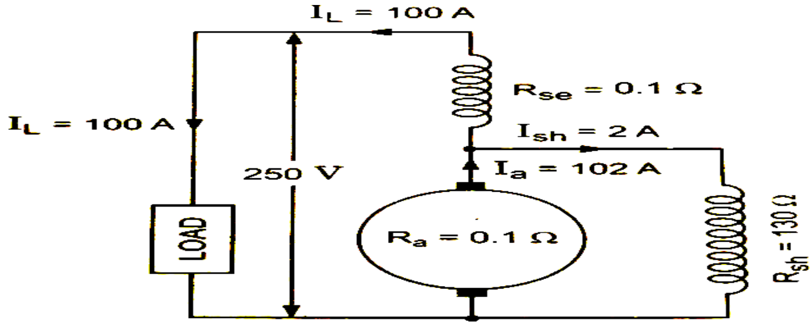
I_{sh} = V_{sh}/R_{sh} =260/130 =2A

I_a = I_{sh}+I =2+100=102A

E_g =V+IaRa+$I_{se}R_{se}$+brush drop = 250+102x0.1+100x0.1+2x1 = 272.2V

(Or) E_g-I_aR_a-brush drop = V_{sh} >>>>E_g =V_{sh}+ I_aR_a+brush drop

=260+102x0.1+2x1=272.2V



1.6.4. EQUIVALENT CIRCUIT OF A DC MACHINE ARMATURE

- The armature of a DC generator can be represented by an equivalent electrical circuit. It can be represented by three series-connected elements E, Ra and V_b.
- The element E in the equivalent circuit diagrams is the generated voltage, Ra is the armature resistance, and V_b is the brush contact voltage drop.

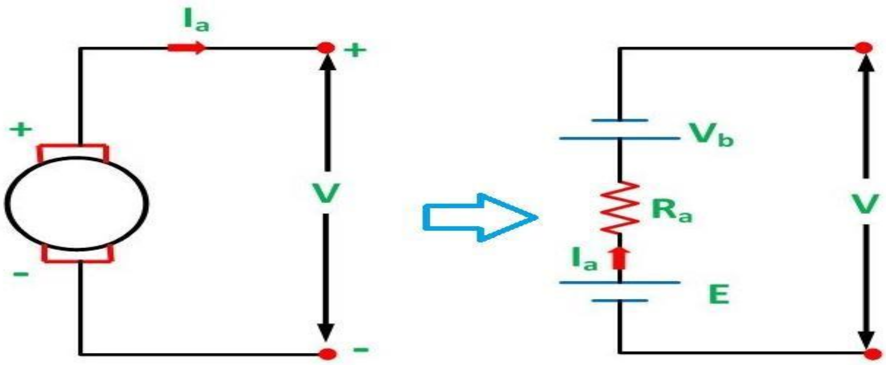


Fig 1.13 Equivalent circuit of dc Generator

1.6.5. Voltage Build up in DC Generator:

In a separately excited generator, we can have a separate source to provide excitation to the field winding.

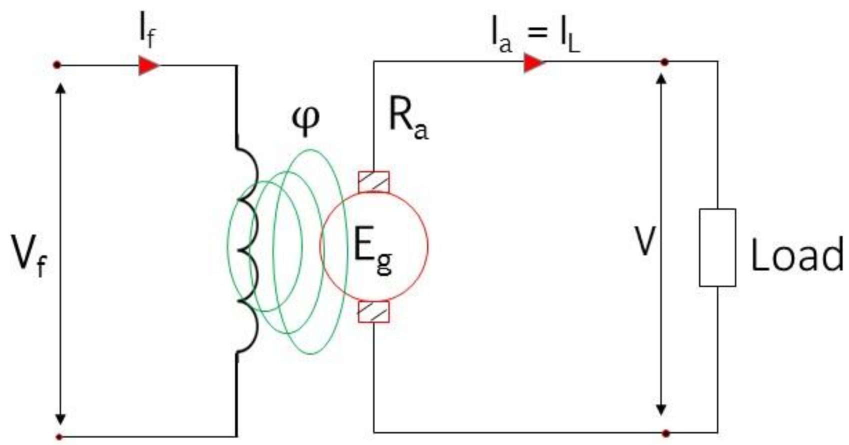


Fig 1.14 Equivalent circuit of dc separately excited generator

But in self excited generators (series ,shunt & compound wound generators) do not have separate source for excitation. In order to build e.m.f, poles should contain some residual flux.

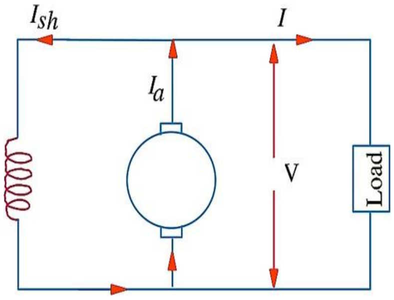


Fig 1.15 Equivalent circuit of dc shunt generator

- **Condition to be met by self excited generators to build EMF.**
  - ✓ Residual flux (φ_R)
  - ✓ Field Resistance < Critical field Resistance (R_f<R_c)
  - ✓ No load

1.6.6 EXCITATION SYSTEM

- Defined as the **System which is used for the production of the flux by passing current in the field winding.**
- The amount of excitation required depends on the load current, load power factor and speed of the machine.
- The magnetic field required for the operation of a d.c. generator is produced by an **electromagnet.**
- This electromagnet carries a field winding which produces required magnetic flux when current is passed through it.
- The field winding is also called **exiting winding** and current carried by the field winding is called an **exciting current**.
- Thus supplying current to the field winding is called excitation and the way of supplying the exciting current is called **method of excitation**.

1.6.6.1 Methods of excitation

Depending on the methods of excitation used, the d.c. generators are classified as,

1. **Separately excited generator**
2. **Self excited generator**

- In **separately excited generator**, a separate external d.c. supply is used to provide exciting current through the field winding.
- The d.c. generator produces d.c. voltage. If this generated voltage itself is used to excite the field winding of the same d.c. generator, it is called **self excited generator**.

1.6.6.2 Voltage Build up in DC shunt Generator:

- Consider a shunt generator to run at rated speed with residual flux in its poles. A small voltage will induce in the armature which will produce additional small current.
- If the generator is on No-load, all the initial current will flow into field winding to produce initial MMF with field winding turns.
- As small amount of current is increased in the field winding a small additional flux will also develop.
- This additional flux will link with the rotating armature and an additional EMF will induced across the winding, resulting in an additional flow of current.
- It's a cumulative process as the current increases the flux out of the pole increased & the induced voltage also increases.

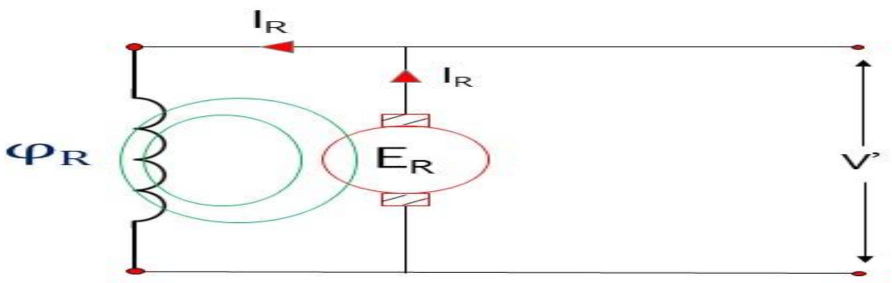


Fig 1.16 dc shunt generator

$$\varphi_R \longrightarrow E_R \longrightarrow I_R$$

$$I_R N_{sh} \longrightarrow \varphi_R + \varphi_1 \longrightarrow E_R + E_1 \longrightarrow I_R + I_1$$

$$(I_R + I_1)\, N_{sh} \longrightarrow \varphi_R + \varphi_1 + \varphi_2 \longrightarrow E_R + E_1 + E_2 \longrightarrow I_R + I_1 + I_2$$

After saturation of the poles, even though the current increases, flux does not increase and so build of voltage stops and is constant.

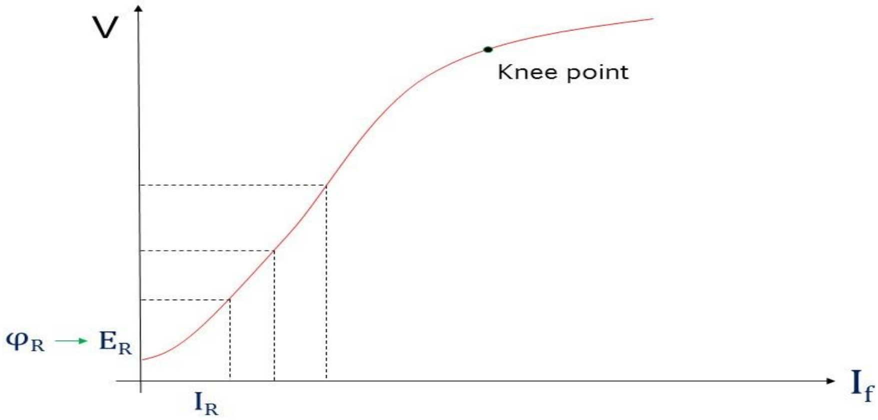
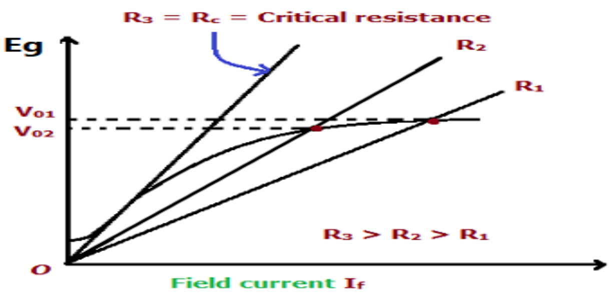
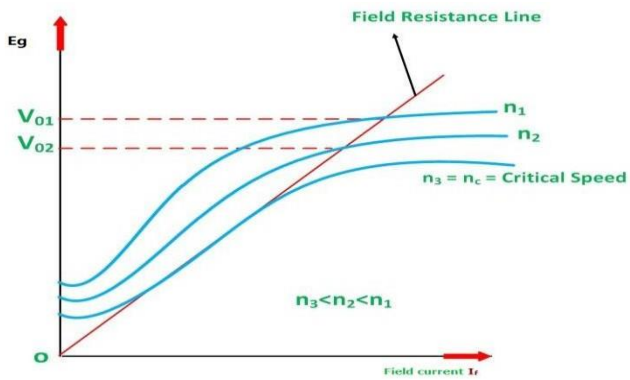


Fig. 1.17 Voltage build up in a shunt generator

1.6.6.3. 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**. **Critical field resistance line** is a tangent to the open circuit characteristics of the generator at a given speed.
- At a particular speed, called the **critical speed**, the field resistance line becomes tangential to the magnetization curve. Below the critical speed, the voltage will not build up.





Determination of Critical Resistance & Critical Speed-

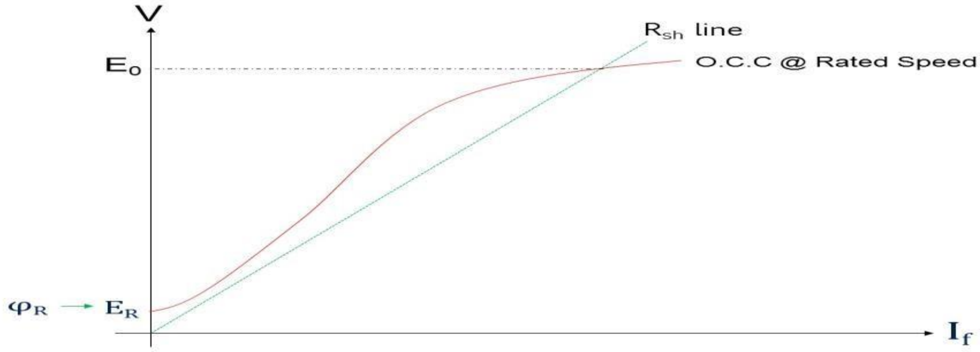
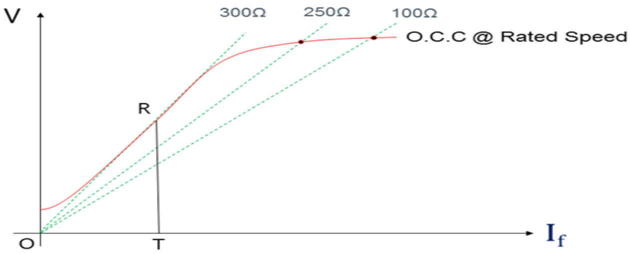


Fig 1.18 OCC curve at rated speed and given field resistance

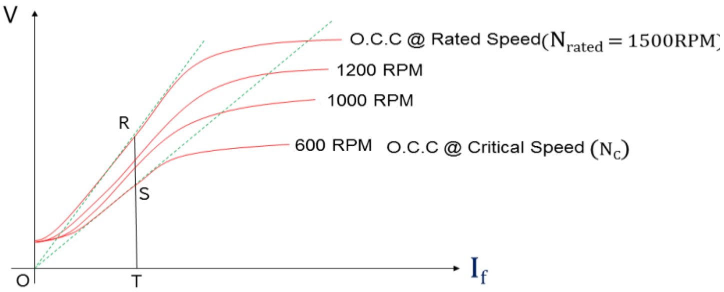
Critical Resistance- The resistance of the field winding above which the generator doesn't build up voltage.
Critical Speed- The speed of generator below which the generator doesn't build up the voltage.

Determination of Critical Resistance-



$$R_C = \frac{RT}{OT}$$

Determination of Critical Speed-



Length of ST $\propto N_C$

Length of RT $\propto N_{Rated}$

$$\frac{ST}{RT} = \frac{N_C}{N_{Rated}} \qquad N_C = \left(\frac{ST}{RT}\right) N_{Rated}$$

- Initially voltage induced due to residual flux is obtained from O.C.C
- Voltage build up process continues as explained before.
- Straight line given by V= $I_f R_f$ shown in the above figure is known as **Field Resistance Line.**
- The final stable operating point (M) will be the point of intersection between the O.C.C and the field resistance line.
- If **field circuit resistance is increased**, final **voltage decreases** as point of intersection shifts toward left.

- The field circuit resistance line which is tangential to the O.C.C is called the critical field resistance.
- If the field circuit resistance is more than the critical value, the machine will fail to excite and no voltage will be induced. The reason being no point of intersection is possible in this case. 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.
- If speed is further reduced to a certain critical speed (Nc), the present field resistance line will become tangential to the O.C.C at Nc. For any speed below Nc, no voltage built up is possible in a shunt generator.

1.7.ARMATURE REACTIUON

1.7.1Definition: The armature reaction simply shows the effect of armature field on the main field. In other words, the armature reaction represents the impact of the armature flux on the main field flux. The armature field is produced by the armature conductors when current flows through them. And the main field is produced by the magnetic poles.

- The armature flux causes two effects on the main field flux.
- The armature reaction distorted the main field flux.
- It reduces the magnitude of the main field flux.

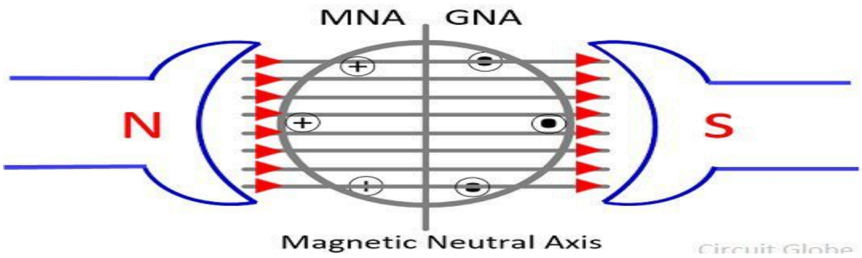


Fig 1.19 Magnetic Neutral axis

Consider the figure below shows the two poles dc generator. When no load connected to the generator, the armature current becomes zero. In this condition, only the MMF of the main poles exists in the generator. The MMF flux is uniformly distributed along the magnetic axis. The magnetic axis means the centre line between the north and south pole. The arrow in the below-given image shows the direction of the magnetic flux Φ_M. The magnetic neutral axis or plane is perpendicular to the axis of the magnetic flux.

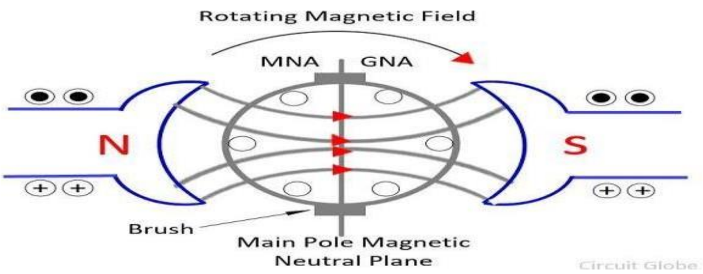


Fig 1.20 Magnetic Neutral axis

The MNA coincides with the geometrical neutral axis (GNA). The brushes of the DC machines are always placed in this axis, and hence this axis is called the axis of commutation.

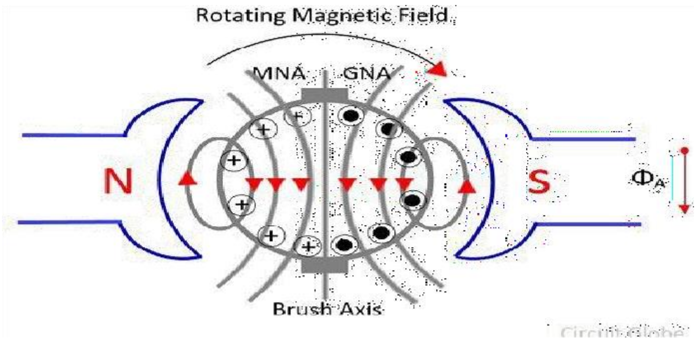
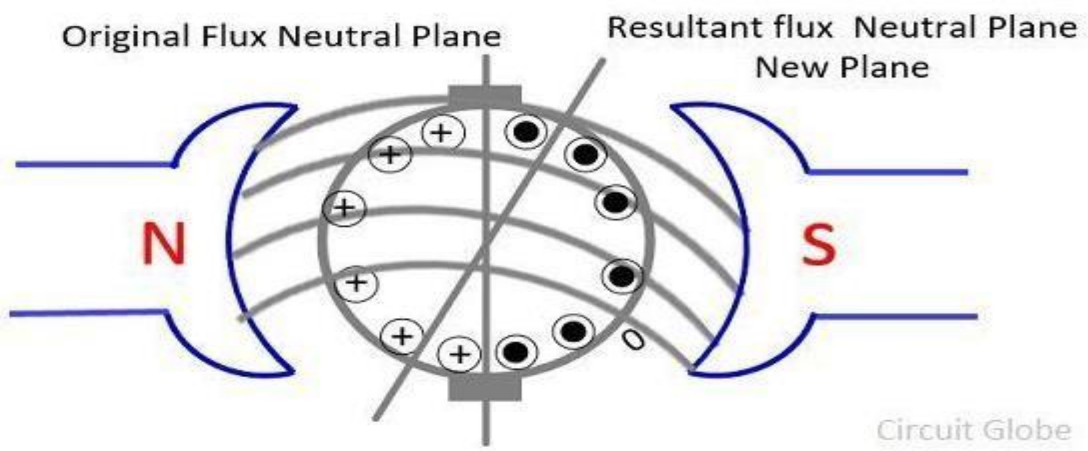


Fig 1.21 Magnetic Neutral axis

Consider the condition in which only the armature conductors carrying current and no current flows through their main poles. The direction of the current remains the same in all the conductors lying under one pole. The direction of current induces in the conductor is given by the Fleming right-hand rule. And the direction of flux generates in the conductors is given by the corkscrew rule.The direction of current on the left sides of the armature conductor goes into the paper (represented by the cross inside the circle). The armature conductors combine their MMF for generating the fluxes through the armature in the downward direction.

Similarly, the right-hand side conductors carry current, and their direction goes out of the paper (shown by dots inside the circle). The conductor on the right-hand sides is also combining their MMF for producing the flux in the downwards direction. Hence, the conductor on both sides combines their MMF in such a way so that their flux goes downward direction. The flux induces in the armature conductor Φ_A is given by the arrow shown above.

The figure below shows the condition in which the field current and the armature current are simultaneously acting on the conductor.



This happens when machines running at no-load condition. Now the machine has two fluxes, i.e., the armature flux and the field pole flux. The armature flux is produced by the current induced in the armature conductors while the field pole flux is induced because of the main field poles. These two flux combines and gives the resultant flux Φ_R as shown in the figure above.

When the field flux enters into the armature, they may get distorted. The distortion increases the density of the flux in the upper pole tip of the N-pole and the lower pole tip of the south pole. Similarly, the density of flux decreases in the lower pole tip of the north pole and the upper pole tip of the south pole.

The resultant flux induces in the generator are shifted towards the direction of the rotation of the generator. The magnetic neutral axis of poles is always perpendicular to the axis of the resultant flux. The MNA is continuously shifted with the resultant flux.

Effect of Armature Reaction

The effects of Armature Reaction are as follows:-

- Because of the armature reaction the flux density of over one-half of the pole increases and over the other half decreases. The total flux produces by each pole is slightly less due to which the magnitude of the terminal voltage reduces.

The effect due to which the armature reaction reduces the total flux is known as the demagnetizing effect.

- The resultant flux is distorted. The direction of the magnetic neutral axis is shifted with the direction of resultant flux in the case of the generator, and it is opposite to the direction of the resultant flux in the case of the motor.
- The armature reaction induces flux in the neutral zone, and this flux generates the voltage that causes the commutation problem.

The MNA axis is the axis in which the value of induced MEF becomes zero. And the GNA divides the armature core into two equal parts.

1.8. COMMUTATION AND METHODS OF IMPROVING COMMUTATION

Commutation in DC machines is the process by which the reversal of current takes place. In DC generator this process is used to convert the induced AC in the conductors to a DC output. In DC motors commutation is used to reverse the directions of DC current before being applied to the coils of the motor.
The device called Commutator helps in this process. Let’s look at the functioning of a DC motor to understand the commutation process. The basic principle on which a motor works is electromagnetic induction. When current is passed through a conductor it produces magnetic field lines around it. We also know that when a magnetic north and magnetic south faces each other, magnetic lines of force move from North Pole magnet to South Pole magnet as shown in the figure below.

When the conductor with a magnetic field induced around it, is placed in the path of these magnetic lines of force, it blocks their path. So these magnetic lines try to remove this obstacle by either moving it upwards or downwards depending upon the direction of current in the conductor. This gives rise to motor effect.

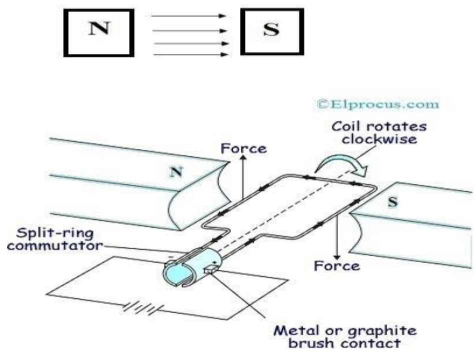
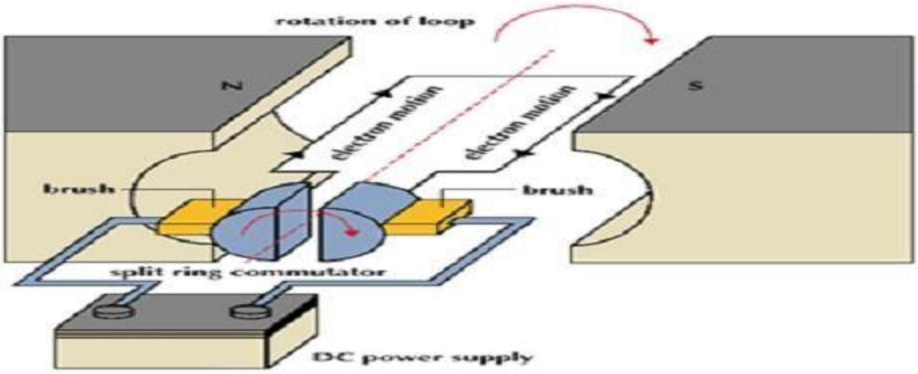


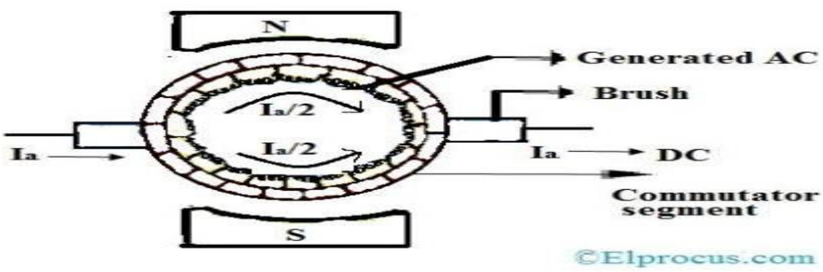
Fig 1.22 Magnetic field

When an **Electromagnetic coil** is placed in between two magnetic with north facing south of another magnet, the magnetic lines moves the coil upwards when current is in one direction and downwards when the current in the coil is in reverse direction. This creates the rotatory motion of the coil. To change the direction of current in the coil, two half-moon shaped metals are attached to each end of the coil called Commutator. Metal brushes are placed with one end attached to the battery and the other end connected to the commutators.



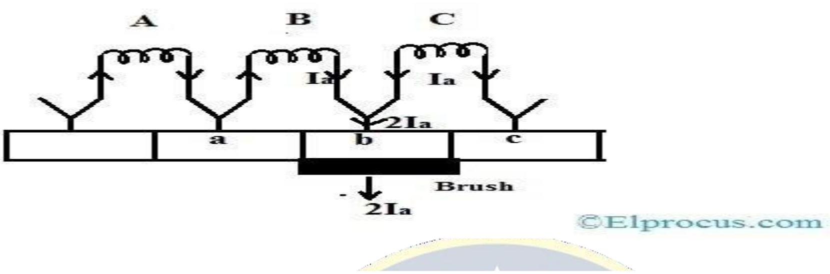
Commutation in DC Machine

Each Armature coil contains two commutators attached at its end. For the transformation of current, the Commutator segments and brushes should maintain a continuously moving contact. To get larger output values more than one coil is used in DC machines. So, instead of one pair, we have a number of pairs of Commutator segments.



DC Commutation:The coil is short-circuited for a very short period of time with the help of brushes. Thisperiod is known as commutation period. Let us consider a DC motor in which the width of the Commutator bars is equal to the width of the brushes. Let the currentflowing through the conductor be Ia. Let a, b, c be the Commutator segments of the motor. The current reversal in the coil .i.e. commutation process can be understoodby the below steps.

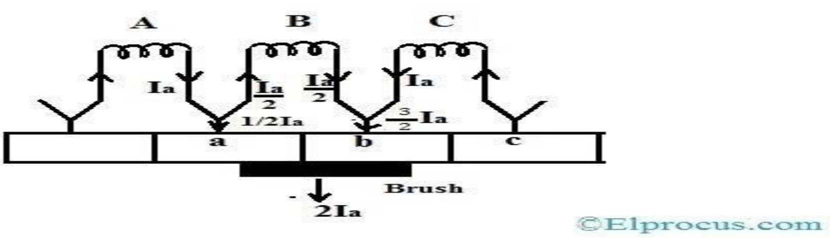
Position-1



Let the Armature starts rotating, then the brush moves over the commutator segments. Let the first position of the brush commutator contact be at segment b as shown above. As the width of the commutator is equal to the width of the brush, in the above position the total areas of commutator and brush are in contact with each other. The total current conducted by the commutator segment into the brush at this position will be 2Ia.

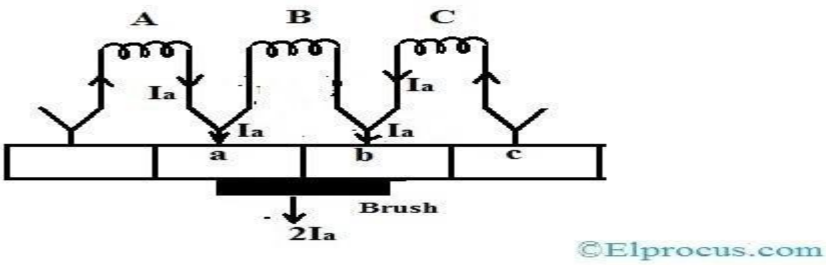
Position-2

Now the armature rotates towards the right and the brush comes in contact with the bar a. At this position, the total conducted current will be 2Ia, but the current in the coil changes. Here the current flows through two paths A and B. 3/4th of the 2Ia comes from the coil B and remaining 1/4th comes from coil A.When KCL is applied at the segment a and b, the current through the coil B is reduced to Ia/2 and the current drawn through segment a is Ia/2.



Position-3

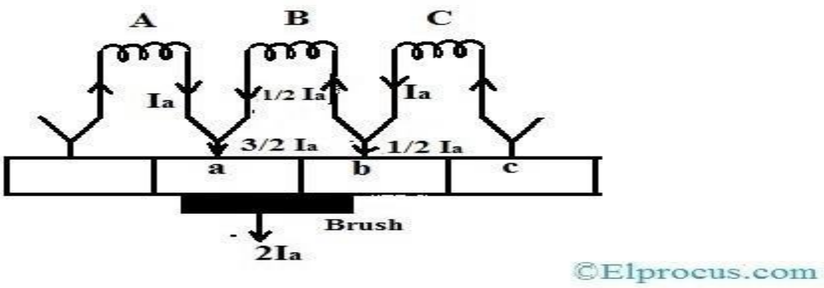
At this position half of the brush, a surface is in contact with segment a and the other half is with segment b. As the total current drawn trough brush is 2Ia, current Ia is drawn through coil A and Ia is drawn through coil B. Using KCL we can observe that the current in coil B will be zero.



position 3

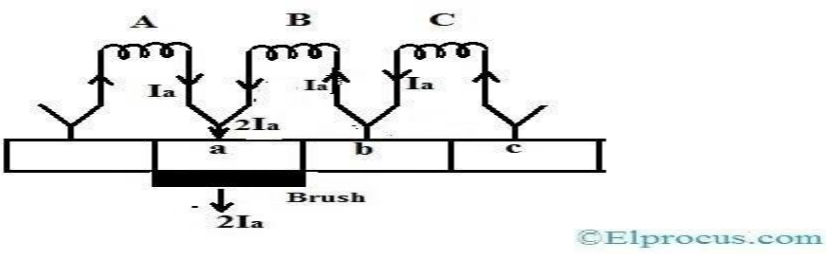
Position-4

In this position, one-fourth of the brush surface will be in contact with segment b and three fourth with segment a. Here the current drawn through coil B is – Ia/2. Here we can observe that the current in coil B is reversed.



Position-5

At this position, the brush is in full contact with segment a and the current from coil B is Ia but is reverse direction to the current direction of position 1.Thus commutation process is completed for segment b.



position 5

Effects of Commutation

The computation is called Ideal commutation when the reversal of current is completed by the end of the commutation period. If the current reversal is completed during the commutation period, sparking occurs at the contact of brushes and overheating occurs damaging the surface of the commutator. This defect is called Poorly commutated Machine.

To prevent this type of defects there are three types of methods for improving commutation.

- Resistance commutation.
- EMF commutation.
- Compensating winding.

Resistance Commutation

To tackle the problem of poor commutation Resistance commutation method is applied. In this method, copper brushes of lower resistance are replaced with carbon brushes of higher resistance. Resistance increases with the decreasing area of cross-section. So, the resistance of the trailing commutator segment increases as the brush moves towards the leading segment. Hence, the leading segment is most favored for the current path and large current takes the path provided by the leading segment to reach the brush. This can be well understood by looking at our figure below.

In the figure above the current from coil 3 can take two paths. Path 1 from coil 3 into coil 2 and segment b. Path 2 from short-circuited coil 2 then coil 1 and segment a. When copper brushes are used current will take the path 1 due to lower resistance offered by the path. But when carbon brushes are used, the current prefers the Path 2 because as the area of contact between brush and segment decreases the resistance increases. This stops the early reversal of current and prevents sparking in the DC machine.

EMF Commutation

Induction property of the coil is one of the reasons for the slow reversal of current during commutation process. This problem can be tackled by neutralizing the reactance voltage produced by the coil by producing the reverse e.m.f in the short circuit coil during the commutation period. This EMF commutation is also known as Voltage commutation.

This can be done in two methods.

- By Brush Shifting method.
- By Using commutating poles.

In brush shifting method, brushes are shifted forward for DC generator and backward in DC motor. This establishes a flux in the neutral zone. As the commutating coil is cutting the flux, a small voltage is induced. As brush position has to be shifted for every variation in load, this method is rarely preferred.

In the second method, commutating poles are used. These are the small magnetic poles placed between main poles mounted to the stator of the machine. These are attached in series connection with the armature. As load current causes back e.m.f. , these commutating poles neutralizes the position of the magnetic field.

Without these commutating poles, the commutator slots would not stay aligned with ideal portions of the magnetic field as magnetic field position changes due to back e.m.f. During the commutation period, these commutating poles induce an e.m.f in the short circuit coil which opposes the reactance voltage and gives spark-less commutation.

The polarity of commutating poles is the same as the main pole situated next to it for the generator whereas the polarity of commutating poles is opposite to the main poles in the motor

1.9 CHARACTERISTICS OF GENERATORS:

- Open Circuit Characteristic (O.C.C.) (E_o/I_f)
- Internal or Total characteristic (E_g/I_a)
- External characteristic (V_t/I_L)
- Load characteristics (V_t/I_f)

1.9.a Open Circuit Characteristic (O.C.C.):

- This curve shows the relation between the generated e.m.f. at no-load (E_0) and the field current (I_f) at constant speed.
- It is also known as magnetic characteristic or no-load saturation curve. Its shape is practically the **same for all generators whether separately or self excited**.
- The data for O.C.C. curve are obtained experimentally by operating the generator at **no load and constant speed** and recording the change in terminal voltage as the field current is varied.

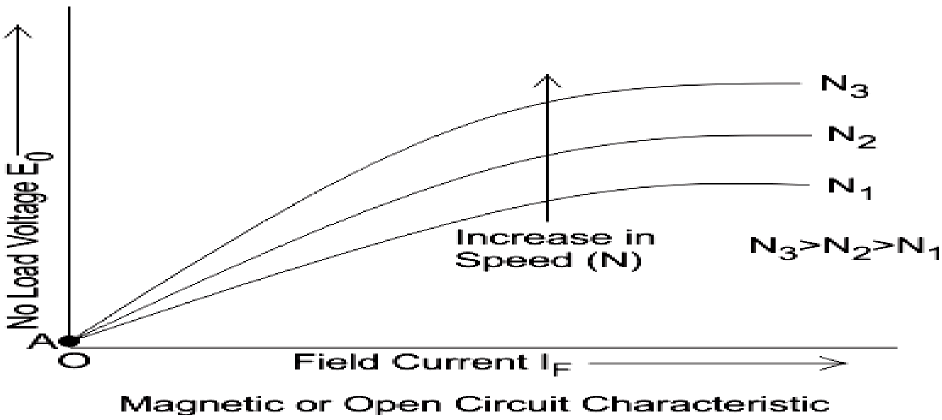


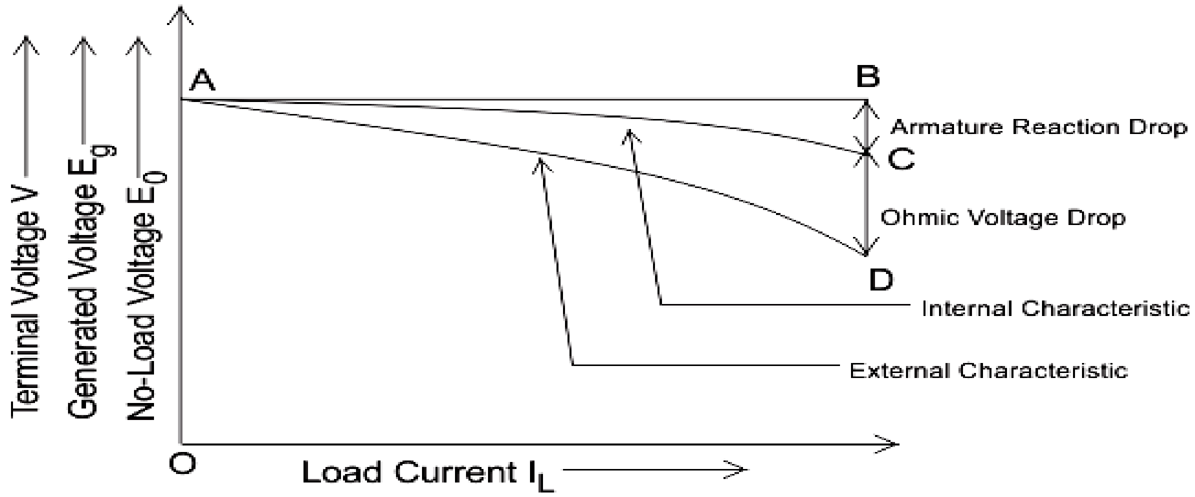
Fig 1.23 OCC curve at No-load condition

1.9.b Internal or Total characteristic (Eg/Ia):

- This curve shows the relation between the generated e.m.f. on load (Eg) and the armature current (Ia).
- The e.m.f. Eg is less than E0 due to the armature reaction. Therefore, this curve will lie below the open circuit characteristic (O.C.C.).
- It cannot be obtained directly by experiment. It is because a voltmeter cannot read the e.m.f. generated on load due to the voltage drop in armature resistance.
- The internal characteristic can be obtained from external characteristic if winding resistances are known because armature reaction effect is included in both characteristics.

1.9.c External characteristic (V/I_L):

- This curve shows the relation between the terminal voltage (V or V_t) and load current (IL). The terminal voltage **V < Eg** due to voltage drop in the armature circuit. Therefore, this curve will lie below the internal characteristic.
- This characteristic is very important in determining the suitability of a generator for a given purpose.
- It can be obtained by making simultaneous measurements of **terminal voltage** and **load current** (with voltmeter and ammeter) of a loaded generator.



Internal and External Characteristic Curve

Fig 1.24 Load characteristics of dc generator

1.9.1 Characteristic of Separately Excited DC Generator

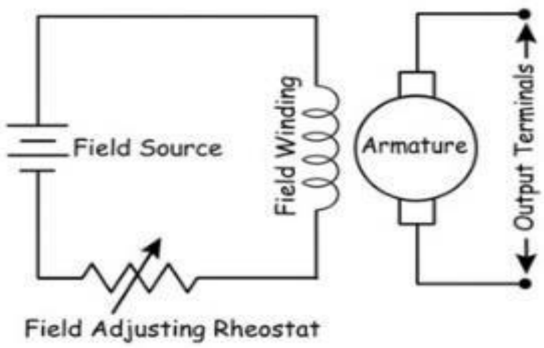


Fig 1.25 Separately Excited dc generator

1.9.1.a Magnetic or Open Circuit Characteristic of Separately Excited DC Generator

- In a separately excited DC generator, the field winding is excited by an external independent source.

- We can see the variation of generated emf on no load with field current for different fixed speeds of the armature.
- For higher value of constant speed, the steepness of the curve is more. is zero, for the effect residual magnetism in the poles, there will be a small initial emf (OA) as show in figure.

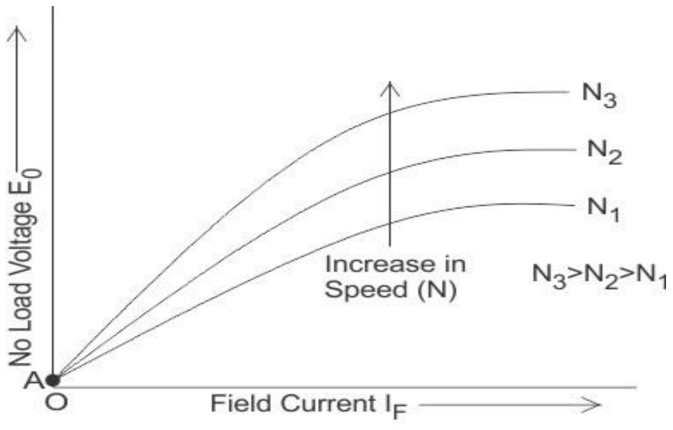


Fig 1.26 OCC curve at No-load condition Separately Excited DC Generator

1.9.1.b Internal or Total Characteristic of Separately Excited DC Generator

- The internal **characteristic of the separately excited DC generator** is obtained by subtracting the drops due to armature reaction from no load voltage.
- This curve of actually generated voltage (E_g) will be slightly dropping. Here, AC line in the diagram indicating the actually generated voltage (E_g) with respect to load current.

1.9.1.C External Characteristic of Separately Excited DC Generator

- The external **characteristic of the separately excited DC generator** is obtained by subtracting the drops due to ohmic loss ($I_a R_a$) in the armature from generated voltage (E_g). Terminal voltage(V) = $E_g - I_a R_a$.
- This curve gives the relation between the terminal voltage (V) and load current. The **external characteristic curve** lies below the **internal characteristic curve**.
- Here, AD line in the diagram below is indicating the change in terminal voltage (V) with increasing load current.
- It can be seen from figure that when load current increases then the terminal voltage decreases slightly.

- This decrease in terminal voltage can be maintained easily by increasing the field current and thus increasing the generated voltage. Therefore, we can get constant terminal voltage.

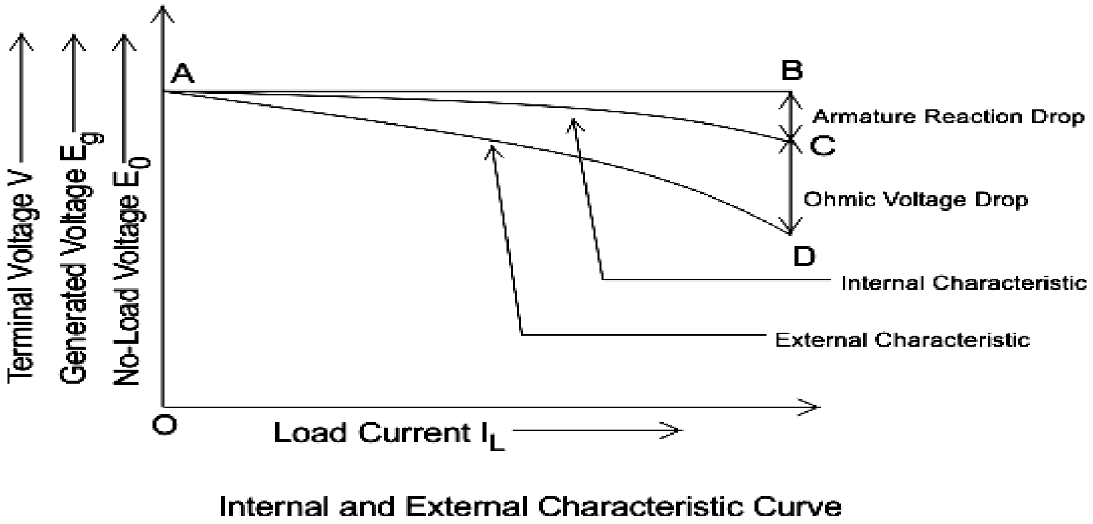


Fig 1.27 Load characteristics of dc separately Excited generator

Conclusion: It can operate in stable condition with any field excitation and gives wide range of output voltage. The main disadvantage of these kinds of generators is that it is very expensive of providing a separate excitation source.

1.9.2 Characteristics of a Shunt Generator

- Magnetic characteristic **(**or) no-load saturation characteristic. O.C.C. curve is obtained by operating the generator at no load and keeping a constant speed.
- Field current is gradually increased and the corresponding terminal voltage is recorded.
- For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.

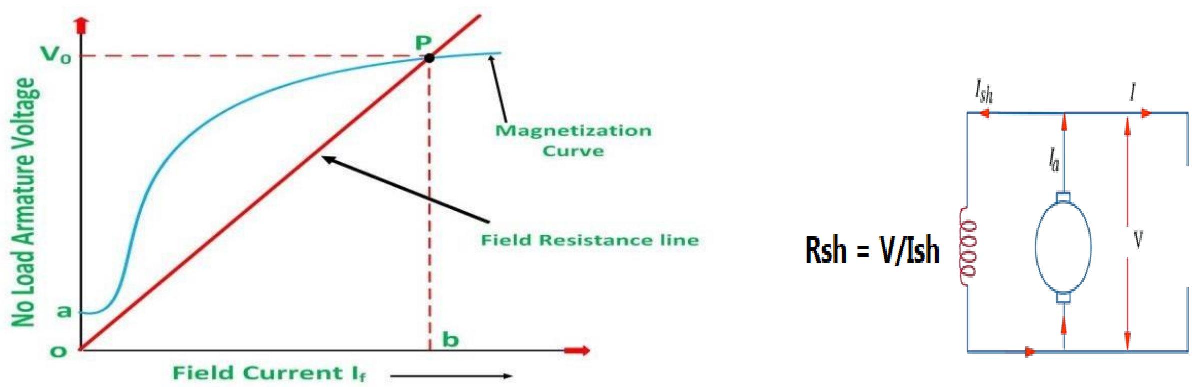


Fig 1.28 OCC characteristic of Dc shunt generator

LOAD CHARACTERISTICS (V_t/I_f):

Internal (E_g/I_a) & External ($V_t/I_L=I_a$) characteristics of 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 (E_R) generated.
- 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.
- As the generator is loaded, terminal voltage decreases due to
  a) The armature winding resistance b) The armature reaction
  c) Because above two factors, field current will decrease ($V=I_f*R_f$).
  This will intern causes the emf and therefore terminal voltage drop too.
- Thus the effects are cumulative and terminal voltage is reduced to a much greater
  extent.
- When **load current increased beyond full load current**, due to the effects of demagnetising armature reaction and voltage drop, further decrease in load resistance causes decrease in load current and characteristics turns back.

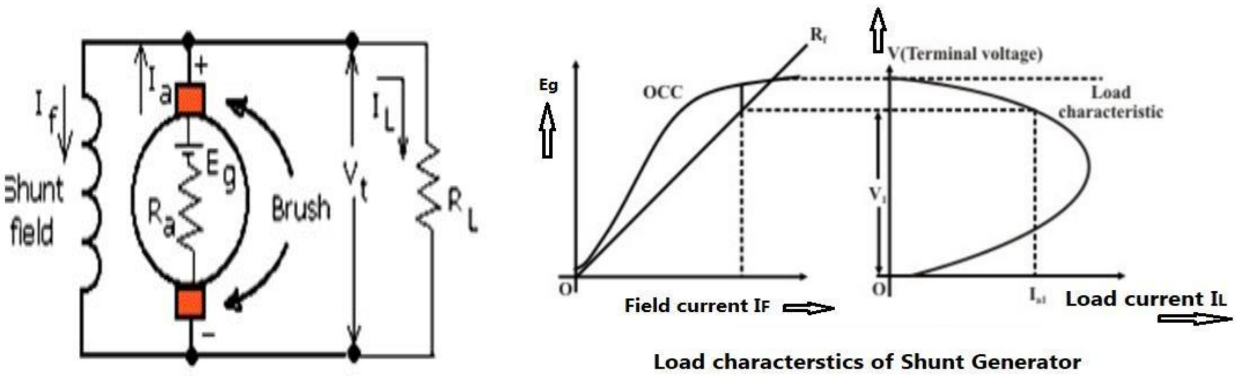


Fig 1.29 Load characteristics of dc shunt generator

- Normally flux is constant in its operating region but after breakdown value a cumulative reduction of terminal voltage tends to zero.
- The characteristics of shunt generator are dropping characteristics. Shunt generator can be consider as constant flux and constant voltage (because drop in voltage from no load to full load is less) machine.

- It is used generally for small dc battery charging application and excitation system in power plant generator (alternator).

1.9.3 LOAD CHARACTERISTICS:

SERIES GENERATOR (Will be started on LOAD conditions)

- The field winding of a series generator is connected 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. (E_g α I_a)
- 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.

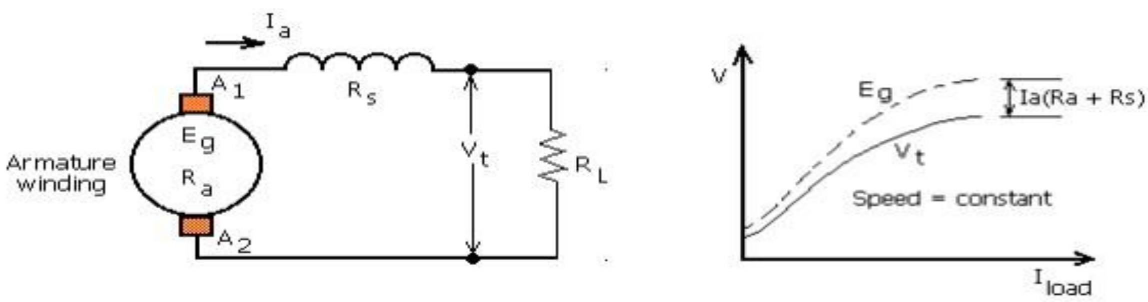


Fig 1.30 load characteristic of a series generator driven at a certain speed.

- The dash line indicated the generated EMF of the same machine with the armature open circuited and the field separately excited. Solid line indicates terminal voltage.
- The difference between the two curves is simply the **voltage drop (**I*R) in the series field and armature winding.

$$V_t = E_g - I_a(R_a + R_f)$$

Where

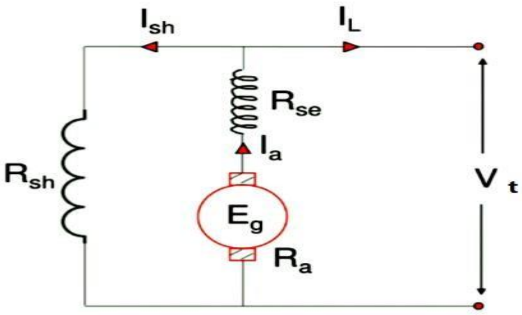
R_f = The series field winding resistance

R_a = The armature winding resistance

- The series generators are obviously not suited for applications requiring good voltage regulation. Because it has raising voltage characteristics and so called variable voltage generator.
- 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 (DC distribution systems)

1.9.4 LOAD CHARACTERISTICS OF 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 **Cumulative compounded**. It combines the characteristics of **both shunt and series.**
- On No-load shunt field winding provides all the field flux since no current in the series field winding.
- With increase in load on the generator, **series field adds flux to the shunt field**. So it has better voltage characteristics then shunt generator & separately excited generator.



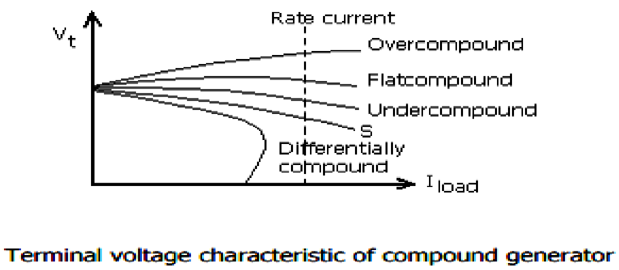


Fig 1.31 Long Shunt DC compound generator & Load characteristics

Curve **S** represent the terminal voltage characteristic of shunt field winding alone.

(a) **Under-compound:** When shunt field excitation is more effective then series field, full load terminal voltage is less than no-load terminal voltage, the generator is said to be under compounded.

(b) **Flat compound :** If the series excitation is increased by increasing the number of a series field turns to rise up terminal voltage when on no-load and full load condition, (terminal voltage is made nearly same value or equal) ($V_t=E_o$)

(c) **Over-compound:** If the number of series field turns is more than necessary to compensate of the reduced voltage , terminal voltage rises with increase in load and generator is said to be over compounded.

(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 fastly, 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.**
- Cumulative compound generator used as voltage source of lighting purpose.
- Flat compound generator used as exciting field of alternator.
- Differentially compound is used in welding purpose.

1.10. LOSSES OF GENERATOR:

A dc generator converts mechanical power into electrical power and a dc motor converts electrical power into mechanical power. Thus, for a dc generator, input power is in the form of mechanical and the output power is in the form of electrical. On the other hand, for a dc motor, input power is in the form of electrical and output power is in the form of mechanical. In a practical machine, whole of the input power cannot be converted into output power as some power is lost in the conversion process. This causes the **efficiency of the machine** to be reduced. Efficiency is the ratio of output power to the input power.

Thus, in order to design rotating dc machines (or any electrical machine) with higher efficiency, it is important to study the losses occurring in them.

Various losses in a rotating DC machine (DC generator or DC motor) can be characterized as follows:

The **losses of generators** may be classified as

Copper losses

- Armature Copper loss = $I_a^2 R_a$
- Field Copper loss= $I_f^2 R_f$
- Loss due to brush contact resistance

Iron (Core) Losses

- Hysteresis loss $W_h = \eta B^{1.6}_{max} f V$ (watts)
- Eddy current loss

Mechanical losses

- Friction loss
- Windage loss

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 armature winding are the field windings, inter-pole and compensate windings. $P = I^2R$; $V_{drop} = I_aR_a$ and I_fR_f

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

- ✓ Bearing Friction Loss
- ✓ Friction of the Rushes Riding On The Commutator
- ✓ 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.

Power output = Power developed across armature – Total losses in generator

Efficiency of generator = Power output/power input

Voltage Regulation =Change in terminal voltage from no load to full load.

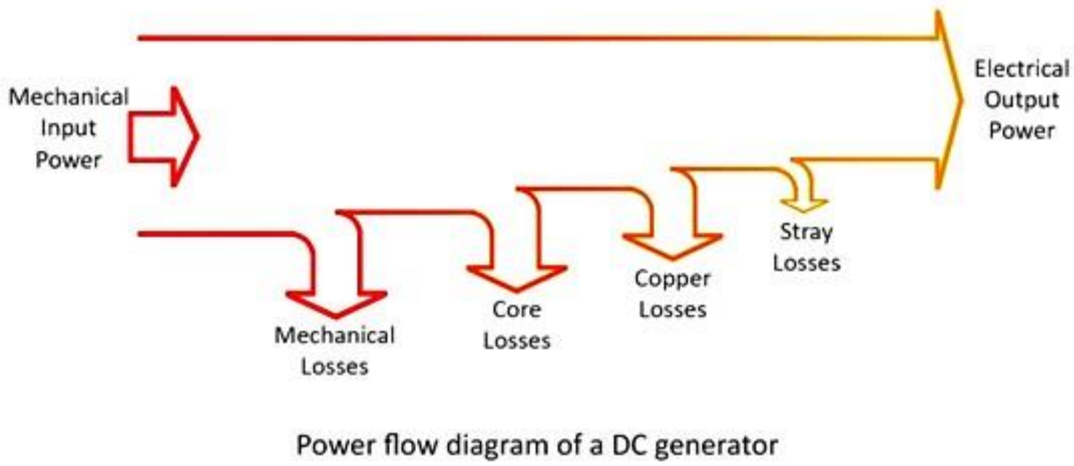


Fig 1.32 Power flow diagram of DC generator

Efficiency of DC Generator:

Efficiency is simply defined as the ratio of output power to the input power. Generator efficiency is given by the equation shown below: if total losses and output are known.

$$\eta_g = \frac{\text{Generator output}}{\text{Generator output+ Losses}}$$

Solved problem:

The open circuit characteristics of a shunt wound dc generator at 800 rpm gives:

Field current (A):	**0**	**0.5**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**
Induced EMF(V):	**10**	**50**	**100**	**175**	**220**	**245**	**262**

Find graphically the critical resistance of shunt field circuit. If the field circuit resistance is changed to 75 ohms, what will be the critical speed for the machine to build up?

Solution:

Draw OCC from given data. Draw the line OC tangent to OCC at the origin. The slope of the line will give the value of critical resistance. To determine the slope of the line OC,take any point B on this line and from point B draw horizontal and vertical lines meeting induced emf axis and field current axis at point F and A respectively.

Critical resistance of the field circuit = slope of the line OC

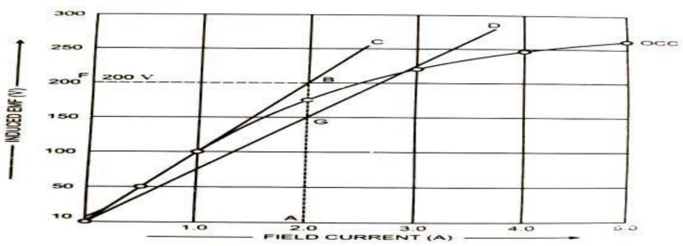
= OF in volts/OA in amperes

=200/2 =100Ω

Draw the line OD representing resistance of 75 Ω

Let ordinate drawn from point B intersect line OD at G.

Critical speed N_c= N* (AG/AB) =800*150/200 = 600 rpm



1.10.1 APPLICATIONS OF DC GENERATORS:

- They are used for general lighting.
- They are used to charge battery because they can be made to give constant output voltage.

- They are used for giving the excitation to the alternators.
- They are also used for small power supply.
- They are used for supplying field excitation current in DC locomotives for regenerative braking.
- For electro plating
- Used to supply dc welding machines.

1.11. PARALLEL OPERATION OF DC GENERATORS

Here this explains you the **parallel operation of dc generators** and load sharing among them for the continuous power supply.In a d.c power plant, power is usually supplied from several generators of small ratings connected in parallel instead offrom one large **generator**. This is due to the following reasons:

(i) Continuity of service:

If a single large generator is used in the power plant, then in case of its breakdown, the whole plant will be shut down. However, if power is supplied from a number of small units **operating in parallel**, then in case of failure of one unit, the continuity of supply can be maintained by other healthy units.

(ii) Efficiency:

Generators run most efficiently when loaded to their rated capacity.Electric power costs less per kWh when the generator producing it is efficiently loaded.Therefore, when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

(iii) Maintenance and repair:

Generators generally require routine-maintenance and repair. Therefore,if **generators are operated in parallel**, the routine or emergency operations can be performed by isolating the affected generator while the load is being supplied by other units. This leads to both safety and economy.

(iv) Increasing plant capacity:

In the modern world of increasing population, the use of electricity is continuously increasing. When added capacity is required, the new unit can be simply paralleled with the old units.In many situations, a single unit of desired large capacity may not be available.In that case, a number of smaller units can be operated in parallel to meet the load requirement. Generally, a single large unit is more expensive.

(v) Non-availability of single large unit:

In many situations, a single unit of desired large capacity may not be available. In that case, a number of smaller units can be **operated in parallel** to meet the load requirement. Generally, a single large unit is more expensive.

Connecting Shunt Generators in Parallel:

The generators in a power plant are **connected in parallel through bus-bars**. The bus-bars are heavy thick copper bars and they act as +ve and -ve terminals.The positive terminals of the **generators** are connected to the +ve side of bus-bars and negative terminals to the negative side of bus-bars.

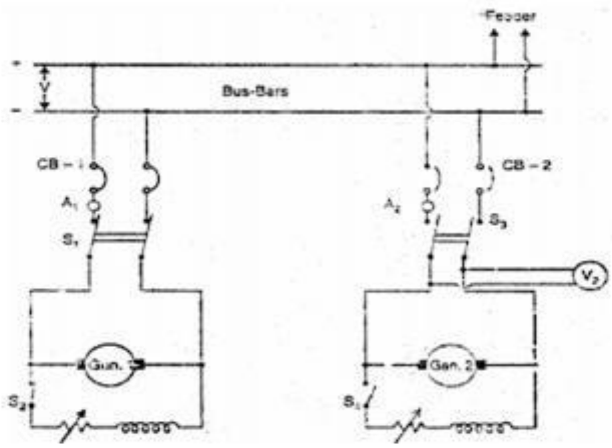


Fig 1.32 Power flow diagram of DC generator

Fig. (3.15) shows shunt generator 1 connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this **generator**, the second shunt generator 2 is connected in parallel with the first tomeet the increased load demand.The procedure for **paralleling generator** 2 with generator 1 is as under:

(i) The prime mover of generator 2 is brought up to the rated speed. Now switch S4 in the field circuit of the generator 2 is closed.

(ii) Next circuit breaker CB-2 is closed and the excitation of **generator** 2 is adjusted till it generates a voltage equal to the bus-bars voltage. This is indicated by voltmeter V2.

(iii) Now the generator 2 is ready to be **paralleled with generator** 1. The main switch S3 is closed, thus putting generator 2 in **parallel with generator** 1. Note that generator 2 is not supplying any load because it's generated e.m.f. is equal to bus-bars voltage.The generator is said to be "floating" (i.e., not supplying any load) on the bus-bars.

(iv) If **generator** 2 is to deliver any current, then it's generated voltage E should be greater than the bus-bars voltage V. In that case, the current supplied by it is I = (E - V)/Ra where Ra is the resistance of the armature circuit. By increasing the field current (and hence induced e.m.f. E), the generator 2 can be made to supply the proper amount of load.

(v) The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if **generator** 1 is to be shut down, the whole load can be shifted onto generator 2 provided it has the capacity to supply that load. In that case, reduce the current supplied by generator 1 to zero (This will be indicated by ammeter A1) open C.B.-1 and then open the main switch S1.

Load Sharing of two generators:

The **load sharing between shunt generators** in parallel can be easily regulated because of their drooping characteristics. The load may be shifted from one generator to another merely by adjusting the field excitation. Let us discuss the load sharing of two **generators** which have unequal no-load voltages.

Let E1, E2 = no-load voltages of the two generators

R1, R2 = their armature resistances

V = common terminal voltage (Bus-bars voltage)

then I1 = (E1 - V)/R1 and I2= (E2-V)/R2

Thus the current output of the **generators** depends upon the values of E1 and E3.These values may be changed by field rheostats. The common terminal voltage (or bus-bars voltage) will depend upon

(i) The e.m.f.s of individual generators and

(ii) The total load current supplied.

It is generally desired to keep the bus bars voltage constant. This can be achieved by adjusting the field excitations of the **generators operating in parallel**.

Compound Generators in Parallel:

Under-compounded generators also operate satisfactorily in parallel but over compounded generators will not operate satisfactorily unless their series fields are paralleled. This is achieved by connecting two negative brushes together as shown in fig (i). The conductor used to connect these brushes is generally called equaliser bar. Suppose that an attempt is made to operate the two **generators** in Fig.

(ii) in parallel without an equaliser bar. If, for any reason, the current supplied by generator 1 increases slightly, the current in its series field will increase and raise the generated voltage.

This will cause generator 1 to take more load. Since total load supplied to the system is constant, the current in generator 2 must decrease and as a result, its series field is weakened. Since this effect is cumulative, the generator 1 will take the entire load and drive **generator** 2 as a motor. Under such conditions, the current in the two machines will be in the direction shown in Fig. (3.16) (ii). After machine 2 changes from a generator to a motor, the current in the shunt field will remain in the same direction, but the current in the armature and series field will reverse.

Thus the magnetising action, of the series field opposes that of the shunt field. As the current taken by the machine 2 increases, the demagnetizing action of series field becomes greater and the resultant field becomes weaker. The resultant field will finally become zero and at that time machine 2 will short circuit machine 1, opening the breaker of either or both machines.

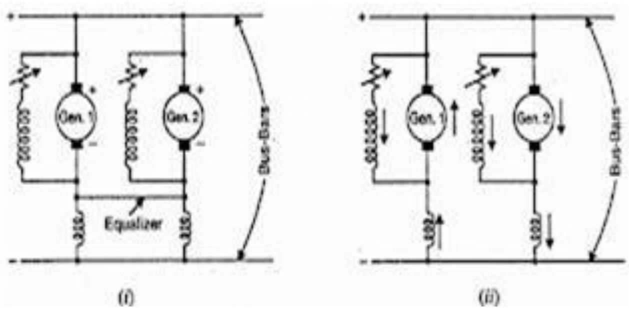


Fig 1.33 Power flow diagram of DC generator

When the equaliser bar is used, a stabilising action exist? and neither machine tends to take all the load.To consider this, suppose that current delivered by generator 1 increases.The increased current will not only pass through the seriesfield of **generator** 1 but also through the equaliser bar and series field of generator 2.Therefore, the voltage of both the machines increases and the generator 2 will take a part of the load.

6. Practice Quiz

1. The yoke of a DC machine is made of

a) Silicon steel
b) Soft iron
c) Aluminum
d) **Cast steel**

2. The armature of a DC machine is made of

a) **Silicon steel**
b) Soft iron
c) Aluminum
d) Cast steel

3. A 4-pole DC machine has............. magnetic circuits

a) 2
b) **4**
c) 8
d) 6

4. The real working part of a DC machine is the.................

a) commutator
b) field winding
c) **armature winding**
d) brush

5. The coupling field between electrical and mechanical systems of Dc machine is magnetic field.

a) **True**
b) False

6. Which type of current in armature conductors of a DC machine

a) DC
b) Pulsating
c) **AC**
d) None

7. How many poles have a small DC machine generally

a) 4
b) 6
c) **2**
d) 8

8. How many parallel paths will have a Triplex wave winding

a) **6**
b) 3
c) 4
d) 8

9. High-voltage DC machines use .... winding

a) Lap
b) **Wave**

c) Either lap or wave
d) None

10. Which losses occurs in the armature of Dc machine

a) Stray load
b) Mechanical
c) Eddy current
d) Cupper

11. Hysteresis loss in a DC machine is directly proportional to speed

a) True
b) False

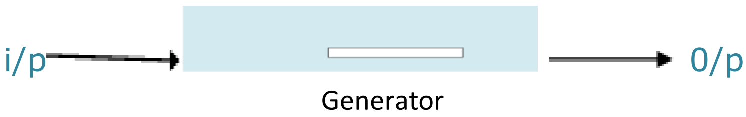
12. A separately excited DC generator is not used because……..

a) Separate DC source is required for field circuit
b) Voltage drops considerably
c) it is costly
d) None

7.Assignments

S.No	Question	BL	CO
1	With neat sketch, explain the construction and working principle of DC generator in detail	2	1
2	Derive the E.M.F. equation in a dc machine.	2	1
3	Draw a developed diagram of a simple 2-layer lap-winding for a 4-pole generator with 16 coils. Hence, point out the characteristics of a lap-winding.	2	1
4	A separately excited dc generator with constant excitation is connected to constant resistance circuit. When the speed is 1500 r.p.m, it delivers 85 A at 450 V. At what speed will the current be reduced to 40 A? Take armature resistance as 0.3 Ω and contact drop/brush as 1 V.	2	1
5	Explain briefly about the no load and the open circuit characteristics of a separately excited generator	3	1
6	Derive the expressions for calculating the demagnetizing and cross magnetizing ampere turns per pole in a DC generator with usual notation	3	1

8.Part A- Question & Answers

S.No	Question& Answers	BL	CO
1	**What is a generator?** **Ans.** An electrical generator is a machine which converts mechanical energy (or) power into electrical energy. This energy conversion is based on the principal of the production of dynamically induced e.m.f is produced in it according to "faraday's laws of electromagnetic induction".  → The mechanical i/p's to the generator is provided by using prime movers such that turbines, motors etc.	1	1
2	**What is Fleming's right hand rule?** **Ans.** This rule is particularly suitable to find the direction of induced e.m.f. and current, when conductor moves at right	1	1
	armature conductors also creates a magnetic flux (called armature flux) that. This armature flux distorts and weakens the flux coming from main poles flux. This distortion and field weakling takes place in both generators and motors. "The action of armature flux on the main flux is known as armature reaction".		
8	**Explain the effects of armature reaction**? **Ans.** When the generator is on no-load condition, a small current flowing in the armature does not appreciable affect the main flux. When the generator is in loaded condition, the armature conductor also creates some flux. In that condition the armature reaction has two effects, 1) Demagnetizing effect 2) Cross-magnetizing effect.	2	1
9	**What is the use of compensating winding?** **Ans.** A compensating winding is placed in slots in the pole faces of the field and is connected series with the armature circuit in such a way that at any point in the gap the current in the compensating winding flows in the direction opposite to the armature circuit. In this way if the compensating winding has the same number of ampere-turns per cm of armature periphery as the armature itself, the e.m.f of the armature is completely neutralized.	2	1

10	**Explain the meaning and significance of critical field resistance of a shunt generator?** **Ans.** Critical field resistance is the total field circuit resistance above which the generator fails to build up the voltage. It means in case of shunt generator, if the shunt field resistance is more than the critical field resistance, there will be no voltage build-up**.**	2	1

9.Part B- Questions

S.No	Question	BL	CO
1	Explain the construction of DC generator in detail.	1	1
2	Draw the magnetization characteristics of DC shunt generator and explain the same	2	1
3	Derive the E.M.F. equation in a dc machine	2	1
4	Explain in detail about commutation and list out the various	3	1
	methods of improving commutation in detail with a neat sketch.		
5	Explain about compensating windings and inter poles.	2	1
6	Draw the winding table for a 2-pole lap connected DC machine with 12 armature conductors. Indicate the brush positions and polarity of induced e.m.f.	2	1
7	Explain the parallel operation of DC generator	3	1
8	What is the principle of operation of dc generator?	3	1
9	Calculate the emf generated by 6 pole dc generator having 480 conductors and driven at speed of 1200 rpm. The flux per pole is 0.012 Wb. Assume the generator to be: (i) Lap wound. (ii) Wave wound.	3	1
10	A 6-pole lap wound dc generator has 600 conductors on its armature. The flux per pole is 0.02 Wb. Calculate the speed at which the generator must be run to generate 300V and what would be the speed if the generator were wave wound?	3	1

DC MACHINES & TRANSFORMERS (20A02302T)

UNIT-III

DC MOTORS

LECTURE NOTES

1. Course Objectives

The objectives of this course is to

1. The constructional features of DC machines and different types of windings employed in DC machines.
2. Characteristics of generators and parallel operation of generators.
3. Methods for speed control of DC motors and application of DC machines.
4. The Constructional Features of transformers, Predetermination of regulation and efficiency of transformers.
5. Various tests on single phase and three phase transformers and parallel operation of transformers.

2. Prerequisites

Students should have knowledge on

1. Engineering Physics
2. Basic Electrical Circuits

3. Syllabus

UNIT III-DC Motors

Force on conductor carrying current, back emf, Torque and power developed by armature, speed control of DC motors (Armature control and Flux control methods), Necessity of starters, constructional details of 3-point and 4-point starters, characteristics of DC motors, Losses in DC machines, condition for maximum efficiency

Testing of DC machines: Brake test, Swinburne's test, Hopkinson's test, Fields test, Retardation test.

4. Course outcomes

1. **Apply** the knowledge of magnetic material properties and fundamentals of energy conversion principles.
2. **Identify** the working principle of Dc machines & Transformers with mechanism and various operations performed
3. **Illustrate** the characteristics of various DC machines & Transformers with various operational conditions to determine efficiency & regulation.
4. **Evaluate** the performance & losses of Machines with help of various testing methods like OCC, speed control and OC & SC test.
5. **Explain** & **analyse** the parallel operation of DC machines & Transformers, Scott connections and phase conversions of transformers.

5. Activity Based Learning

1. Speed control of DC motor armature, flux control methods
2. Brake test on DC shunt and compound Motors
3. Swinburns test on DCmachine

6. Lecture Notes

1.1 INTRODUCTION

In an industry, DC motor plays important role . A DC motor is any of a class of rotary electrical motors that converts direct current electrical energy into mechanical energy. The most common types rely on the forces producedby magnetic fields. Nearly all types of DC motors have some internal mechanism, either electromechanical or electronic, to periodically change the direction of current in part of the motor .

1.2 WORKING PRINCIPLE OF A DC MOTOR

The DC motor is the device which converts the direct current into the mechanical work. It works on the principle of Lorentz Law, which states that "the current carrying conductor placed in a magnetic and electric field experience a force". And that force is called the Lorentz force. The Fleming left-hand rule gives the direction of the force.

1.2.1 Fleming Left Hand Rule

If the thumb, middle finger and the index finger of the left hand are displaced from each other by an angle of 90°, the middle finger represents the direction of the magnetic field. The index finger represents the direction of the current, and the thumb shows the direction of forces acting on the conductor.

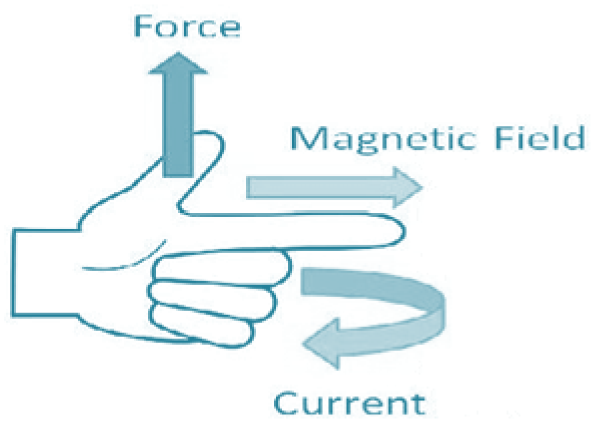


Fig 3.1 Flemings left hand rule

The formula calculates the magnitude of the force,

$F = BIl$ newton

Before understanding the working of DC motor first, we have to know about their construction. The armature and stator are the two main parts of the DC motor. The armature is the rotating part, and the stator is their stationary part. The armature coil is connected to the DC supply.

The armature coil consists the commutators and brushes. The commutators convert the AC induces in the armature into DC and brushes transfer the current from rotating part of the motor to the stationary external load. The armature is placed between the north and South Pole of the permanent or electromagnet.

For simplicity, consider that the armature has only one coil which is placed between the magnetic field shown below in the figure A. Whenthe DC supply is given to the armature coil the current starts flowingthrough it. This current develops their own field around the coil. Figure B shows the field induces around the coil.

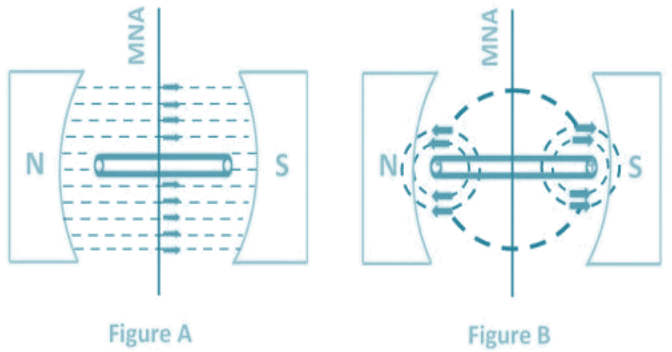


Fig 3.2 magnetic field induces around the coil.

By the interaction of the fields (produces by the coil and the magnet), resultant field develops across the conductor. The resultant field tends to regain its original position, i.e. in the axis of the main field. The field exerts the force at the ends of the conductor, and thus the coil starts rotating.

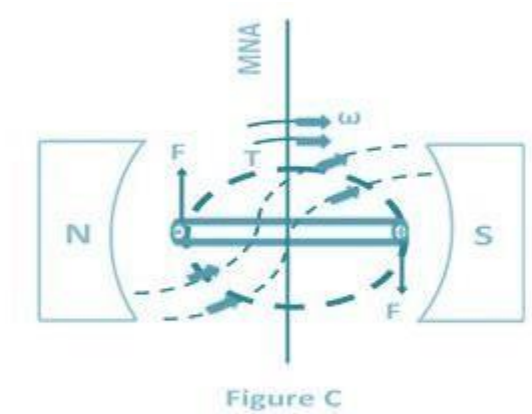


Fig 3.3 Field produced due to poles alone

Let the field produces by the main field be Fm, and this field rotates in the clockwise direction. When the current flows in the coil, they produce their own magnetic field says Fr. The field Fr tries to come in the direction of the main field. Thereby, the torque act on the armature coil.

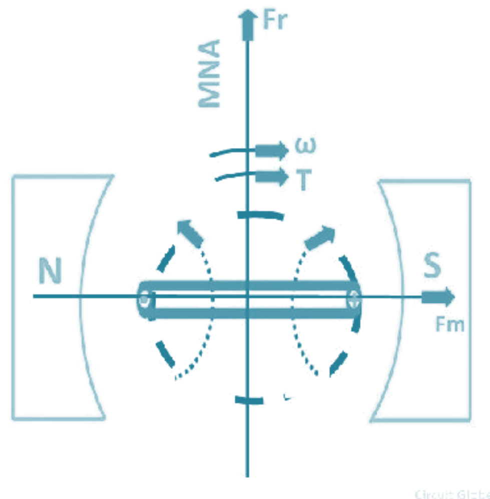


Fig:3.4Field produced due to conductors alone

The actual DC motor consists a large number of armature coils. The speed of the motor is directly proportional to the number of coils used in the motor. These coils are kept under the impact of the magnetic field.

The one end of the conductors are kept under the influence of north pole, and the other end is kept under the influence of the South pole. The current enters into the armature coil through the north pole and move outwards through the south pole. When the coil moves from one brush to another, at the same time the polarity of the coil also changes. Thus, the direction of the force or torque acting on the coil remains same.

The torque induces in the coil become zero when the armature coil is perpendicular to the main field. The zero torque means the motor stops rotating. For solving this problem, the number of armature coil is used in the rotor. So if one of their coils is perpendicular to the field, then the other coils induce the torque. And the rotor moves continuously.

Also, for obtaining the continuous torque, the arrangement is kept in such a way that whenever the coils cut the magnetic neutral axis of the magnet the direction of current in the coils become reversed. This can bedone with the help of the commutator.

1.3 BACK EMF AND ITS SIGNIFICANCE IN DC MOTOR

When a dc voltage V is applied across the motor terminals, the armature starts rotating due to the torque developed in it.

As the armature rotates, armature conductors cut the pole magnetic field, therefore, as per law of electromagnetic induction, an emf called back emf is induced in them.

The back emf (also called counter emf) is given by

$$E_b = \frac{P\Phi ZN}{60A}$$

where, P=number of poles of dc motor;
Φ= flux per pole
Z=total number of armature conductors
N=armature speed

A=number of parallel paths in armature winding

As all other parameters are constant,

therefore, Eb a N

As per Lenz's law, the induced flux always opposes the cause of its production". Here, the cause of generation of back emf is the rotation of armature. Rotation of armature is due to armature torque. Torque is due to armature current and armature current is due to supply dc voltage V. Therefore,the ultimate cause of production of Eb is the supply voltage V.Therefore, back emf is always directed opposite to supply voltage V.

1.3.1Significance of back emf in dc motor

(1) As the back emf opposes supply voltage V, therefore, supply voltage has to force current through the armature against the back emf, to keep armature rotating. The electric work done in overcoming and causing the current to flow against the back emf is converted into mechanical

energy developed in the armature.

It follows, therefore, that energy conversion in a dc motor is only possible due to the production of back emf.

Mechanical power developed in the armature = EbIa

(2) Back emf makes dc motor a self-regulating motor i.e Eb makes motor to adjust Ia automatically as per the load torque requirement. Lets see how.

$$I_a = \frac{V - E_b}{R_a}$$

From the motor figure,

V and Ra are fixed, therefore, armature current Ia dpends on back emf, which in turn depends on speed of the motor.

(a) when the motor is running at no-load, small torque (Ta=KIa) is required by the motor to overcome friction and windage. Therefore, a small current is drawn by the motor armature and the back emf is almost equal to the supply voltage.

(b) If the motor is suddenly loaded, the load torque beomes greater than the armature torque and the motor starts to slow down. As motor speed decreases, back emf decreases and therefore, armature current starts increasing. With increasing Ia , armature torque increases and at some point it becomes equal to the load torque. At that moment, motor stops slowing down and keeps running at this new speed.

(c) If the load on the motor is suddenly reduced, the driving torque becomes more than the load torque and the motor starts accelerating. As the motor speed increases, back emf increases and therefore, armature current decreases. Due to this reducing armature current, armature developed torque decreases and at some point becomes equal to the load torque. That point onwards, motor will stop accelerating and will start rotating uniformly at this new slightly increased speed.

So, this shows how important is back emf in dc motor. Without back emf, the electromagnetic energy conversion would not have been possible at the first place.

1.4 POWER EQUATION OF A D.C. MOTOR

The voltage equation of a d.c. motor is given by,

$$V = E_b + I_a R_a$$

Multiplying both sides of the above equation by I_a we get,

$$V I_a = E_b I_a + I_a^2 R_a$$

This equation is called power equation of a d.c. motor.

VI_a = Net electrical power input to the armature measured in watts.

$I_a^2R_a$ = Power loss due the resistance of the armature called armature copper loss.

So difference between VI_a and $I_a^2R_a$

i.e. input - losses gives the output of the armature.

So $E_b I_a$ is called electrical equivalent of gross mechanical power developed by the armature. This is denoted as P_m.

Power input to the armature - Armature copper loss
= Gross mechanical power developed in the armature.

Condition for Maximum Power

For a motor from power equation it is known that,

$$P_m = \text{Gross mechanical power developed}$$
$$= E_b I_a$$
$$= VI_a - I_a^2R_a$$

For maximum P_m, $dP_m/dI_a = 0$

$\therefore \quad 0 = V - 2I_aR_a$

$\therefore \quad I_a = V/2R_a$ i.e.

$I_aR_a = V/2$ Substituting in voltage equation,

$V = E_b + I_aR_a = E_b + (V/2)$

... Eb = V/2..................... Condition for maximum power

Key Point : This is practically impossible to achieve as for this, current required is much more than its normal rated value. Large heat will be produced and efficiency of motor will be less than 50 %.

1.5 TORQUE EQUATION OF A DC MOTOR

When a DC machine is loaded either as a motor or as a generator, the rotor conductors carry current. These conductors lie in the magnetic field of the air gap. Thus, each conductor experiences a force. The conductors lie near the surface of the rotor at a common radius from its centre. Hence, a torque is produced around the circumference of the rotor, and the rotor starts rotating.

When the machine operates as a generator at a constant speed, this torque is equal and opposite to that provided by the prime mover. When the machine is operating as a motor, the torque is transferred to the shaft of the rotor and drives the mechanical load. The expression is same for the generator and motor.

When the current carrying current is placed in the magnetic field, a force is exerted or it which exerts turning moment or torque F x r. This torque is produced due to the electromagnetic effect, hence is called Electromagnetic torque. The torque which is produced in the armature is not fully used at the shaft for doing the useful work. Some part of it where lost due to mechanical losses. The torque which is used for doing useful work in known as the shaft torque.

Since,

$$V = E_b + I_a R_a \quad \ldots\ldots\ldots (1)$$

Multiplying the equation (1) by Ia we get

$$VI_a = E_b I_a + I_a^2 R_a \quad \ldots\ldots\ldots (2)$$

Where,
VIa is the electrical power input to the armature. I2aRa is the copper loss in the armature.
We know that,

Total electrical power supplied to the armature = Mechanical power developed by the armature + losses due to armature resistance

Now, the mechanical power developed by the armature is Pm.

$$P_m = F_b I_a \dots\dots(3)$$

Also, the mechanical power rotating armature can be given regarding torque T and speed n.

$$P_m = \omega T = 2\pi\, nT \quad \dots\dots(4)$$

Where n is in revolution per seconds (rps) and T is in Newton-Meter. Hence,

$$2\pi\, nT = E_b I_a \quad \text{or}$$

$$T = \frac{E_b I_a}{2\pi n}$$

But,

$$E_b = \frac{\varphi ZNP}{60\ A}$$

Where N is the speed in revolution per minute (rpm) and

$$n = \frac{N}{60}$$

Where, n is the speed in (rps).
Therefore,

$$E_b = \frac{\varphi ZnP}{A}$$

So, the torque equation is given as

$$T = \frac{\varphi ZP}{2\pi A} . I_a$$

For a particular DC Motor, the number of poles (P) and the number of conductors per parallel path (Z/A) are constant.

$$T = K\varphi I_a$$

Where,

$$K = \frac{ZP}{2\pi A} \quad \text{or}$$

$$T \propto \varphi I_a \; \dots \dots (5)$$

Thus, from the above equation (5) it is clear that the torque produced in the armature is directly proportional to the flux per pole and the armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the current in armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed, and direction of torque does not change.

Shaft Torque

In a DC Motor whole of the electromagnetic torque (T) developed in the armature is not available on the shaft. A part of it is lost to overcome the iron and mechanical (friction and windage) losses. Therefore, shafttorque (Tsh) is somewhat less than the torque developed in the armature.

Definition: Thus, in the case of DC motors, the actual torque available at the shaft for doing useful mechanical work is known as Shaft Torque. It is so called because it is available on the shaft of the motor. It is represented by the symbol Tsh. The output of the motor is given by the equation shown below where Tsh is the shaft torque in r.p.s and the N is the rotation of the motor in r.p.m. The shaft torque is expressed as

$$Output = T_{sh} \times 2\pi N$$

$$T_{sh} = \frac{Outputs\ in\ watts}{2\pi N}\ N - m\ in\ r.p.s$$

$$T_{sh} = \frac{Outputs\ in\ watts}{2\pi N/_{60}}\ N - m\ in\ r.p.m$$

$$T_{sh} = \frac{60}{2\pi}\frac{Output}{N} = 9.55\frac{Output}{N}\ N - m\ in\ r.p.s$$

The difference between the armature torque and the shaft torque (Ta – Tsh) is known as the lost torque and is due to the formation of the torque.

Brake Horse Power (B.H.P)

In the case of the motor, the mechanical power available at the shaft is known as Brake Horse Power. If
Tsh is the shaft torque in Newton Meter and N is the speed in r.p.m then,

$$\text{Useful output power} = \omega T_{sh} = \frac{2\pi N T_{sh}}{60} \quad \text{watts}$$

$$\text{Output in B.H.P} = \frac{2\pi N T_{sh}}{60 \text{ x } 735.5} \quad \ldots\ldots (1)$$

The output brake horsepower is given by the equation (1) shown above.

1.6 TYPES OF DC MOTOR

A Direct Current Motor, DC is named according to the connection of the field winding with the armature. Mainly there are two types of DC Motors. First, one is Separately Excited DC Motor and Self-excited DC Motor. The self-excited motors are further classified as Shunt wound or shunt motor, Series wound or series motor and Compound wound or compound motor.

The dc motor converts the electrical power into mechanical power is known as dc motor. The construction of the dc motor and generator are same. But the dc motor has the wide range of speed and good speed regulation which in electric traction.The working principle of thedc motor is based on the principle that the current carrying conductor is placed in the magnetic field and a mechanical force experience by it.

The DC motor is generally used in the location where require protective enclosure, for example, drip- proof, the fireproof, etc. according to the requirements. The detailed description of the various types of the motor is given below.

1.6.1 Separately Excited DC Motor

As the name signifies, the field coils or field windings are energized by a separate DC source as shown in the circuit diagram shown below.

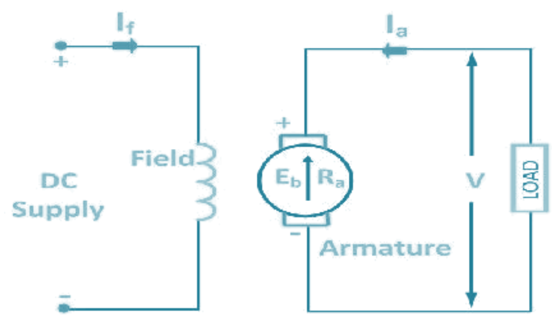


Fig 3.5Separately Excited DC Motor

1.6.2 Self Excited DC Motor

As the name implies self-excited, hence, in this type of motor, the current in the windings is supplied by the machine or motor itself. Self-excited DC Motor is further divided into shunt wound, and series wound motor. They are explained below in detail.

1.6.2.1 Shunt Wound Motor

This is the most common types of DC Motor. Here the field winding is connected in parallel with the armature as shown in the figure below.

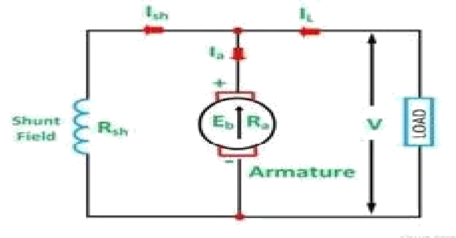


Fig 3.6 Shunt Wound DC Motor

The current, voltage and power equations for a shunt motor are written as follows. By applying KCL at the junction A in the above figure.
The sum of the incoming currents at A = Sum of the outgoing currents at A.

$$I = I_a + I_{sh} \dots\dots\dots (1)$$

Where,
I is the input line current I_a is the armature current
Ish is the shunt field current Equation (1) is the current equation.

The voltage equations are written by using Kirchhoff's voltage law (KVL) for the field winding circuit.

$$V = I_{sh} R_{sh} \dots\dots (2)$$

For armature winding circuit the equation will be given as

$$V = E + I_a R_a \dots\dots\dots (3)$$

The power equation is given as
Power input = mechanical power developed + losses in the armature + loss

$$VI = P_m + I_a^2R_a + I_{sh}^2R_{sh} \quad ....(4)$$

$$VI = P_m + I_a^2R_a + VI_{sh}$$

$$P_m = VI - VI_{sh} - I_a^2R_a = V(I - I_{sh}) - I_a^2R_a$$

$$P_m = VI_a - I_a^2R_a = (V - I_aR_a)I_a$$

$$P_m = EI_a \dots\dots\dots (5)$$

in the field.

Multiplying equation (3) by Ia we get the following equations.

$$VI_a = EI_a + I_a^2R_a \dots\dots\dots (6)$$

$$VI_a = P_m + I_a^2R_a \dots\dots\dots (7)$$

Where,
VIa is the electrical power supplied to the armature of the motor.

1.6.2.2Series Wound Motor

In the series motor, the field winding is connected in series with the armature winding. The connection diagram is shown below.

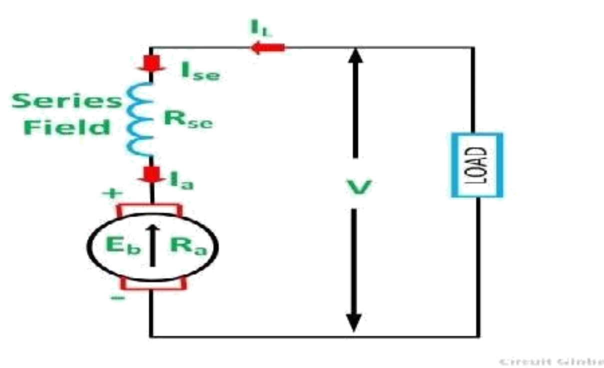


Fig 3.7 Series Wound Motor

By applying the KCL in the above figure

$$I = I_{se} = I_a$$

Where,
Ise is the series field current
The voltage equation can be obtained by applying KVL in the above figure

$$V = E + I\,(R_a + R_{se}) \ldots\ldots\ldots (8)$$

The power equation is obtained by multiplying equation (8) by I we get

$$VI = EI + I^2\,(R_a + R_{se}) \ldots\ldots\ldots (9)$$

Power input = mechanical power developed + losses in the armature + losses in the field

$$VI = P_m + I^2R_a + I^2R_a \ldots\ldots..(10)$$

Comparing the equation (9) and (10), we will get the equation shown

$$P_m = EI \ldots\ldots\ldots (11)$$

below.

1.6.2.3 Compound Wound Motor

A DC Motor having both shunt and series field windings is called a Compound Motor. The connection diagram of the compound motor is shown below.

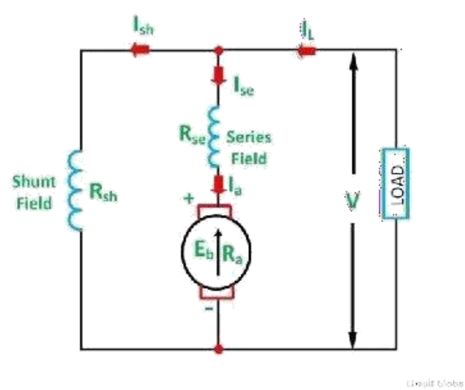


Fig 3.8Compound Motor

The compound motor is further subdivided as Cumulative Compound Motor and Differential Compound Motor. In cumulative compound motor the flux produced by both the windings is in the same direction, i.e.

In differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding, i.e.

The positive and negative sign indicates that direction of the flux produced in the field windings.

1.7 CHARACTERISTICS OF DC MOTORS

Generally, three characteristic curves are considered important for DC motors which are,

(i) Torque vs. armature current,
(ii) Speed vs. armature current and
(iii) Speed vs. torque.

These are explained below for each type of DC motor. These characteristics are determined by keeping the following two relations in mind.

$$T_a \propto \phi . I_a \text{ and } N \propto E_b/\phi$$

These above equations can be studied at - emf and torque equation of dc machine. For a DC motor, magnitude of the back emf is given by the same emf equation of a dc generator

i $$E_b = P\phi NZ / 60A.$$

For a machine, P, Z and A are constant, therefore,

$$N \propto E_b/\phi$$

1.7.1Operating Characteristics of D.C Shunt Motor:

By applying constant voltage, the current flowing through the field winding is constant, so the flux produced from the field winding is constant in D.C shunt machine (motor).

I_{sh} = constant

Shunt machine is a constant speed machine.

1) Speed Vs Armature Current Characteristics (N Vs Ia):

$$E_b = V - I_a R_a.$$

If load , then Ia , Ia Ra , then (V – Ia Ra)

Þ Eb & N .

Speed is directly proportional to back emf and inversely proportional to flux, i.e. N. In shunt motor, Φ is almost constant. Hence speed, N Eb, i.e. V – I a Ra. As 'Ia' increases, then IaRa drop increases and (V – Ia Ra) drop decreases.

Speed decreases very slightly because Ia Ra drop is very small. Shunt motor can be used for constant speed application.

2) Torque Vs Armature Current Characteristics (T Vs Ia):

T= Φ Ia (where Φ = constant)

Torque is directly proportional to product of flux and armature current. In shunt motor, flux is constant. Torque is directly proportional to Ia. The curve is straight line passing through the origin i.e. the total torque developed in the armature.

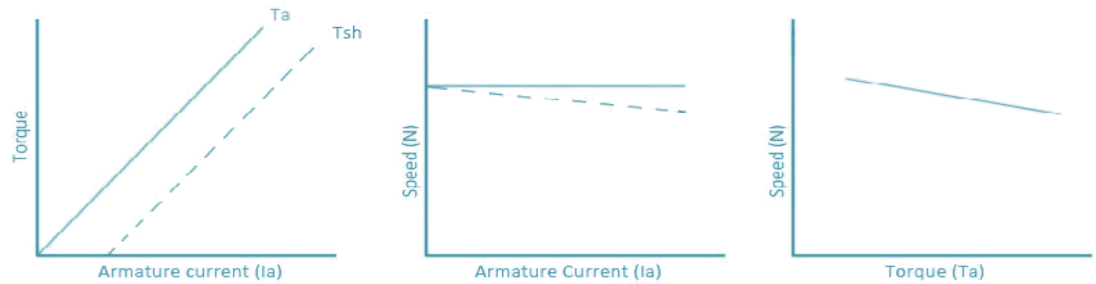
3) Speed Vs Torque (N Vs T):

Shunt motor is a constant speed motor. The shunt motor is used i Fans

2) Pumping of water

3) Lake machines

4) Hydraulic machines



Characteristics of DC shunt motor

Fig 3.9 Characteristics Of shunt Motor

3.7.1 Characteristics Of Series Motor [It Acts as constant Power Drives]:

$N \propto \frac{Eb}{\theta}$

$\Phi \propto Ia$

As speed is directly proportional to Eb and inversely proportional to flux. In series motor, Φ is directly proportional to Ia i.e. Φ I a and hence N. At no load, the I a is very small because, the power input to motor has to overcome the no load losses only i.e. friction and iron losses. Then the no load speed N , Φ Ia0 No load speed of the series motor dangerously high due to no load current, thus the series motor always start and operate under loaded condition.

1) Speed Vs Armature Current Characteristics (N Vs Ia):

As speed is directly proportional to back emf, Eb and inverselyproportional to Ia. Hence N . If curve is drawn between N & Ia, before saturation Φ Ia. As armature current increases, speed decreases, the curve is a straight line up to saturation. After saturation, Φ is almost constant and hence speed is approximately constant. With the increase of Ia, the curve is rectangular hyperbola as shown in figure.

2) T Vs Ia:

As Torque is proportional to product of Ia & Φ . In series motor Φ Ia.

T Ia^2. On light loads the Torque is directly proportional to square of Ia. If the curve is drawn between Ia & T, it is a parabola up to saturation point. After saturation, Φ is constant and torque is proportional to Ia. Hence characteristics become straight line as shown in figure.

From these characteristics, we can conclude that the starting Torque of series motors is high. So series motor are best suited for high starting torque requirement

3) N Vs Ta:

The speed-torque characteristics can be drawn from the above relations. Speed increases, Torque decreases and vice-versa. Seriesmotor acts as Constant Power Drive.

3.7.2 Characteristics of Separately Excited Motor

Characteristics of Separately Excited Motor are similar to that of shunt Motor.perating Characteristics Of Compound Motor:

For Cumulative compound Motor:

→ In cumulative, Φ = Φsh. + Φse

→ Under no load, Φse = 0

i.e. Φ = Φsh

→When load increase; load current increase.

And Φse . \Φ, N

Φ , speed .

For differential Compound Motor:

→Φ = Φsh - Φse

Under no load, Φse = 0

→When load increase; load current increase.

Φse

Total flux Φ decreases, then finally speed Increases.

1) N Vs Ia:

The cumulative compound motor runs under no load condition are constant speed i.e.

Here Φ = Φsh + Φse i.e.
constant. Then the speed of
the motor is constant

Þ When load , load current , Φse inc. & Φ\ speed decreases

For differential compound motor, ϴs runs under no load condition is rated speed.

Φ= Φsh – Φse.

When load inc, Φse due to inc. in Ia.

\ Φ decrease and speed increases.

2) T Vs Ia:

$T \propto \Phi\ Ia$

Þ $\Phi = \Phi sh + \Phi se$ $T \propto (\Phi sh + \Phi se)\ Ia$

Under no load condition, $Ia = 0$ and $\Phi se = 0$ and $Te = 0$. As the Ia series with load,

Φsh remains almost constant, but series field flux, Φse rises. As a result the motor Torque also rises.

But in a cumulative compound motors developed torque is higher than that developed in a dc shunt motor.

So cumulative compound motors are best suited for where the high starting torque is required.

3) N Vs T:

These characteristics are similar to N Vs I a characteristics.

$T \propto \Phi\ I\ a$

$\Phi = \Phi sh + \Phi se$

$T \propto (\Phi sh. + \Phi se)$

$Ia\ N \propto \frac{Eb}{\Phi}$

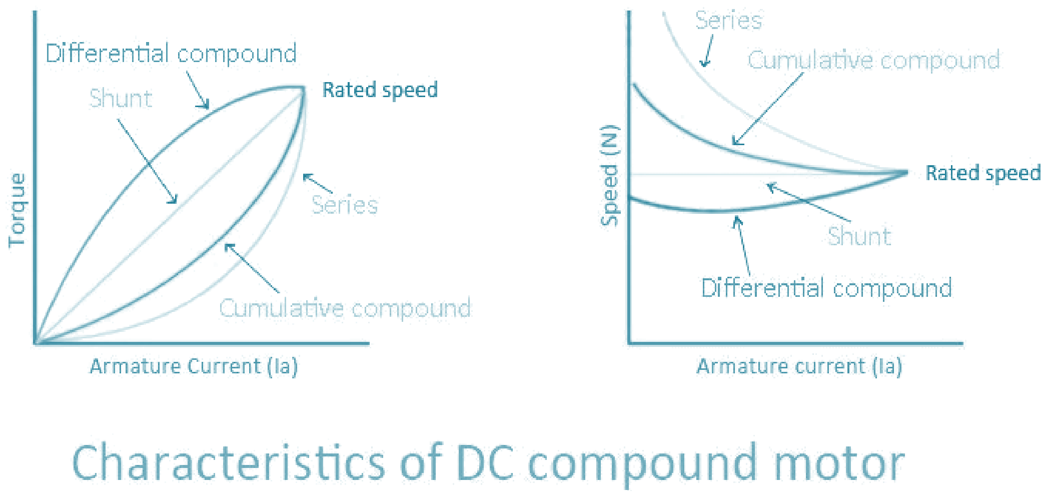


Fig 3.10 compound motors

1.8 SPEED CONTROL OF DC MOTOR:

The dc motor converts the mechanical power into dc electrical power. One of the most important features of the dc motor is that their speed can easily be control according to the requirement by using simple methods. Such type of control is impossible in an AC motor.

The concept of the speed regulation is different from the speed control. In speed regulation, the speed of the motor changes naturally whereas in dc motor the speed of the motor changes manually by the operator or by some automatic control device. The speed of the DC Motor is given bythe relation shown below.

The equation (1) that the speed is dependent upon the supply voltage V, the armature circuit resistance
Ra and the field flux φ, which is produced by the field current.

$$N = \frac{V - I_a R_a}{k\varphi} \quad \dots\dots\dots\dots (1)$$

For controlling the speed of DC Motor, the variation in voltage, armature resistance and field flux is taken into consideration. There are three general methods of speed control of a DC Motor. They are as follows.

1. Variation of resistance in the armature circuit.This method is called Armature Resistance or Rheostatic control.
2. Variation in field flux.This method is known as Field Flux Control.
3. Variation in applied voltage.This method is also known as Armature Voltage Control. The detailed discussion of the various method of controlling the speed is given below.

1.8.1 Armature Resistance Control of DC Motor Shunt Motor

The connection diagram of a shunt motor of the armature resistance control method is shown below. In this method, a variable resistor Re is putin the armature circuit. The variation in the variable resistance does noteffect the flux as the field is directly connected to the supply mains.

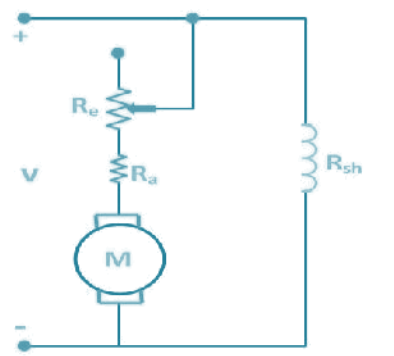


Fig 3.11Connection diagram of a shunt motor

Fig 3.11Connection diagram of a shunt motor of the armature resistance control method The speed current characteristic of the shunt motor is shown below.

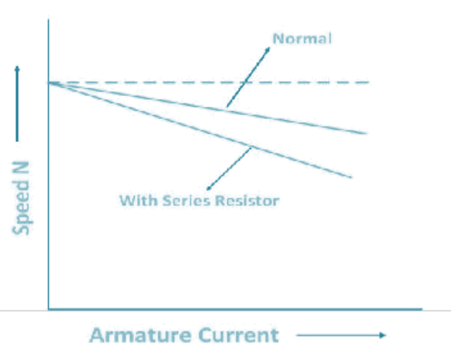


Fig 3.12Connection diagram of a shunt motor Speed current characteristic of the shunt motor

1.8.2 Series Motor:

Now, let us consider a connection diagram of speed control of the DC Series motor by the armature resistance control method.

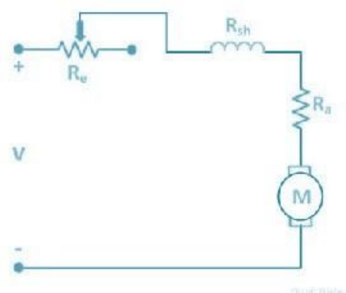
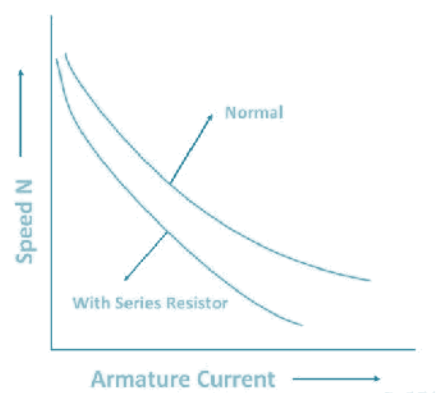


Fig 3.1 Diagram of speed control of the DC Series motor

By varying the armature circuit resistance, the current and flux both are affected. The voltage drop in the variable resistance reduces the applied voltage to the armature, and as a result, the speed of the motor is reduced. The speed–current characteristic of a series motor is shown in the figure



below.

Fig 3.14 Speed–current characteristic of a series motor

When the value of variable resistance Re is increased, the motor runs at a lower speed. Since the variable resistance carries full armature current, it must be designed to carry continuously the full armature current.
Disadvantages of Armature Resistance Control Method

- A large amount of power is wasted in the external resistance Re.
- Armature resistance control is restricted to keep the speed below the normal speed of the motor and increase in the speed above normal level is not possible by this method.
- For a given value of variable resistance, the speed reduction is not constant but varies with the motor load.
- This speed control method is used only for small motors.

Field Flux Control Method of DC Motor

Flux is produced by the field current. Thus, the speed control by this method is achieved by control of the field current.
Shunt Motor
In a Shunt Motor, the variable resistor RC is connected in series with the shunt field windings as shown in the figure below. This resistor RC is known as a Shunt Field Regulator.

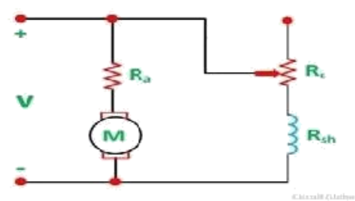


Fig 3.15 Shunt Field
Regulator The shunt field current is given by the

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

equation shown below.
The connection of RC in the field reduces the field current, and hence the flux is also reduced. This reduction in flux increases the speed, and thus, the motor runs at speed higher than the normal speed. Therefore, this method is used to give motor speed above normal or to correct the fall of speed because of the load.
The speed-torque curve for shunt motor is shown below.

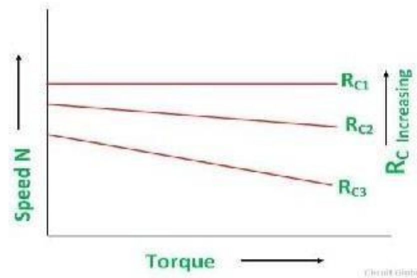


Fig 3.16 speed-torque curve for shunt motor

1.8.3 Series Motor

In a series motor, the variation in field current is done by any one method, i.e. either by a diverter or by a tapped field control.

By Using a Diverter:

A variable resistance Rd is connected in parallel with the series field windings as shown in the figure below.

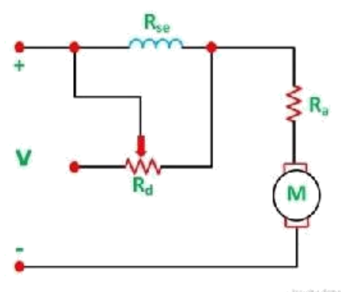


Fig 3.17 Diverter is connected in parallel with the series field windings

The parallel resistor is called a Diverter. A portion of the main current is diverted through a variable resistance Rd. Thus, the function of a diverter is to reduce the current flowing through the field winding. The reduction in field current reduces the amount of flux and as a result the speed of the motor increases.

Tapped Field Control:

The second method used in a series motor for the variation in field current is by tapped field control. The connection diagram is shown below.

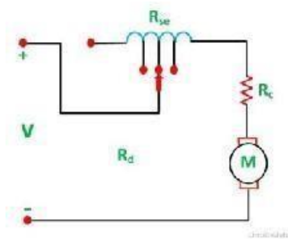


Fig 3.18 Tapped Field Control

Here the ampere turns are varied by varying the number of field turns. This type of arrangement is used in an electric traction system. The speed of the motor is controlled by the variation of the field flux. The speed-torque characteristic of a series motor is shown below.

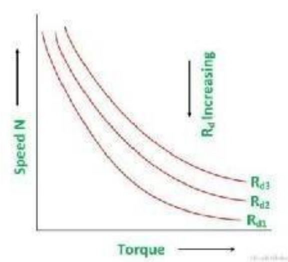


Fig 3.19Speed-torque characteristic

Advantages of Field Flux Control

The following are the advantages of the field flux control method.

- This method is easy and convenient.
- As the shunt field is very small, the power loss in the shunt field is also small.

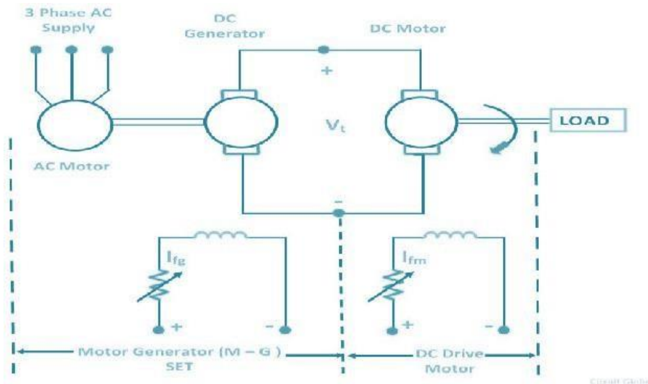
The flux cannot usually be increased beyond its normal values because of the saturation of the iron. Therefore, speed control by flux is limited to the weakening of the field, which gives an increase in speed. This method is applicable over only to a limited range because if the field is weakened too much, there is a loss of stability.

Armature Voltage Control of DC Motor

In armature voltage control method the speed control is achieved by varying the applied voltage in the armature winding of the motor. This speed control method is also known as Ward Leonard Method, which is discussed in detail under the topic Ward Leonard Method or Armature Voltage Control.

1.8.4 Ward Leonard Method Of Speed Control Or Armature Voltage Control

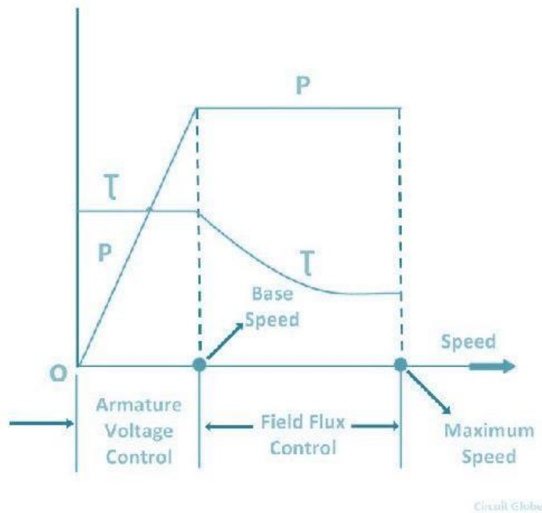
Ward Leonard Method of speed control is achieved by varying the applied voltage to the armature. This method was introduced in 1891. The connection diagram of the Ward Leonard method of speed control of aDC shunt motor is shown in the figure below.



In the above system, M is the main DC motor whose speed is to be controlled, and G is a separately excited DC generator. The generator G is driven by a 3 phase driving motor which may be an induction motor or a synchronous motor. The combination of AC driving motor and the DC generator is called the Motor-Generator (M-G) set.

The voltage of the generator is changed by changing the generatorfield current. This voltage when directly applied to the armature of the main DC motor, the speed of the motor M changes. The motor field current Ifm is kept constant so that the motor field flux φm also remains constant. While the speed of the motor is controlled, the motor armature current Ia is kept equal to its rated value.
The generated field current Ifg is varied such that the armature voltage Vtchanges from zero to its rated value. The speed will change from zero to the base speed. Since the speed control is
carried out with the rated current Ia and with the constant motor field flux, a constant torque is directly proportional to the armature current, and field flux up to rated speed is obtained. The product of torque and speed is known as power, and it is proportional to speed. Thus, with the increase in power, speed increases automatically.

The Torque and Power Characteristic is shown in the figure below.



Hence, with the armature voltage control method, constant torque and variable power drive is obtained from speed below the base speed. The Field flux control method is used when the speed is above the base speed. In this mode of operation, the armature current is maintained constant at its rated value, and the generator voltage Vt is kept constant.

The motor field current is decreased and as a result, the motor field flux also decreases.This means that the field is weakened to obtain the higher speed. Since VtIa and EIa remain constant, the electromagnetic torque is directly proportional to the field flux φm and the armature current Ia. Thus, if the field flux of the motor is decreased the torque decreases.

Therefore, the torque decreases, as the speed increases. Thus, in the field control mode, constant power and variable torque are obtained for speeds above the base speed. When the speed control over a widerange is required, a combination of armature voltage control and field fluxcontrol is used. This combination permits the ratio of maximum to minimumspeed available speeds to be 20 to 40. For closed loop control, this range can be extended up to 200.

The driving motor can be an induction or synchronous motor. An induction motor operates at a lagging power factor. The synchronous motor may be operated at a leading power factor by over-excitation of its field. Leading reactive power is generated by over excited synchronous motor. It compensates for the lagging reactive power taken by other inductive loads. Thus, the power factor is improved.

A Slip ring induction motor is used as p prime mover when the load is heavy and intermittent. A flywheel is mounted on the shaft of the motor. This scheme is known as Ward Leonard-Ilgener scheme. It prevents heavy fluctuations in supply current.

When the Synchronous motor is acting as a driving motor, the fluctuations cannot be reduced by mounting a flywheel on its shaft, because the synchronous motor always operates at a constant speed. In another form of Ward Leonard drive, non-electrical prime movers can also be used to drive the DC generator.

For example – In DC electric locomotive, DC generator is driven by a diesel engine or a gas turbine and ship propulsion drives. In this system, Regenerative braking is not possible because energy cannot flow in the reverse direction in the prime mover.

Advantages of Ward Leonard Drives

The main advantages of the Ward Leonard drive are as follows:-

1. Smooth speed control of DC motor over a wide range in both the direction is possible.
2. It has an inherent braking capacity.
3. The lagging reactive volt-amperes are compensated by using an overexcited synchronous motor as the drive and thus, the overall power factor improves.

When the load is intermittent as in rolling mills, the drive motor is an induction motor with a flywheel mounted to smooth out the intermittent loading to a low value.

Drawbacks of Classical Ward Leonard System

The Ward Leonard system with rotating Motor Generator sets has following drawbacks.

1. Larger size and weight.
2. Requires large floor area
3. Costly foundation
4. Maintenance of the system is frequent.
5. Higher losses.
6. Lower efficiency.
7. The drive produces more noise.

8. The Initial cost of the system is high as there is a motor generator set installed, of the same rating as that of the main DC motor

Applications of Ward Leonard Drives

The Ward Leonard drives are used where a smooth speed control of the DC motors over a wide range in both the directions is required. Some of the examples are as follows:-

1. Rolling mills
2. Elevators
3. Cranes
4. Paper mills
5. Diesel-electric locomotives
6. Mine hoists

1.9 STARTING OF DC MOTORS

A starter is a device to start and accelerate a motor. A controller is a device to start the motor, control and reverse the speed of the DC motorand stop the motor. While starting the DC motor, it draws the heavy current which damages the motor. The starter reduces the heavy current and protects the system from damage.

1.9.1 Need of Starters for DC Motors

The dc motor has no back EMF. At the starting of the motor, the armature current is controlled by the resistance of the circuit. The resistance of the armature is low, and when the full voltage is applied at the standstill condition of the motor, the armature current becomes very high which damage the parts of the motor.

Because of the high armature current, the additional resistance is placed in the armature circuit at starting. The starting resistance of the machine iscut out of the circuit when the machine gains it speeds. The armature current of a motor is given by

$$I_a = \frac{V - E}{R_a} \;\ldots\ldots\ldots\; (1)$$

Thus, Ia depends upon E and Ra, if V is kept constant. When the motor is first switched ON, the armature is stationary. Hence, the back EMF Eb is also zero. The initial starting armature current Ias is given by the equation shown below.

$$I_{as} = \frac{V - 0}{R_a} = \frac{V}{R_a} \ldots\ldots\ldots\ldots (2)$$

Since, the armature resistance of a motor is very small, generally less than one ohm. Therefore, the starting armature current Ias would be very large. For example – if a motor with the armature resistance of 0.5 ohms is connected directly to a 230 V supply, then by putting the values in the equation (2) we will get.

$$I_{as} = \frac{V}{R_a} = \frac{230}{0.5} = 460 \quad \text{Ampere}$$

This large current would damage the brushes, commutator and windings. As the motor speed increases, the back EMF increases and the difference (V – E) go on decreasing. This results in a gradual decrease of armature current until the motor attains its stable speed and the corresponding back EMF. Under this condition, the armature current reaches its desired value. Thus, it is found that the back EMF helps the armature resistance in limiting the current through the armature.
Since at the time of starting the DC Motor, the starting current is very large. At the time of starting of all DC Motors, except for very small motors, an extra resistance must be connected in series with the armature. This extra resistance is added so that a safe value of the motor is maintained and to limit the starting current until the motor has attained its stable speed.

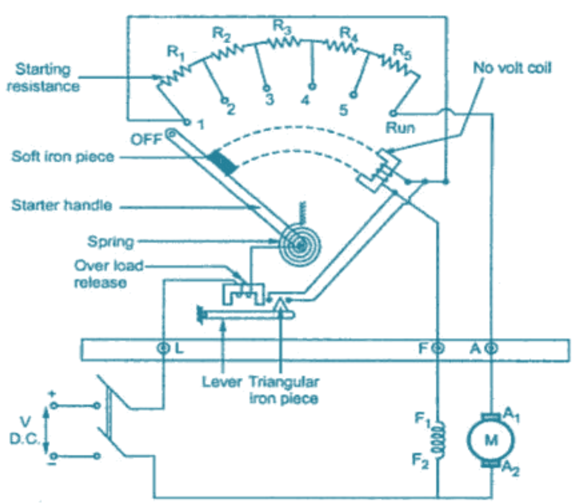
The series resistance is divided into sections which are cut out one by one, as the speed of the motor rises and the back EMF builds up. The extra resistance is cut out when the speed of the motor builds up to its normal value.

3.9.1 3-POINT STARTER

3 Point Starter is a device whose main function is starting and maintaining the speed of the DC shunt motor. The 3 point starter connects the resistance in series with the circuit which reduces the high starting current and hence protects the machines from damage. Mainly there are three main points or terminals in 3 point starter of DC motor. They are as follows

- L is known as Line terminal, which is connected to the positive supply.
- A is known as the armature terminal and is connected to the armature
- F or Z is known as the field terminal and is connected to the field terminal windings.

It consists of a graded resistance R to limit the starting current. The handle H is kept in the OFF position by a spring S. The handle H is manually moved, for starting the motor and when it makes contact with resistance stud one the motor is said to be in the START position. In this initial start position, the field winding of the motor receives the full supply voltage, and the armature current is limited to a certain safe value by the resistance (R = R1 + R2 + R3+ R4).



3 point Starter

Fig 3.18 3 Point Starter

Working of 3 Point Starter

The starter handle is now moved from stud to stud, and this builds up the speed of the motor until it reaches the RUN position. The Studs are the contact point of the resistance. In the RUN position, three main points are considered. They are as follows.

- The motor attains the full speed.

- The supply is direct across both the windings of the motor.
- The resistance R is completely cut out.

The handle H is held in RUN position by an electromagnet energised by a no volt trip coil (NVC). This no volt trip coil is connected in series with the field winding of the motor. In the event of switching OFF, or when the supply voltage falls below a predetermined value, or the complete failure of supply while the motor is running, NVC is energised. The handle is released and pulled back to the OFF position by the action of the spring. The current to the motor is cut off, and the motor is not restartedwithout a resistance R in the armature circuit. The no voltage coil also provides protection against an open circuit in the field windings.
The No Voltage Coil (NVC) is called NO-VOLT or UNDERVOLTAGE protection of the motor. Without this protection, the supply voltage mightbe restored with the handle in the RUN position. The full line voltage is directly applied to the armature. As a result, a large amount of current is generated.

The other protective device incorporated in the starter is the overload protection. The Over Load Trip Coil (OLC) and the No Voltage Coil (NVC) provide the overload protection of the motor. The overload coil is made up of a small electromagnet, which carries the armature current. The magnetic pull of the Overload trip coil is insufficient to attract the strip P, for the normal values of the armature current

When the motor is overloaded, that is the armature current exceeds the normal rated value, P is attracted by the electromagnet of the OLC and closes the contact aa thus, the No Voltage Coil is short-circuited, shown in the figure of 3 Point Starter. As a result, the handle H is released, which returns to the OFF position, and the motor supply is cut off.
To stop the motor, the starter handle should never be pulled back as this would result in burning the starter contacts. Thus, to stop the motor, the main switch of the motor should be opened.

Drawbacks of a 3 Point Starter

The following drawbacks of a 3 point starter are as follows:-

- The 3 point starter suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat.

- To increase the speed of the motor, the field resistance should be increased. Therefore, the current through the shunt field is reduced.
- The field current may become very low because of the addition of high resistance to obtain a high speed.
- A very low field current will make the holding electromagnet too weak to overcome the force exerted by the spring.
- The holding magnet may release the arm of the starter during the normal operation of the motor and thus, disconnect the motor from the line. This is not a desirable action.

Hence, to overcome this difficulty, the 4 Point Starter is used.

3.9.2 4POINT STARTER

A 4 Point Starter is almost similar in functional characteristics like 3 Point Starter. In the absence of back EMF, the 4 Point Starter acts as a current limiting device while starting of the DC motor.

4 Point Starter also acts a protecting device.

The basic difference in 4 Point Starter as compared to 3 Point Starter is that in this a holding coil is removed from the shunt field circuit. This coil after removing is connected across the line in series with a current limiting resistance R. The studs are the contact points of the resistance represented by 1, 2, 3, 4, 5 in the figure below. The schematic connectiondiagram of a 4 Point Starter is shown below.

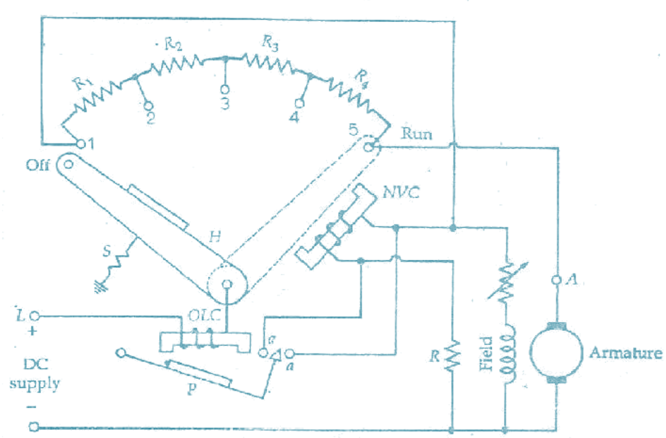


Fig: 4 Point Starter

The above arrangement forms three parallel circuits. They are as follows:-

- Armature, starting the resistance and the shunt field winding.

- A variable resistance and the shunt field winding.
- Holding coil and the current limiting resistance.

With the above three arrangements of the circuit, there will be no effect on the current through the holding coil if there is any variation in speedof the motor or any change in field current of the motor. This is because the two circuits are independent of each other.

The only limitation or the drawback of the 4 point starter is that it cannot limit or control the high current speed of the motor. If the field winding of the motor gets opened under the running condition, the field current automatically reduces to zero. But as some of the residual flux is still present in the motor, and we know that the flux is directly proportional tothe speed of the motor. Therefore, the speed of the motor increases drastically, which is dangerous and thus protection is not possible. This sudden increase in the speed of the motor is known as High- Speed Actionof the Motor.

Nowadays automatic push button starters are also used. In the automatic starters, the ON push

button is pressed to connect the current limiting starting resistors in series with the armature circuit. As soon as the full line voltage is available to the armature circuit, this resistor is gradually disconnected by an automatic controlling arrangement.

The circuit is disconnected when the OFF button is pressed. Automatic starter circuits have been developed using electromagnetic contactors and time delay relays. The main advantage of the automatic starter is that it enables even the inexperienced operator to start and stop the motor without any difficulty.

1.10 LOSSES IN DC MACHINE

The losses that occur in a DC Machine is divided into five basiccategories. The various losses are Electrical or Copper losses (I2R losses),Core losses or Iron losses, Brush losses, Mechanical losses, Stray load losses.These losses are explained below in detail.

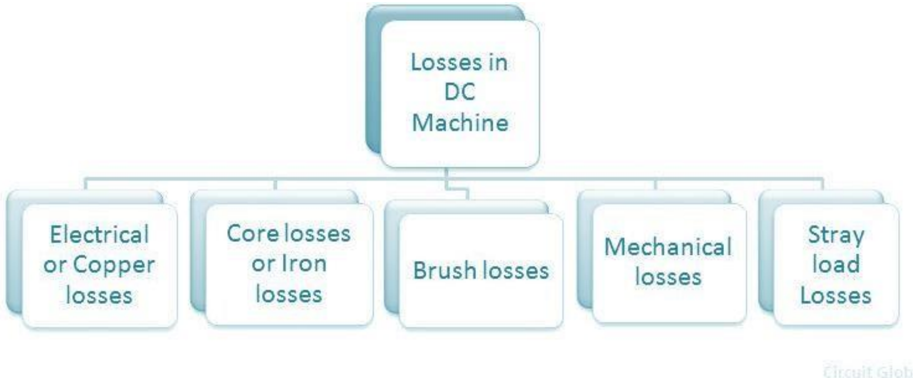


Fig: Classification of losses in DC machnes

Electrical or Copper Losses in dc machine

These losses are also known as Winding losses as the copper loss occurs because of the resistance of the windings. The ohmic loss is produced by the current flowing in the windings. The windings that are present in addition to the armature windings are the field windings, interpoles and compensating windings.

Armature copper losses = $I_a^2R_a$ where I_a is armature current, and R_a is the armature resistance. These losses are about 30 percent of the total full load losses.

In shunt machine, the Copper loss in the shunt field is $I_{sh}^2R_{sh}$, where I_{sh} is the current in the shunt field, and R_{sh} is the resistance of the shunt field windings. The shunt regulating resistance is included in R_{sh}.

In a series machine, the copper loss in the series windings is $I_{se}^2R_{se}$, where, I_{se} is the current through the series field windings, and R_{se} is the resistance of the series field windings. In a Compound machine, both the shunt and the series field losses occur. These losses are almost 20 percent of the full load losses.

Copper losses in the interpole windings are written as $I_a^2R_i$ where R_i is the resistance of the interpole windings.

Copper loss in the compensating windings if any is $I_a^2R_c$ where R_c is the resistance of compensating windings.

Magnetic Losses or Core Losses or Iron Losses in dc machine

The core losses are the hysteresis and eddy current losses. These losses are considered almost constant as the machines are usually operated at constant flux density and constant speed. These losses are about 20 percent of the full load losses.

Brush Losses in dc machine

Brush losses are the losses taking place between the commutator and the carbon brushes. It is the power loss at the brush contact point. The brush drop depends upon the brush contact voltage drop and the armature current Ia. It is given by the equation shown below.

The voltage drop occurring over a large range of armature currents, across a set of brushes is approximately constant If the value of brush voltage drop is not given than it is usually assumed to be about 2 volts. Thus, the brush drop loss is taken as 2Ia.

Mechanical Losses in dc machine

The losses that take place because of the mechanical effects of the machines are known as mechanical losses. Mechanical losses are divided into bearing friction loss and windage loss. The losses occurring in the moving parts of the machine and the air present in the machine is known as Windage losses. These losses are very small.

Stray Losses in dc machine

These losses are the miscellaneous type of losses. The following factors are considered in stray load losses.

- The distortion of flux because of armature reaction.
- Short circuit currents in the coil, undergoing commutation.

These losses are very difficult to determine. Therefore, it is necessary to assign the reasonable value of the stray loss. For most machines, stray losses are taken by convention to be one percent of the full load output power.

1.11 EFFICIENCY OF DC GENERATOR

Efficiency is simply defined as the ratio of output power to the input power.

Let R = total resistance of the armature circuit (including the brush contact resistance, at series winding resistance, inter-pole winding resistance and compensating winding resistance). The efficiency of DC generator is explained below in the line diagram.

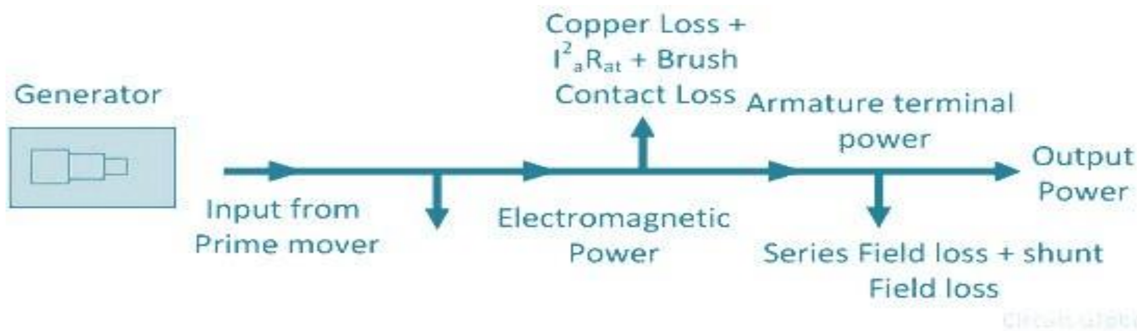


Fig 3.20 Power flow diagram

- I is the output current
- Ish is the current through the shunt field
- Ia is the armature current = I + Ish
- V is the terminal voltage.

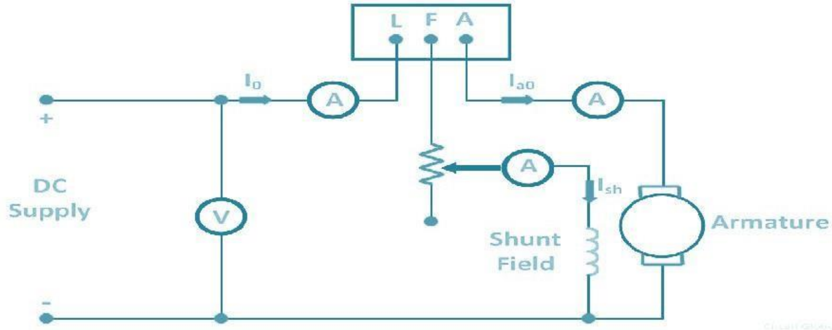
Total copper loss in the armature circuit = Ia2Rat
Power loss in the shunt circuit = VIsh (this includes the loss in the shunt regulating resistance). Mechanical losses = friction loss of bearings + friction loss at a commutator + windage loss.
Core losses = hysteresis loss + eddy
current loss Stray loss = mechanical
loss + core loss
The sum of the shunt field copper loss and stray losses may be considered as a combined fixed (constant) loss that does not vary with the load current I. Therefore, the constant losses (in shunt and compound generators) = stray loss + shunt field copper losses.

$$\text{Total Losses} = I_a^2 R_{at} + p_K + V_{BD} I_a$$

1.12 TESTS ON DC MACHINE

1.12.1 SWINBURNE'S TEST

Swinburne's Test is an indirect method of testing of DC machines. In this method the losses are measured separately and the efficiency at any desired load is predetermined. Machines are tested for finding out losses, efficiency and temperature rise. For small machines direct loading test is performed. For large shunt machines, indirect methods are used like



Swinburne's or Hopkinson's test.

The machine is running as a motor at rated voltage and speed. The connection diagram for DC shunt machine is shown in the figure below.

Fig 3.21 Swinburne's Test

Let

V be the

supply voltage

I0 is the no-

load current

Ish is the shunt field current

Therefore, no load armature current is given by the equation shown below.

$$I_{a0} = I_0 - I_{sh}$$

No-load input = VI0

The no-load power input to the machine supplies the following, as given below.

- Iron loss in the core
- Friction losses in the bearings and commutators.
- Windage loss
- Armature copper loss at no load.

When the machine is loaded, the temperature of the armature winding and the field winding increases due to I2R losses. For calculating I2R losseshot resistances should be used. A stationary measurement of resistances at room temperature of t degree Celsius is made by passing current through the armature and

then field from a low voltage DC supply. Then the heated resistance, allowing a temperature rise of 50°C is found. The equations are as follows:-

$$R_{t1} = R_0\,(1 + \alpha_0 t_1)$$

$$R_{t1+50^0} = R_0\,[1 + \alpha_0\,(t_1 + 50^\circ)]$$

Where, α0 is the temperature coefficient of resistance at 0ºC Therefore,

$$R_{t1+50^0} = R_{t1}\frac{1+\ \alpha_0\,(t_1+\ 50^\circ)}{1+\ \alpha_0 t_1}$$

Stray loss = iron loss + friction loss + windage loss = input at no load – field copper loss
– no load armature copper loss

Also,

$$= VI_0 - p_f - p_{a0} = p_s$$

$$p_c = \text{no load input} - \text{no load armature copper loss}$$

$$p_c = p_s + p_f$$

constant losses

If the constant losses of the machine are known, its efficiency at any other load can be determined as follows.
Let I be the load current at which efficiency is required. Efficiency when the machine is running as a Motor.

$$\text{Motor input} = VI$$

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

$$\text{Constant losses} = p_c$$

Therefore, total losses is given as

$$\text{Total losses} = (I - I_{sh})^2\,R_a + p_c$$

The efficiency of the motor is given below.

$$\eta_m = \frac{\text{input} - \text{losses}}{\text{input}}$$

$$\eta_m = \frac{VI - (I - I_{sh})^2\,R_a + p_c}{VI}$$

Efficiency when the machine is running as a Generator.

$$\text{Generator output} = VI$$

$$\text{Armature current} = I_a = I + I_{sh}$$

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

$$\text{Constant losses} = p_c$$

Therefore, total losses is given as

$$\text{Total losses} = (I + I_{sh})^2 R_a + p_c$$

The efficiency of the generator is given below.

$$\eta_g = \frac{\text{output}}{\text{output} + \text{losses}}$$

$$\eta_g = \frac{VI}{VI + (I + I_{sh})^2 R_a + p_c}$$

Advantages of Swinburne's Test:

The main advantages of the Swinburne's test are as follows:-

- The power required to test a large machine is small. Thus, this method is an economical and convenient method of testing of DC machines.
- As the constant loss is known the efficiency can be predetermined at any load.

Disadvantages of Swinburne's Test:

- Change in iron loss is not considered at full load from no load. Due to armature reaction flux is distorted at full load and, as a result, iron loss is increased.
- As the Swinburne's test is performed at no load. Commutation on full load cannot be determined whether it is satisfactory or not and whether the temperature rise is within the specified limits or not.

1.12.2 BRAKE TEST ON DC SHUNT MOTOR:

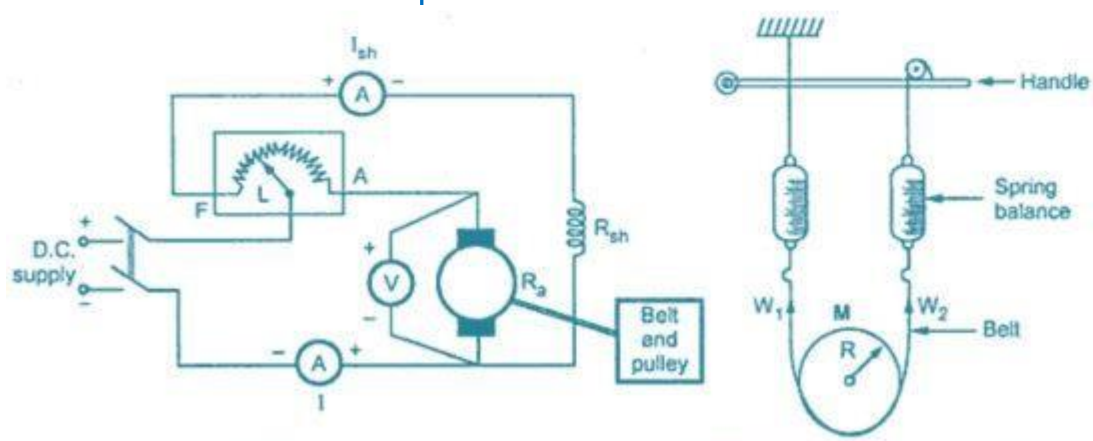
Brake test is a method of finding efficiency of dc motors. We took dc shunt motor as running machine. Brake test also called as direct loading test of testing the motor because loading will be applied directly on shaft of the motor by means of a belt and pulley arrangement.

Test Requirements:

1. DC shunt motor
2. Water-cooled pulley
3. Spring balance

Procedure of Brake Test on DC Shunt Motor:

1. By adjusting the handle of the pulley take different readings of the spring balance.
2. The tension in the belt can be adjusted using the handle. The tension in kg can be obtained from the spring balance readings.
3. Adjusting the load step by step till full load, number of readings can be obtained. By increasing the load is slowly, adjust to get rated load current.
4. The power developed gets wasted against the friction between belt and shaft.
5. The speed can be measured by tachometer. Thus all the motor characteristics can be plotted.



(a) Experimental setup (b) Belt and pulley arrangement

Calculation of Brake Test on DC Shunt Motor

Let R (or) r= Radius of pulley in meters N = Speed in R.P.M.

W1 = spring balance reading on

tight side in kg W2 = spring balance
reading on slack side in kg
So, net pull on the belt due to friction at the pulley is the difference between the two spring balance readings.

Net pull on the rope = (W - S) kg = (W - S) X 9.81 newtons (1)
As radius R and speed N are known, the shaft torque developed can be obtained as, Tsh = Net pull X R = (W - S) X 9.81 X R ....(2)

Now let, V = Voltage applied in volts I = Total line current drawn in amps.
As we know V and I are input parameters of dc motors in brake test. Then,
Pin=V.I Watts .. (3)
We have output and input. Then why late go and find the efficiency of dc shunt motor. Efficiency (η)=Output/Input [No units]
From equation (2) & (3)

$$\text{Output power} = \frac{2\pi\ N\ T_{sh}}{60} = \frac{2\pi\ N \times (W - S) \times 9.81 \times r}{60} \quad \text{watts}$$

Advantages of Brake Test on DC Shunt Motor:

1. Actual efficiency of the motor under working conditions can be found out.
2. Brake test is simple and easy to perform.
3. It is not only for dc shunt motor, also can be performed on any type of D.C. motor.

Disadvantages of Brake Test on DC Shunt Motor:

1. In brake test due the belt friction lot of heat will be generated and hence there is large dissipation of energy.
2. Cooling arrangement is necessary to minimize the heat. Mostly in our laboratories we use water as cooling liquid.
3. Convenient only for small rated machines due to limitations regarding heat dissipation arrangements.
4. Power developed gets wasted hence brake test method is little expensive.
5. The efficiency observed is on lower side.

1.12.3 H OPKI NSON' S TEST

Hopkinson's Test is also known as Regenerative Test, Back to Back test and Heat Run Test. In Hopkinson Test, two identical shunt machinesare required which are coupled both mechanically and electrically in parallel. One is acting as a motor and another one as a generator. The input to the motor is given by the supply mains.

The mechanical output of motor drives the generator, and the electrical output of the generator is used in supplying the input to the motor. Thus, the output of each machine acts as an input to the other machine. When both the machines are running on the full load, the supply input is equal to the total losses of the machines. Hence, the power input from the supply is very small.

The Circuit Diagram of the Hopkinson's Test is shown
in the figure below.

Supply is given and with the help of a starter, the machine M starts and work as a motor. The switch S is kept open. The field current of M is adjusted with the help of rheostat field RM, which enables the motor to run at rated speed. Machine G acts as a generator. Since the generator is mechanically coupled to the motor, it runs at the rated speed of the motor.

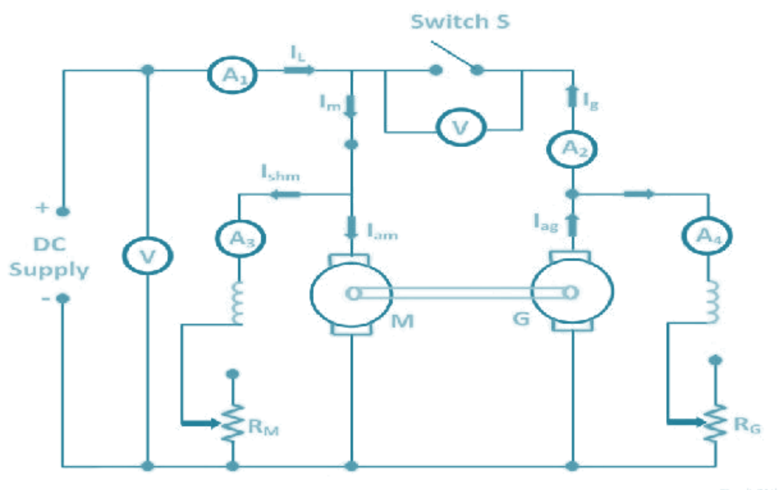


Fig:3.23 Hopkinson's Test

The excitation of the generator G is so adjusted with the help of its field rheostat RG that the voltage across the armature of the generator is slightly higher than the supply voltage. In actual the terminal voltageof the generator is kept 1 or 2 volts higher than the supply voltage.

When the voltage of the generator is equal and of the same polarity as the of the busbar supply voltage, the main switch S is closed, and the generator is connected to the busbars. Thus, both the machines are now in parallel across the supply. Under this condition, when the machines are running parallel, the generator are said to float. This means that the generator is neither taking any current nor giving any current to the supply.

Now with the help of a field rheostat, any required load can be thrown on the machines by adjusting the excitation of the machines with the help of field rheostats.

Let,

V be the supply voltage

IL is the line current

Im is the input current to the motor

Ig is the input current to the generator

Iam is the motor armature current

Ishm is the motor shunt field current

Ishg is the generator shunt field current

Ra is the armature resistance of each machine

Rshm is the motor shunt field resistance

Rshg is the generator shunt field resistance

Eg is the generator induced voltage

Em is the motor induced voltage or back emf

$$E_g = V + I_{ag}R_a$$

$$E_m = V - I_{am}R_a$$

Therefore,

$$E_g > E_m$$

But,

$$E_g \propto \varphi_g N \quad \text{and} \quad E_m \propto \varphi_m N$$

Hence,

$$\varphi_g > \varphi_m$$

Since the field flux is directly proportional to the field current.

Thus, the excitation of the generator shall always be greater than that of the motor.

Calculation of the Efficiency of the Machine by Hopkinson's Test

Power input from the supply = VIL = total losses of both the machines

Armature copper loss of the motor = I2am Ra

Field copper loss of the motor = I2shm Rshm

Armature copper loss of the generator = I2ag Ra

Field copper loss of the generator = = I2shg Rshg

The constant losses Pc like iron, friction and windage losses are assumed to be equal and is written as given below.

Constant losses of both the machines = Power drawn from the supply – Armature and shunt copper losses of both the machines.

$$\varphi \propto I_f$$

$$I_{shg} > I_{shm}$$

$$P_C = VI_L - \left(I_{am}^2 R_a + I_{shm}^2 R_{shm} + I_{ag}^2 R_a + I_{shg}^2 R_{shg}\right)$$

Assuming that the constant losses known as stray losses are divided equally between the two machines. Total stray loss per machine = ½ PC

Efficiency of the Generator

Output = VIag

Constant losses for generator is given as PC/2

Armature copper loss = I2ag Ra

Field copper loss = I2shg Rshg

The Efficiency of the generator is given by the equation shown below

$$\eta_g = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

$$\eta_g = \frac{VI_{ag}}{VI_{ag} + I_{ag}^2 R_a + I_{shg}^2 R_{shg} + \frac{1}{2} P_C}$$

Efficiency of the Motor

$$\text{Input} = VI_m = V(I_{am} + I_{shm})$$

Constant losses of the motor is given as PC/2
Armature copper loss = I2am Ra
Field copper loss = I2shm Rshm
The Efficiency of the motor is given by the equation shown

$$\eta_m = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{losses}}{\text{Input}}$$

$$\eta_m = \frac{V(I_{am} + I_{shm}) - \left(\frac{P_C}{2} + I_{am}^2 R_a + I_{shm}^2 R_{shm}\right)}{V(I_{am} + I_{shm})}$$

below

Advantages of Hopkinson's Test

The main advantages of using Hopkinson's test are as follows:-

1. The temperature rise and the commutation conditions can be checked under rated load conditions.
2. Stray losses are considered, as both the machines are operated under rated load conditions.
3. Large machines can be tested at rated load without consuming much power from the supply.
4. Efficiency at different loads can be determined.
5. This method is very economical.

Disadvantage of Hopkinson's Test

The main disadvantage of this method is the necessity of two practically identical machines for
performing the Hopkinson's test. Hence, this test is suitable for large DC machines.

1.12.4 FIE L D'S T E S T :

This is one of the methods of testing the D.C. series motors. Unlike shunt motors, the series motor cannot be tested by the methods which area available for shunt motors as it is impossible to run the motor on no-load.

It may run at dangerously high speed on no load. In case of small series motors brake test may be employed.

The series motors are usually tested in pairs. The field test is applied to two similar series motors which are coupled mechanically. The connection diagram for the test is shown in the Fig

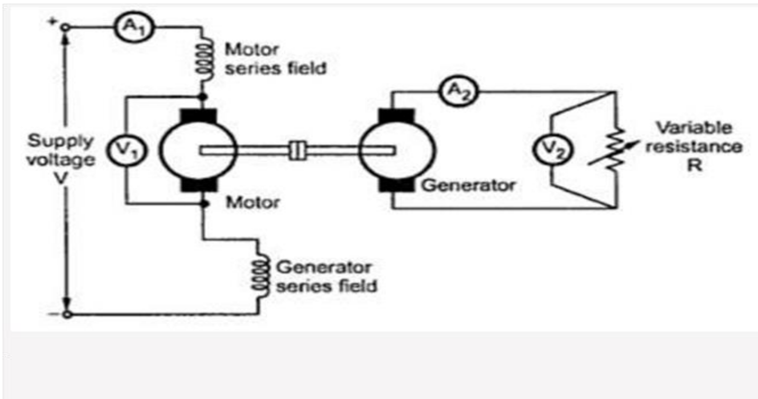


Fig. 3.24 Field test

As shown in the Fig. 1 one machine is made to run as a motor while the other as a generator which is separately excited. The fields of the two machines are connected in series so that both the machines are equally excited. This will make iron losses same for the two machines. The two machines are running at the same speed. The generator output is given to the variable resistance R.

The resistance R is changed until the current taken by motor reaches full load value. This will be indicated by ammeter A1. The other readings of different meters are then recorded.

LetV = Supply
voltage I1 =
Current taken by
motor I2 = Load
current
V2 = Terminal p.d. of generator
Ra, Rse = Armature and series field resistance of

each machine Power taken from supply = VI1
Output obtained from generator = V2 I2
Total losses in both the machines, WT = VI1 - V2 I2
Armature copper and field losses, WCU = (Ra + 2 Rse)
I12 + I22 Ra

$$\text{Stray losses per machine, } W_s = \frac{W_T - W_{cu}}{2}$$

Total stray losses = WT - WCU
Since the two machines are equally excited and are running at same speed the stray loses are equally divided.
For Motor;
Input to motor = V1 I1
Total losses = Aramture Cu loss + Field Cu loss + Stray loss
= I12 (Ra + Rse) + Ws
Output of motor = Input - Total losses = V1 I1 - [I12 (Ra + Rse) + Ws]

$$\text{Efficiency of motor, } \eta_m = \frac{\text{Output}}{\text{Input}}$$

$$\boxed{\eta_m = \frac{V_1 I_1 - [I_1^2 (R_a + R_{se}) + W_s}{V_1 I_1}}$$

1.12.5 RETARDATION TEST OR RUNNING DOWN TEST

This method is generally employed to shunt generators and shunt motors. From this method we can get stary losses. Thus if armature and shunt copper losses at any given load current are known then efficiency of a machine can be easily estimated.

The machine whose test is to be taken is run at a speed which is slightly above its normal speed. The supply to the motor is cut off while the field iskept excited. The armature consequently slows down and its kinetic energy is used in supplying the rotational or stray losses which includes iron, friction and winding loss.

If I is the amount of inertia of the armature ans is the angular velocity. Kinetic energy

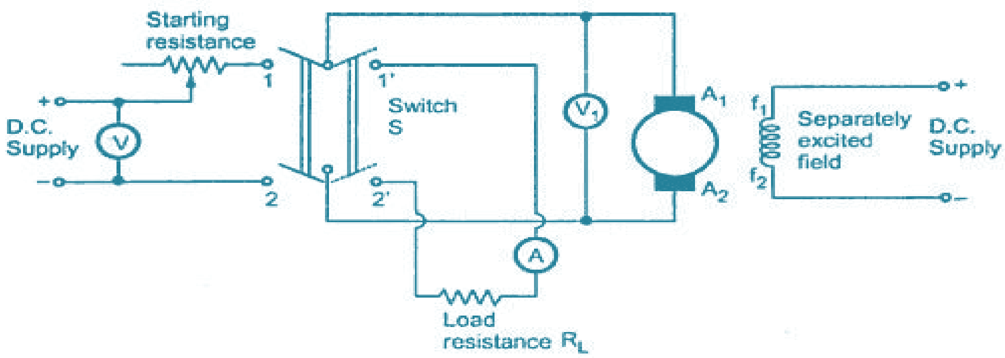


Fig. 3.25 Retardation test

of armature = 0.5 Iω2

... Rotational losses, W = Rate of change of kinetic energy

Angular velocity, ω = (2 πN)/60

Thus, to find the rotational losses, the moment of inertia I and dN/dt must be known. These quantities can be found as follows;

Determination of dN/dt

The voltmeter V1 which is connected across the armature will read the back e.m.f. of the motor. We know that back e.m.f. is proportional to speed so that voltmeter is calibrated to read the speed directly.

When motor is cut off from the supply, the speed decrease in speed is noted with the help of stop watch. A curve showing variation between time and speed which is obtained from voltmeter which is suitably calibrated is shown in the Fig. 3.

At any point C corresponding to normal speed, a tangent AB is drawn. Then

The value obtained from above can be substituted in the expression for W which can give the rotational loses.

Determination of moment of inertia (I):

Method 1: Using Flywheel

The armature supply is cut off and time required for definite change in speed is noted to draw the corresponding curve as we have drawn in previous case.This curve is drawn considering only armature of the machine. Now a flywheelwith known moment of the inertia say is I1 keyed onto the shaft and the same curve is drawn again. The slowing down time will be extended as combined moment of inertia of the two is increased.

For any given speed (dN/dt1) and (dN/dt2) are determined same as previous case. It can be seen that the losses in both the cases are almost same as addition of flywheel will not make much difference to the losses.

In the first case where flywheel is not there then,

Adding the flywheel to the motor armature in second case we

Method 2: without using Flywheel

In this method time is noted for the machine to slow down by say 5 % considering the armature alone. The a retarding torque either mechanical or electrical is applied. Preferably electrical retarding torque is applied and time required to slow down by 5% is noted again. The method by which electrical torque can be provided is shown in the Fig. 1 in which the switch S after disconnecting from the supply is thrown to terminals 1'2'. The machine then gets connected to a non-inductive load resistance RL. The power drawn by this resistance will acts as a retarding torque on the armature which will make it slow more quickly.

The additional loss in the resistance will be equal to product of ammeter reading and the average reading of the voltmeter (for a fall of 5% of voltmeterreading, the time is noted.) The ammeter reading is also changing so its average reading is taken. Thus the additional losses is Ia2 (Ra + R). Let t1 be the time when armature is considered alone and t2 be the time when armature is connected across a load resistance, V be average voltage across R and Ia be the average current and W' is additional retarding electrical torque supplied by motor.

If dN i.e. change in speed is same in two cases then

Here dN/dt1 is rate of change in speed without extra load whereas dN/dt2 is rate change in speed with extra electrical load which provides retarding torque.

7.Practice Quiz

1----------- used to determine the direction of rotation of D.C. motor ? [ ]
(a) Lenz's law (b) Faraday's law (c) Coloumb's law (d) Fleming's left-hand rule

2.What will happen if the back e.m.f. of a D.C. motor vanishes suddenly? [ ]

(a) The motor will stop (b) The motor will continue to run (c) The armature may burn (d) The motor will run noisy

3. The mechanical power developed by a shunt motor will be maximum when the ratio of back e.m.f. to applied voltage is [ ]

(a) 4.0 (b) 2.0 (c) 1.0 (d) 0.5

4. The current drawn by the armature of D.C. motor is directly proportional to

(a) the torque required (b) the speed of the motor
(c) the voltage across the terminals (d) none of the above

5.Which D.C. motor will be preferred for machine tools ? [ ]

(a) Series motor (b) Shunt motor
(c) Cumulative compound motor (d) Differential compound motor

6.As -the load is increased the speed of D.C. shunt motor will [ ]

(a) reduce slightly (b) increase slightly (c) increase proportionately (d) remains unchanged

7.No-load speed of which of the following motor will be highest ? [ ]

(a) Shunt motor (b) Series motor
(c) Cumulative compound motor (d) Differentiate compound motor

8.The direction of rotation of a D.C. series motor can be changed by [ ]

(a) interchanging supply terminals (b) interchanging field terminals
(c) either of (a) and (b) above (d) None of the above

9.If a D.C. motor is to be selected for conveyors, which motor would be preferred ? [ ]

(a) Series motor (b) Shunt motor

(c) Differentially compound motor (d) Cumulative compound motor

10. Differentially compound D.C. motors can find applications requiring [ ]

(a) high starting torque (b) low starting torque (c) variable speed (d) frequent on-off cycles

11. Which D.C. motor is preferred for elevators ? [ ]

(a) Shunt motor (b) Series motor
(c) Differential compound motor (d) Cumulative compound motor

12. If a D.C. motor is connected across the A.C. supply it will [ ]

(a) run at normal speed (b) not run
(c) run at lower speed
(d) burn due to heat produced in the field winding by .eddy currents

13. The speed of a D.C. shunt motor more than its full-load speed can be obtained by [ ]

(a) decreasing the field current (b) increasing the field current
(c) decreasing the armature current (d) increasing the armature current

14.The starting resistance of a D.C. motor is generally [ ]

(a) low (b) around 500 ohms (c) 1000 ohms (d) infinitely large

15.Starters are used with D.C. motors because [ ]

(a) these motors have high starting torque (b) these motors are not self-starting
(c) back e.m.f. of these motors is zero initially
(d) to restrict armature current as there is no back e.m.f. while starting

16.A direct on line starter is used: for starting motors [ ]

(a) up to 5 H.P. (b) up to 10 H.P. (c) up to 15 H.P. (d) up to 20 H.P.

17.A three point starter is considered suitable for [ ]

(a) shunt motors (b) shunt as well as compound motors (c) shunt, compound and series motors (d) all D.C. motors

18. Speed control by Ward Leonard method gives uniform speed variation [ ]

(a) in one direction (b) in both directions
(c) below normal speed only (d) above normal speed only

19. Which of the following motor has the poorest speed regulation ? [ ]

(a) Shunt motor (b) Series motor
(c) Differential compound motor (d) Cumulative compound motor

20. The speed of a motor falls from 1100 r.p.m. at no-load to 1050 r.p.m. at rated load. The speed regulation of the motor is [ ]

(a) 2.36% (b) 4.76% (c) 6.77% (d) 8.84%

8.Assignments

S.No	Question	BL	CO
1	1. With a neat sketch, explain the construction and working of a 3-point starter. What are the limitations of 3-point starter?	2	1
2	A 4 Pole, lap wound 750 r.p.m. DC shunt generator has an armature resistance of 0.4 Ω and field resistance of 200 Ω. The armature has 720 conductors and the flux per pole is 30 mWb. If the load resistance is 15 Ω. Determine the terminal voltage.	2	1
3	a. What is the need of starter? With neat diagram, explain the four point starter. b. Explain different methods of speed control of DC shunt motor.	2	1
4	A 220 volts DC Shunt motor on no-load runs at a speed of 1000 RPM and draw a current of 6Amperes.The armature and shunt field resistances are 0.3 ohm and 110 ohms respectively. Calculate the back EMF induced and speed, when loaded and drawing a current of 50 Amperes.	2	1
5	(a) What is critical filed resistance and critical speed. (b) Draw different characteristics of shunt, series and compound motors.	3	1
6	(a) What is an equalizer connection? What is necessity of equalizer connection? (b) An 8-pole, DC generator has per pole flux of 40 mWb and winding is connected in lap with 960 conductors. Calculate the generated EMF on open circuit when it runs at 400 r.p.m. If the armature is wave wound, at what speed must the machine be driven to generate the same voltage.	3	1

9.Part A- Question & Answers

S.No	Question& Answers	BL	CO
1	**What is the necessity of starter in dc motors?** When a dc motor is directly switched on, at the time of starting, the motor back emf is zero. Due to this, the armature current is very high. Due to the very high current, the motor gets damaged. To reduce the starting current of the motor a starter is used.	1	1
2	**Mention the types of braking of dc motor?** **(i)** Regenerative braking **(ii)** Dynamic braking **(iii)** Plugging	1	1
3	**What is the principle of motor?** When a current carrying conductor is placed in a magnetic field it experiences a mechanical force tending to move it	1	1
4	**What are different methods of speed control in DC shunt motor?** (i) Armature control (ii) Flux or field control (iii) Applied voltage control	1	1
5	**When is a four point DC starter required in DC motors?** A four point DC starter is required for dc motor under field control	1	1
6	**How does dc motor differ from dc generator in construction?** Generators are normally placed in closed room and accessed by skilled operators only. Therefore on ventilation point of view they may be constructed with large opening in the frame. Motors have to be installed right in the place of use which may have dust, dampness, Inflammable gases, chemical etc. to protect the motors against these elements the motor frames are used partially closed or totally closed or flame proof.	1	1
7	**How will you change the direction of rotation of dc motor?** Either the field direction or direction of current through armature conductors is to be reversed.	2	1
8	**What is the result if field circuit of a Dc motor is opened?** Due to Weakening of Field flux the armature will race up to abnormally high speeds and the armature windings may get permanently damaged due severe centrifugal forces	2	1
9	**What is the function of no-voltage release coil in d.c. motor starter?** As long as the supply voltage is on healthy condition the current	2	1

	through the NVR coil produceeforce of attraction and retain the starter handle in ON position against spring force. When the supply voltage fails or becomes lower than a prescribed value then electromagnet may not have enough force to retain so handle will come back to OFF position due to spring force automatically.		
10	**Enumerate the factors on which speed of a d.c.motor depends?** N= (V-IaRa)/Φ so speed depends on voltage applied to armature, flux per pole, resistance of armature.	**2**	**1**

10.Part B- Questions

S.No	Question	BL	CO
1	With a neat sketch, explain the construction and working of a 3-point starter. What are the limitations of 3-point starter?	**1**	**1**
2	A 4 Pole, lap wound 750 r.p.m. DC shunt generator has an armature resistance of 0.4 Ω and field resistance of 200 Ω. The armature has 720 conductors and the flux per pole is 30 mWb. If the load resistance is 15 Ω. Determine the terminal voltage.	**2**	**1**
3	a. What is the need of starter? With neat diagram, explain the four point starter. b. Explain different methods of speed control of DC shunt motor.	**2**	**1**
4	A 220 volts DC Shunt motor on no-load runs at a speed of 1000 RPM and draw a current of 6 Amperes.The armature and shunt field resistances are 0.3 ohm and 110 ohms respectively. Calculate the back EMF induced and speed, when loaded and drawing a current of 50 Amperes.	**3**	**1**
5	(a) What is critical filed resistance and critical speed. (b) Draw different characteristics of shunt, series and compound motors.	**3**	**1**

DC MACHINES & TRANSFORMERS (20A02302T)

UNIT-IV

Single Phase Transformers

LECTURE NOTES

1. Course Objectives

The objectives of this course is to

a. The constructional features of DC machines and different types of windings employed in DC machines.
b. Characteristics of generators and parallel operation of generators.
c. Methods for speed control of DC motors and application of DC machines.
d. The Constructional Features of transformers, Predetermination of regulation and efficiency of transformers.
e. Various tests on single phase and three phase transformers and parallel operation of transformers.

2.Syllabus

UNIT 4

Single Phase Transformers

Principle, construction and operation of single-phase transformers, equivalent circuit, phasor diagrams(no load and on load), Magnetizing current, effect of nonlinear B-H curve of magnetic core material, harmonics in magnetization current, losses and efficiency Testing - open circuit and short circuit tests, voltage regulation, Sumpner's test, separation of hysteresis and eddy current losses. Paralleloperation of single-phase transformers, Autotransformers - construction, principle, applications and comparison with two winding transformer.

3.Course outcomes

1. **Apply** the knowledge of magnetic material properties and fundamentals of energy conversion principles.
2. **Identify** the working principle of Dc machines & Transformers with mechanism and various operations performed
3. **Illustrate** the characteristics of various DC machines & Transformers with various operational conditions to determine efficiency & regulation.
4. **Evaluate** the performance & losses of Machines with help of various testing methods like OCC, speed control and OC & SC test.
5. **Explain** & **analyse** the parallel operation of DC machines & Transformers, Scott connections and phase conversions of transformers.

4.Lecture Notes

4.1 INTRODUCTION:

- A transformer is ‘‘a static device which is used to transfer power from one electric circuit to other electric circuit at constant frequency and power”.
- Transformer operates on **mutual inductance** principle.
- During the power transfer, the voltages are either increase or decrease simultaneously the currents are decrease or increase to maintain constant power.
- Transformer is a **singly excited** device and works for **time varying field (a.c.),** produces **statically induced emf**.
- It essentially consists of two windings (HV and LV), the winding connected to the a.c. source is called primary winding and the one connected to load is called secondary winding.
- The single- or three-phase transformers with ratings up to 500 kVA are defined as distribution transformers, whereas those transformers with ratings over 500 kVA are defined as power transformers.
- Constructionally, there are two types of transformers,
  1. Core type transformer
  2. Shell type transformer
- Whenever a conductor placed in a time varying magnetic field emf in a conductor according to faradays law of electromagnetic induction. This type of emf is known as statically induced emf.

$$E_{rms} = 4.44\phi_m fN \quad \text{volts}$$

4.2 TRANSFORMER CONSTRUCTION:

The various main components of a simplified transformer explained as follows:

Tank

- The tank of a transformer is made with steel, contains the transformer core and coil assembly.
- It is filled with transformer oil that is used as an insulating and cooling medium.

Transformer Core and Coils

- The transformer core is made with ferromagnetic material which having high permeability, it provides magnetic circuit to link the transformer windings.
- The transformer windings made with copper, provide the electrical circuit, the current flow in the transformer.

- The source winding is known as primary winding and the load winding is known as secondary winding.

Bushings

- A bushing provides an insulated entrance for the conductor into the transformer, it is made with porcelain.

Conservator tank:

- On larger transformers, a reservoir of oil is maintained in a tank at a level above the cover of the transformer which is connected to the transformer by a pipe.
- The conservator tank keeps the main tank completely full of oil at all times, permitting expansion and contraction of transformer oil.
- An oil level indicator with an alarm circuit is provided to indicate the oil level in the conservator tank.

Breather

- The conservator tank has a breather to the outside. In order to take care of the expansion and contraction of the cooling oil external disturbances, prevent the entry of moisture, snow, etc., into the transformer.

Gas Relay

- The gas (Buchhoz) relay is located at the top of the transformer and is used to detect gas or air in the transformer.

TRANSFORMER CORE

- Transformer core made with Ferro magnetic material (silicon) and it should have high permeability which helps to give a low reluctance path for the flux.
- Silicon steel sheets usually used in order to reduce the magnetic losses (hysteresis and eddy current losses).
- In transformer, the magnetic cores are made up of stacks of laminations cut from silicon-steel sheets. Silicon-steel sheets usually contain about 3% silicon and 97% steel to reduce magnetizing losses.
- Better magnetic properties are obtained by Cold Rolled Grain Oriented (CRGO) process.
- The core is properly staged without any empty space; otherwise there is a noise present in the transformer due to magnetostriction.
- To minimize the use of copper and decrease copper loss, the magnetic cores of large transformers are built in stepped cores, as shown in Figure.

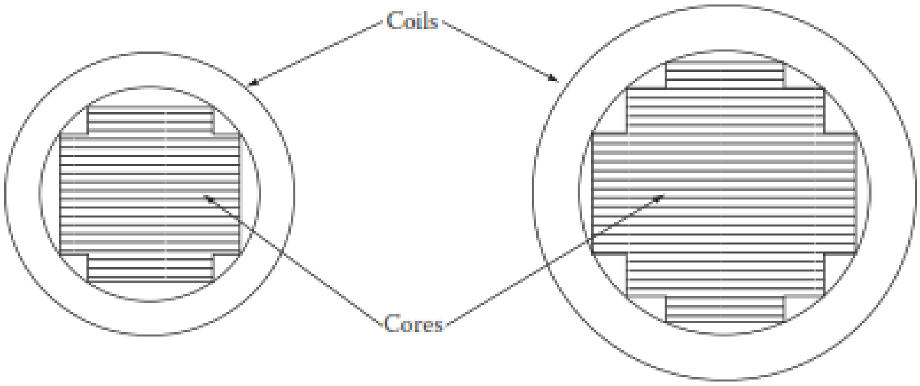


Fig. 3.1. Types of trnsformer core

4.3 TYPES OF TRANSFORMERS:

Constructionally, the transformers are two types, these are differ the primary and secondary coils are placed around the transformer core. The two types are known as

1. **Core-type**
2. **Shell type.**

Core Type **Shell Type**

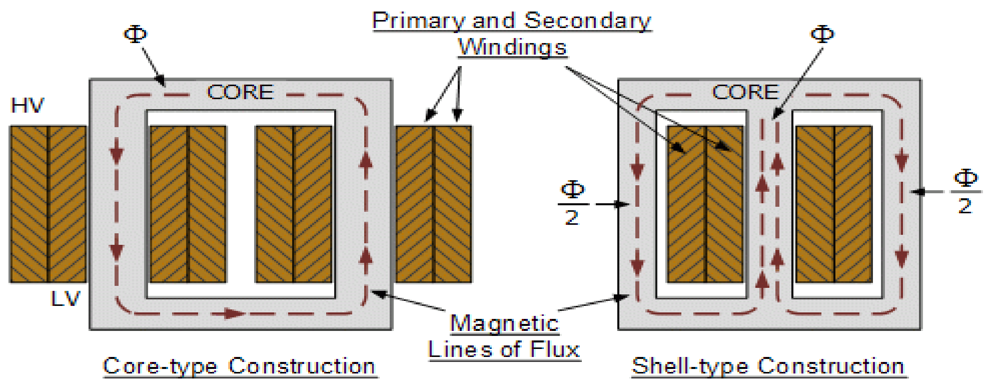


Fig. 3.2. Types of trnsformer based on core

1. Core Sounded by winding	1. Winding is surrounding by the core
2. For the passage of the flux only single path is present (series magnetic circuit)	2. For the passage of flux two paths are present (parallel magnetic circuit)
3. Area of cross section of two legs are equal	3. Area of cross section of outer legs is half of the area of cross section of central leg.
4. Leakage flux is high	4. Leakage flux is less
5. Mechanical strength is less	5. Mechanical strength is high
6. Regulation is high since leakage reactance is high	6. Regulation is less since leakage reactance is less
7. Less insulating material is required	7. More insulating material is required
8. It is used for high voltage applications	8. It is used for low voltage applications
9. More copper material is required	9. Less copper material is required
10. It is used for low current applications	10. It is used for high current applications.

N

Advantages of placing LV winding near to the transformer:

1. It requires less amount of insulation
2. Easily placing tapping's on HV windings.
3. It reduces the cost.

Leakage flux:

The flux which cuts either LV or HV winding is known as leakage flux. If flux cuts both HV and LV winding known as common flux or useful flux

4.4 EMF EQUATION (or) TRANSFORMER PRINCIPLE

- Transformer works on the principle of MUTUAL INDUCTANCE.
- When the time varying magnetic field is applied to the stationary conductors, statically induced emf is produced according to faraday's law of electromagnetic induction.
- Due to the time varying magnetic field, the emf produced in its neighbouring coil due to mutual inductance principle.

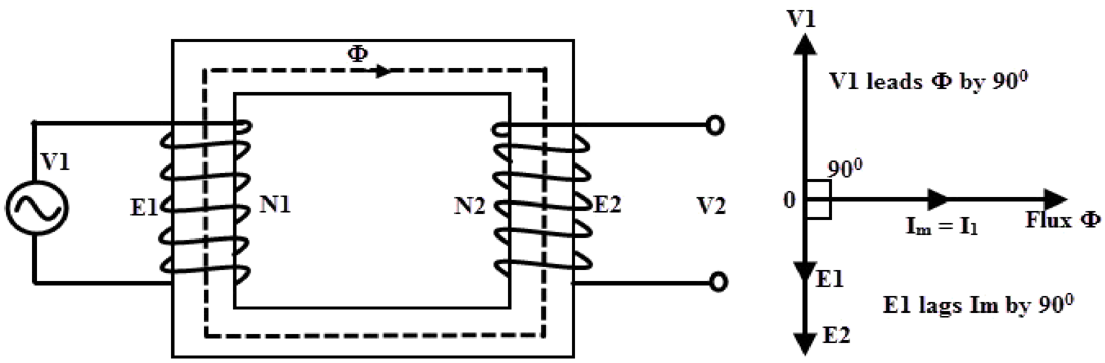


Fig. 3.3. Transformer under No-load

- When AC voltage V(t) is applied to the HV winding it produces flux $\phi(t)$ in the transformer core so, according to faraday's law. EMF in HV winding is given by,

$$e_1(t) \alpha \frac{d\psi}{dt}$$

$$\psi = N_1 \phi(t) \qquad \phi(t) = \phi_m \sin \omega t$$

$$e_1(t) = -\frac{d\psi}{dt} = -N_1 \frac{d\Phi}{dt} = -N_1 \Phi_m \omega \cos\omega t = N_1 \Phi_m \omega \sin(\omega t - \frac{\pi}{2})$$

$$at \quad \omega t = 180^0$$

$$e_{1max} = N_1 \Phi_m \omega \, ,$$

$$e_{1rms} = \frac{e_{1max}}{\sqrt{2}} = \frac{N_1 \Phi_m 2\pi f}{\sqrt{2}}$$

$$E_1 = e_{1rms} = 4.44 \phi_m f N_1 \quad \text{volts}$$

$$\phi_m = B_m A$$

$$E_{rms} = 4.44 B_m A f N_1 \quad \text{volts}$$

- According to mutual inductance principle, due to $\phi(t)$ EMF induced in LV winding,

$$e(t) = -\frac{d\psi}{dt} = -N_2\frac{d\Phi}{dt} = -N_2\Phi_m\omega\cos\omega t = N_2\Phi_m\omega\sin(\omega t - \frac{\pi}{2})$$

$$\psi = N_2\,\phi(t)$$

$$\text{at } \omega t = 180^0 \qquad e_{2\,max} = N_2\Phi_m\omega$$

$$e_{2rms} = \frac{e_{2\,max}}{\sqrt{2}} = \frac{N_2\Phi_m 2\pi f}{\sqrt{2}}, \qquad \phi_m = B_m A$$

$$E_2 = e_{2rms} = 4.44 B_m A f N_2 \quad \text{volts}$$

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 B_m A f = 4.44\phi_m f$$

- In case of transformer induced emf per number of turns is constant for both HV and LV windings.

$$N_1 > N_2 \Rightarrow E_1 > E_2 \Rightarrow \text{step down transformer}$$

$$N_1 < N_2 \Rightarrow E_1 < E_2 \Rightarrow \text{step up transformer}$$

$$N_1 = N_2 \Rightarrow E_1 = E_2 \Rightarrow \text{isolation (or) one to one transformer}$$

Transformer under No Load (Ideal Transformer)

$$V(t) = V_m\sin(\omega t + \frac{\pi}{2})$$

$$\phi(t) = \Phi_m\sin\omega t$$

$$e_1(t) = N_1\Phi_m\omega\sin(\omega t - \frac{\pi}{2})$$

$$e_2(t) = N_2\Phi_m\omega\sin(\omega t - \frac{\pi}{2})$$

Transformation Ratio: $\frac{N_2}{N_1} = \frac{E_2}{E_1} = K = \frac{I_1}{I_2}$

Turns ratio: $\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{1}{K} = \frac{I_2}{I_1}$

4.5 TRANSFORMER OPERATION UNDER NO LOAD AND LOAD CONDITION:

Consider a transformer with two windings, a primary winding of N1 turns and a secondary winding of N2 turns, as shown in Figure. Assume that the transformer is an ideal transformer with the following properties:

1. It requires infinite amount of permeability.
2. Core losses is zero
3. The winding resistances are zero.
4. Leakage flux will be zero.
5. The B-H curve is linear.

Transformer under No Load Condition:

Fig. 3.4.

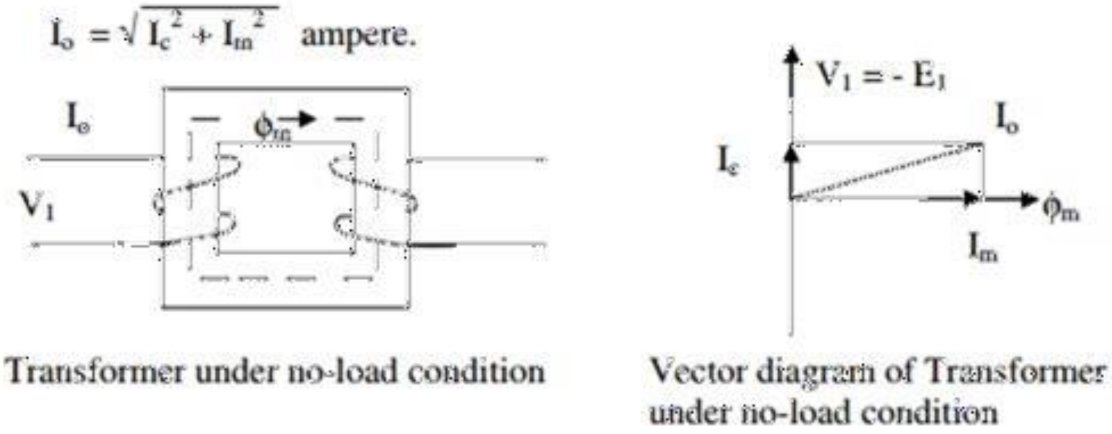


Fig. 3.4. Trnasformer under no-load condition

- The AC voltage V(t) is applied to the transformer HV winding due to finite permeability I_μ links with N_1turns. The resultant MMF is $N_1 I_\mu$.
- Due to the MMF produces the time varying magnetic field $f(t)=\Phi_m \sin\omega t$
- According to Faradays law of electromagnetic induction, the self-induced EMF induced in HV winding. $e_1(t)=N_1\Phi_m\omega\sin(\omega t-\frac{\pi}{2})$
- The mutual induced EMF is, $e_2(t)=N_2\Phi_m\omega\sin(\omega t-\frac{\pi}{2})$
- Due to the losses occurring in the transformer active component of current I_w add with I_μ. Resultant $I_0=I_\mu+I_w$
- Where I_w is active component of current, it is in phase with the supply voltage.
- Where I_μ is reactive component of current, it is 90^0 lagging with supply voltage.
- Here the $I_\mu >> I_w$.

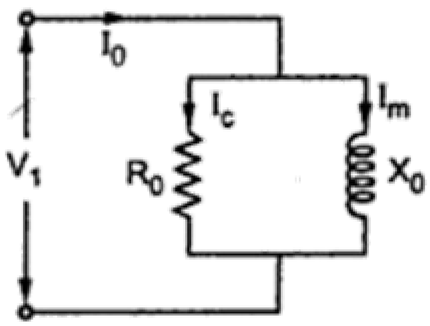


Fig. 3.5. Equivalent Circuit of Trnasformer under no-load condition

Transformer under Load Condition:

- When the load is applied, secondary current I_2 flown in the circuit due to the closed circuit

- The secondary current I_2 links with N_2 number of turns and the resultant MMF is N_2I_2. This MMF produces the flux ϕ_2 which opposes the main field flux according to Lenz's law.

- The resultant flux in the transformer core decreases, simultaneously reduces the EMF E_1 and E_2
- But the supply voltage V and E_1 both are in parallel. So, need to maintain the constant voltage, for that reason in order to nullify the flux ϕ_2 the primary winding takes some additional current I_1^1 from the source.

- Due to $I_1^1 \Rightarrow MMF = N_1 I_1^1$
- Due to $MMF \Rightarrow flux \Rightarrow \phi_1^1$, Now the flux ϕ_1^1 opposing ϕ_2

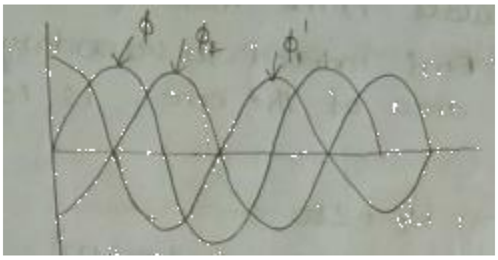


Fig. 3.6. Transformer core flux under reunning condition

- Hence the flux in the transformer core is constant even under load condition.

$$I_0 = I_\mu + I_w$$

$$I_1 = I_0 + I_1^1$$

$$I_1 = I_0 + KI_2$$

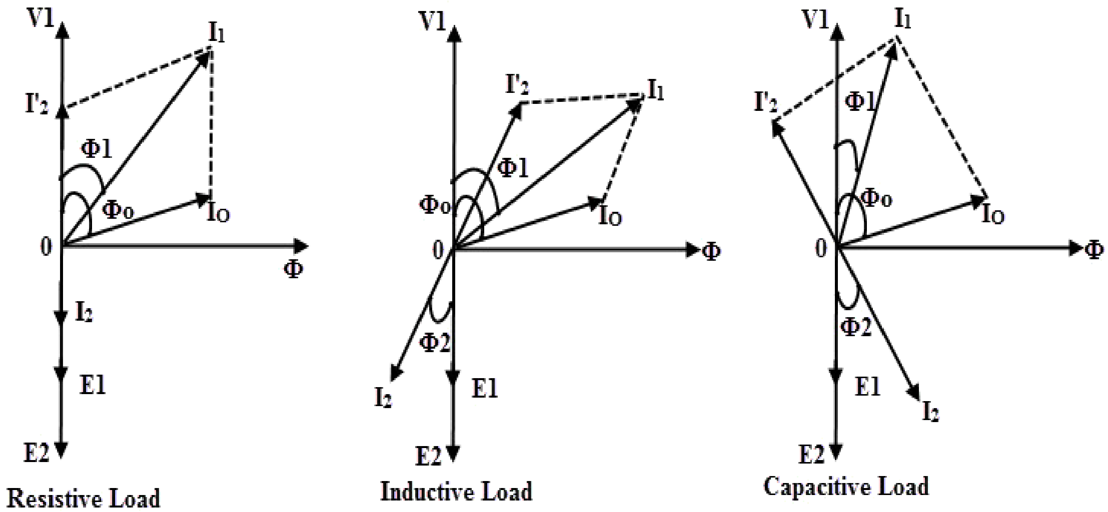


Fig. 3.7. Transformer phasor diagram under reunning condition

4.6 EQUIVALENT CIRCUIT:

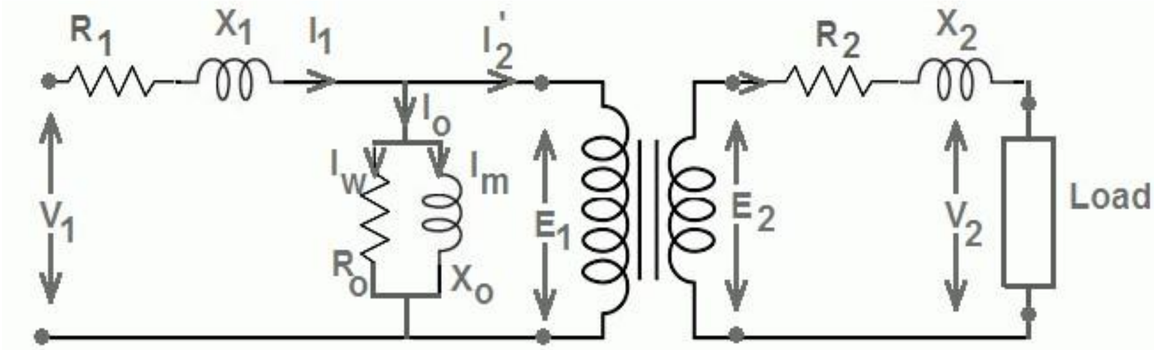


Fig. 3.8. Transformer equivalent circuit under reunning condition

Where $V(t)=V_m \sin(\omega t+\frac{\pi}{2})$ input supply given to the HV winding.

$I_0 \Rightarrow$ noload current

$I_1^1 \Rightarrow$ additionalcurrent taken fromsource tosatisfylenz's law

$I_1 \Rightarrow$ Primarycurrent

$I_1 = I_0 + I_1^1$

Where, $I_0 = I_\mu + I_w$,

$I_w \Rightarrow$ Activecomponent of current $= I_0 \cos\phi_0$

$I_\mu \Rightarrow$ Reactivecomponent of current $= I_0 \sin\phi_0$

ϕ_0 is the angle between supply voltage and no-load current.

Apply KVL to the circuit,

$V_1 = -E_1 + I_1^1(R_1 + jX_1)$, $E_2 = V_2 + I_2(R_2 + jX_2)$

$R_1, R_2 \Rightarrow$ primaryandsecondary winding resistances

$X_1, X_2 \Rightarrow$ primaryandsecondary winding reactances

Equivalent resistance referred to primary winding:

$$R_{01} = R_1 + R_2^1 = \left[R_1 + \frac{R_2}{K^2}\right] \qquad \left(I_2^2 R_2 = I_1^2 R_2^1 \Rightarrow R_2^1 = \frac{I_2^2 R_2}{I_1^2} = \frac{R_2}{K^2}\right)$$

Equivalent resistance referred to secondary winding:

$$R_{02} = R_2 + R_1^1 = \left[R_2 + K^2 R_1\right] \qquad \left(I_1^2 R_1 = I_2^2 R_1^1 \Rightarrow R_1^1 = \frac{I_1^2 R_1}{I_2^2} = K^2 R_1\right)$$

Equivalent reactance referred to primary winding:

$$X_{01} = X_1 + X_2^1 = \left[X_1 + \frac{X_2}{K^2}\right] \qquad \left(\frac{I_2 X_2}{E_2} = \frac{I_1 X_2^1}{E_1} \Rightarrow X_2^1 = \frac{X_2}{K^2}\right)$$

Equivalent reactance referred to secondary winding:

$$X_{02} = X_2 + X_1^1 = \left[X_2 + K^2 X_1\right] \quad \left(\frac{I_1X_1}{E_1} = \frac{I_2X_1^1}{E_2} \Rightarrow X_1^1 = K^2 X_1\right)$$

Equivalent impedance referred to primary:

$$R_{01} + jX_{01} = \left[R_1 + \frac{R_2}{K^2}\right] + j\left[X_1 + \frac{X_2}{K^2}\right] = \left(R_1 + R_2^1\right) + j\left(X_1 + X_2^1\right)$$

Equivalent impedance referred to secondary:

$$R_2 + jX_{02} = \left(R_2 + R_1K^2\right) + j\left(X_2 + K^2X_1\right) = \left(R_2 + R_1^1\right) + j\left(X_2 + X_1^1\right)$$

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2} \qquad Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$$

4.7 LOSSES IN TRANSFORMER:

- Transformer is a static device. Hence there are no friction and Windage losses.
- Major losses in transformer are

1. Core losses → Hysterisis losses
   → eddycurrent losses

2. Copper losses

Hysteresis losses:

- This loss occur due to reversal of magnetization of transformer core whenever its subjected to alternating nature of magnetic core.

$$W_h = \eta B_m^{1.6} f V$$

When $\frac{V}{f}$ = constant then $W_h = Af$

Otherwise $W_h = AV^{1.6}f^{-0.6}$

Eddy current losses:

- Eddy current losses are basically I^2R losses produce in core due to presence of eddy currents in the core

Because of its conductivity

$$W_e = KB_M^2 f^2 t^2 \quad \left[\because W_e \alpha \sigma\right]$$

When $\frac{V}{f}$ = constant then, $W_e = Bf^2$

Otherwise $W_e = BV^2$

- Finally, when $\frac{V}{f}$ = constant, $w_i = Af + Bf^2$
- Otherwise, $w_i = AV^{1.6} f^{-0.6} + BV^2$
- The flux in the transformer core constant irrespective of the load. Hence core losses are treated as constant losses

Copper losses:

- Total copper in transformer = $I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} = I_2^2 R_{02}$
- Copper losses at 'x' at load = $x^2 *$ copper losses
- Copper losses depend upon loading condition. Hence copper losses treated as variable losses.
- Per unit resistance of transformer equal to the per unit full load copper lasses.
- At maximum efficiency copper losses equal to the iron losses

Minor losses

- In case of solid conductor due to the presence of stray currents additional I^2R losses present treated as copper stray load losses
- Copper stray load losses are reduced by using stranded conductor
- Iron stray load losses are occur due to leakage flux present in the inactive parts. Losses are reduced by using distributed windings on the transformer limbs

Rating of Transformer:

- Two types of major losses are present in the transformer these losses are wasted as heat and temperature of the transformer rises
- For fixed cooling system rating of any electrical machine decided by temperature rise of the machine.
- In transformer copper loss depends on current and iron loss depends on voltage, total loss depends on volt – ampere
- That's why rating of transformers in KVA and not in KW.

4.8 EFFICIENCY OF TRANSFORMER

- Practical transformer consist mainly two types of losses namely core and copper losses.
- Efficiency is defined as

$$\eta = \frac{output\ power\ in\ kw}{output\ power\ in\ kw + core loss + copper\ loss}$$

- Efficiency of transformer for general loading, $\eta = \frac{XS\cos\phi}{XS\cos\phi + P_{core} + X^2 P_{cu}}$
- Maximum efficiency of transformer occurs when copper losses equal to the iron losses.

i.e $X^2 P_{cu} = p_{core}$,loading for η_{max}: $X = \sqrt{\frac{P_{core}}{P_c}}$

- At maximum efficiency total losses equal two times core losses.
- If the power factor of the load is kept constant and degree of loading of the transformer is varied, load curve as shown in figure.
- Transformer was operate at maximum efficiency when it's loaded to $\sqrt{\frac{P_{core}}{P_{cu}}}$ S KVA

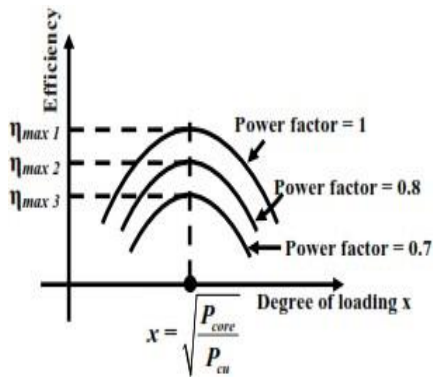


Fig. 3.9. Efficiency of transformer with variation of load

4.9 VOLTAGE REGULATION

- The change in secondary terminal voltage from no load to full load at a specific power factor and the change is expressed as % of fraction of no load secondary voltage

  $V_2 \Rightarrow$ Full load secondary terminal voltage

  $V_{20} \Rightarrow$ no load secondary terminal voltage

- Regulation = $\frac{V_{20} - V_2}{V_{20}}$
- In the secondary winding of the transformer

$$E_2 = V_2 + I_2 (R_{02} + jX_{02})$$

$$E_2 - V_2 = I_2 (R_{02} + jX_{02})$$

when the load is inductive $\quad I_2 = I_2 \angle -\phi_2 = I_2 (\cos\phi_2 - j\sin\phi_2)$

when the load is capacitive $\quad I_2 = I_2 \angle \phi_2 = I_2 (\cos\phi_2 + j\sin\phi_2)$

- At a specific power factor, Regulation = $\frac{I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}{V_{20}}$

$$= \left(\frac{I_2 R_{02}}{V_{20}}\right)\cos\phi \pm \left(\frac{I_2 X_{02}}{V_{20}}\right)\sin\phi$$

= (P.U. Resistance drop) $\cos\phi \pm$ (P.U. Reactance drop) $\sin\phi$

% regulation = $\%R\cos\phi \pm \%X\sin\phi$

Here '+' for lagging

'-' for leading

Condition for maximum regulation

- It's possible only for lagging power factor load's

$$\frac{d(reg)}{d\phi} = 0 \Rightarrow -\%R\sin\phi + \%\cos\phi = 0$$

$$\tan\phi = \frac{\%X}{\%R}$$

Value of maximum regulation $=\%R\left[\frac{\%R}{\%Z}\right]+[\%X]\left[\frac{\%X}{\%Z}\right] = \%Z$

Condition for zero voltage regulation

- It's possible only for leading power factor loads

Voltage regulation = 0

$$\%R\cos\phi - \%X\sin\phi = 0$$

$$\tan\phi = \frac{\%R}{\%X}$$

- At zero voltage regulation:

$$\cos\phi = \frac{\%X}{\%Z}; \qquad \phi_{load} + \theta = 90^o$$

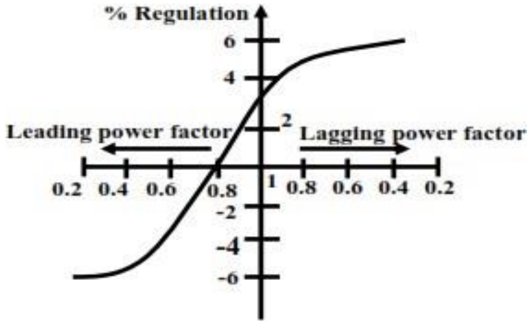


Fig. 3.10. Voltage regulation curve of transformer

- % regulation at U.P.F = % R= % full load copper losses.
- A typical plot of regulation verses power factor for rated current as shown in figure.

4.10 TESTING OF TRANSFORMER

Determination of equivalent circuit parameters

- If the complete design data of a transformer are available, the necessary parameters can be computed from the dimensions and properties of the materials used.
- Two tests performed to determine the parameters of the equivalent circuit.
- These two tests are known as the **open-circuit** test and the **short-circuit** test.

4.10.1 OPEN-CIRCUIT TEST:

- The **c**onnection diagram for open circuit test as shown in figure.

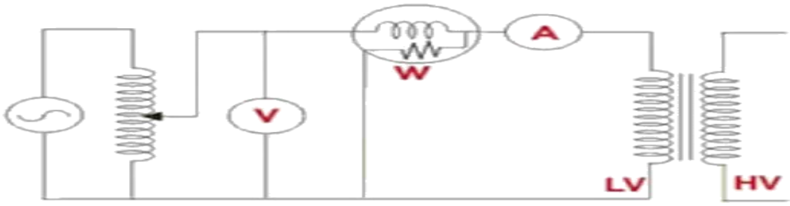


Fig. 3.11 Open circuit test of transformer

- In order to flow the rated flux in the transformer core applying rated voltage and rated frequency with the help of variac on LV side.
- The HV side of the transformer is kept open.
- After the reading the rated LV side voltage, note down the all meter readings.
- The wattmeter reading : $W_0 = V_0 I_0 \cos\phi_0 = \text{corelosses}$

$$\Rightarrow \cos\phi_o = \frac{W_o}{V_i I_0} \qquad \sin\phi_o = \sqrt{1-\cos^2\phi_0}$$

$I_W \Rightarrow$ Activecomponent of current $= I_0 \cos\phi_0$

$I_\mu \Rightarrow$ Reactivecomponent of current $= I_0 \sin\phi_0$

- During the open circuit test transformer efficiency is zero, because the input of the transformer becomes iron losses.
- The purpose of the OC test is to calculate iron losses and load parameters R_0, X_0

$$R_0 = \frac{V}{I_W} \qquad X_0 = \frac{V}{I_\mu}$$

- During the OC test neglecting the Copper losses because very small amount of current flowing in the transformer windings.

Note: why the OC test conducted on LV side by keeping the HV winding open

- In order to accurate measures 5 to 10% of full load current during open circuit.
- To get the rated flux, OC test requires rated voltage.
- Hence in the low voltage winding the no load current is higher value, the rated voltage is lesser value, that's why OC test conducted on LV side rather than HV side.

4.10.2 SHORT CIRCUIT TEST

- This test is performed by short-circuiting one winding (usually the low-voltage winding) and applying a *reduced* voltage to the other winding, as shown in Figure.
- Short circuit test is generally carried out by energizing the HV side with LV side shorted.
- Voltage applied is such that the *rated* current flows in the windings.
- Voltmeter, ammeter and the wattmeter readings are noted corresponding to the rated current of the windings.

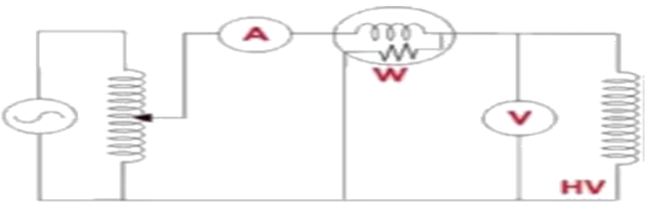


Fig. 3.11 Short circuit test of transformer

- Core loss is negligibly small compared to the winding copper losses as rated current flows in the windings. Magnetizing current too small.

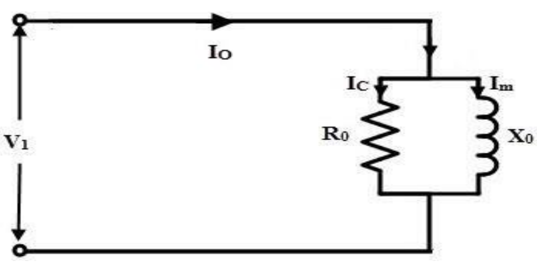


Fig. 3. 12 The equivalent circuit of the transformer under OC test

1. Wattmeter reading ≈Full load copper losses

2. $W_{sc}=I_{sc}^2R_{01} \Rightarrow R_{01}=\frac{W_{sc}}{I_{sc}^2}$, $Z_{01}=\frac{V_{sc}}{I_{sc}}$ $R_{01}=\sqrt{Z_{01}^2-R_{01}^2}$ $\cos\phi_{sc}=\frac{R_{01}}{Z_{01}}$

(approximately 0.5 to 0.6)

3. % R = % full load copper losses

$\% Z = \frac{V_{sc}}{E_1}\times 100$ $\quad \%X=\sqrt{(\%Z)^2-(\%R)^2}$

4.11 SUMPNER TEST/BACK-TO-BACK TEST/TYPE TEST/HEAT RUN TEST

- This test provides data for finding the regulation, efficiency and heating under load conditions and is employed only when two similar transformers are available.
- One transformer is loaded on the other and both are connected to supply. The power taken from the supply is that necessary for supplying the losses of both transformers and the negligibly small loss in the control circuit.
- As shown in Figure, **primaries of the two transformers are connected in parallel** across the same a.c. supply.
- With switch *S* open, the wattmeter W_1 reads the core loss for the two transformers. Similar to open circuit test.
- The **secondaries are so connected that their potentials are in opposition** to each other.
- Hence, *W* 1 continues to read the core loss and *W* 2 measures full-load Cu loss (or at any other load current value *I*2). Obviously, the power taken in is twice the losses of a single transformer.
- Calculating efficiency at any fraction of load by usingabove wattmeter readings as,

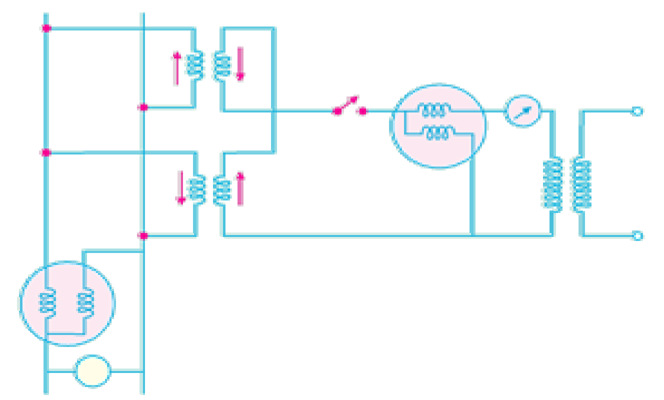


Fig. 3. 12. Circuit diagram for Sumpner's test

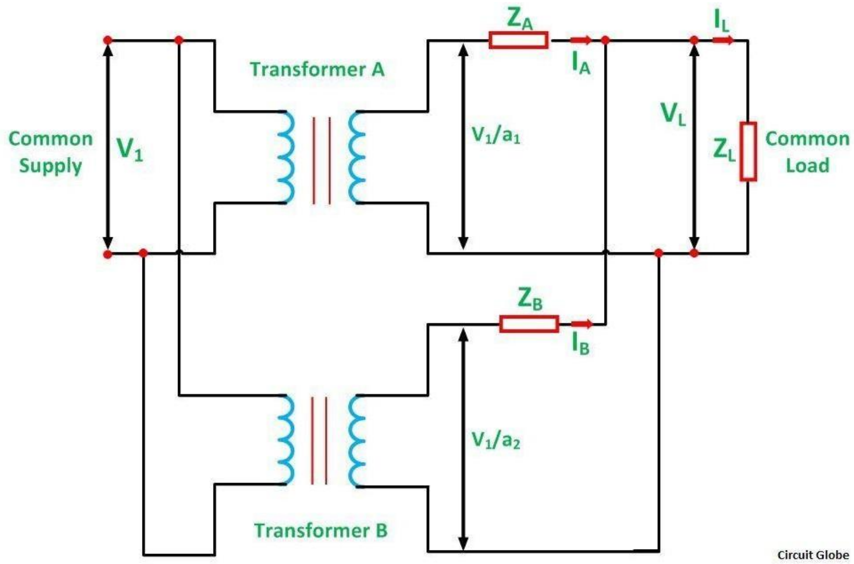
$$\%\eta_{of\ F.L}=\frac{X\,VI\cos\phi}{XVI\cos\phi+X^{2}W^{2}+W_1}$$

2 2

- The accuracy of this transformer depends on identity of both transformers.

4.12 Parallel Operation Of Single Phase Transformers

Parallel Operation of a Single Phase Transformer means that the two or more transformers having the same polarities, same turn ratios, same phase sequence and the same voltage ratio are connected in parallel with each other.
The circuit diagram of two single-phase transformer A and B connected in parallel are shown below:



Let,
a1 is the turn ratio of the transformer A
a2 is the turn ratio of transformer B
ZA is the equivalent impedance of the transformer A referred to secondary
ZB is the equivalent impedance of the transformer B referred to secondary
ZL is the load impedance across the secondary
IA is the current supplied to the load by the secondary of the transformer A
IB is the current supplied to the load by the secondary of the transformer B
VL is the secondary load voltage
IL is the load current
Applying Kirchhoff’s Current Law,

$$I_A + I_B = I_L \dots\dots\dots(1)$$

By Kirchhoff’s Voltage Law,

$$V_L = \frac{V_1}{a_1} - I_A Z_A \dots\dots\dots(2) \text{ and}$$

$$V_L = \frac{V_1}{a_2} - I_B Z_B \dots\dots\dots(3)$$

Now putting the value of IB from the equation (1) in equation (3) we will get,

$$V_L = \frac{V_1}{a_2} - (I_L - I_A)\ Z_B \ldots\ldots\ldots(4)$$

Solving equations (2) and (4) we will get,

$$I_A = \frac{Z_B I_L}{Z_A + Z_B} + \frac{V_1\ (a_2 - a_1)}{a_1 a_2\ (Z_A + Z_B)} \ldots\ldots\ldots(5)$$

$$I_B = \frac{Z_A I_L}{Z_A + Z_B} + \frac{V_1\ (a_2 - a_1)}{a_1 a_2\ (Z_A + Z_B)} \ldots\ldots\ldots(6)$$

The current IA and IB have two components. The first component represents the transformers share of the load currents and the second component is a circulating current in the secondary windings of the single-phase transformer.
The undesirable effects of the circulating currents are as follows

- They increase the copper loss.
- The circulating current overloads the one transformer and reduce the permissible load kVA.

Equal Voltage Ratio
In order to eliminate circulating currents, the voltage ratios must be identical. That is a1=a2

Under this condition,

$$I_A = \frac{Z_B I_L}{Z_A + Z_B} \ldots\ldots\ldots(7)$$

$$I_B = \frac{Z_A I_L}{Z_A + Z_B} \ldots\ldots\ldots(8)$$

Equating equation (7) and (8) we will get:

$$\frac{I_A}{I_B} = \frac{Z_B}{Z_A} \ldots\ldots\ldots(9)$$

From the above equation (9), it is clear that the transformer currents are inversely proportional to the transformer impedance. Thus, for the efficient parallel operation of the two single-phase transformers, the potential differences at full load across the transformer internal impedance should be equal.
This condition ensures that the load sharing between the two single-phase transformer is according to the rating of each transformer. If the per-unit equivalent impedance are not equal, then the transformer will not share the load in proportion to their kVA ratings. As a result, the overall rating of the transformer bank will be reduced.
Equation (9) can also be written as

$$I_A Z_A = I_B Z_B \ldots\ldots\ldots(10)$$

The current in the equations (7) and (8) is changed into volt-amperes by multiplying the two equations by the common load voltage VL.
Therefore, we know that,
The total load in volt-ampere (VA) is

$$S_L = V_L I_L$$

The volt-ampere of transformer A is

$$S_A = V_L I_A$$

Similarly, the volt-ampere of transformer B is

$$S_B = V_L I_B$$

Hence, the various equations will be written as shown below

$$S_A = \frac{Z_B}{Z_A + Z_B} S_L \quad \dots\dots\dots.(11)$$

$$S_B = \frac{Z_A}{Z_A + Z_B} S_L \quad \dots\dots\dots.(12)$$

Equating the equation (11) and (12) we will get

$$\frac{S_A}{S_B} = \frac{Z_B}{Z_A} \quad \dots\dots\dots.(13)$$

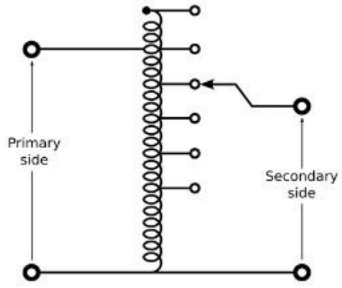
Equation (13) tells that the volt-ampere load on each single-phase transformer is inversely proportional to its impedance.
Hence, to share the load in proportion to their ratings, the transformers should have the impedance which is inversely proportional to their ratings.

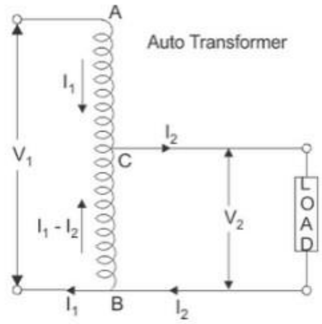
4.13 Auto Transformer- Construction & Principle

An **autotransformer** (or **auto transformer**) is a type of electrical transformer with only one winding. The "auto" prefix refers to the single coil acting alone (Greek for "self") – not to any automatic mechanism. An auto transformer is similar to a two winding transformer but varies in the way the primary and secondary winding of the transformer are interrelated.

Autotransformer Theory

In an auto transformer, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose. A circuit diagram of auto transformer is shown below.





The winding AB of total turns N1 is considered as primary winding. This winding is tapped from point 'C' and the portion BC is considered as secondary. Let's assume the number of turns in between points 'B' and 'C' is N2.

If V1 voltage is applied across the winding i.e. in between 'A' and 'C'. $So\ voltage\ per\ turn\ in\ this\ winding\ is\ \frac{V_1}{N_1}$

Hence, the voltage across the portion BC of the winding, will be, $\frac{V_1}{N_1} X N_2\ and\ from\ the\ figure\ above,\ this\ voltage\ is\ V_2$

$$Hence,\ \frac{V_1}{N_1} X N_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = Constant = K$$

As BC portion of the winding is considered as secondary, it can easily be understood that value of constant 'k' is nothing but turns ratio or voltage ratio of that **auto transformer**. When load is connected between secondary terminals i.e.between 'B' and 'C', load current I2 starts flowing. The current in the secondary winding or common winding is the difference of I2 and I1.

Copper Savings in Auto Transformer

Now we will discuss the savings of copper in auto transformer compared to conventional two winding transformer.

We know that weight of copper of any winding depends upon its length and cross-sectional area. Again length of conductor in winding is proportional to its number of turns and cross-sectional area varies with rated current.So weight of copper in winding is directly proportional to product of number of turns andrated current of the winding.

Therefore, weight of copper in the section AC proportional to,and $(N_1 - N_2)I_1$

similarly, weight of copper in the section BC proportional to,

Hence, total weight of copper in the winding of auto transformer proportional to,
$(N_1 - N_2)I_1 + N_2(I_2 - I_1)$

$\Rightarrow N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1$

$\Rightarrow N_1I_1 + N_2I_2 - 2N_2I_1$

$\Rightarrow 2N_1I_1 - 2N_2I_1(Since,\ N_1I_1 = N_2I_2)$

$\Rightarrow 2(N_1I_1 - N_2I_1)$

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,
$N_1I_1 - N_2I_2$

$\Rightarrow 2N_1I_1 \qquad (Since,\ in\ a\ transformer\ N_1I_1 = N_2I_2)$

N1I1 + N2I2

⇒2N1I1 (Since, in a transformer N1I1 = N2I2)

Let's assume, Wa and Wtw are weight of copper in auto transformer and two winding transformer respectively,

$$Hence,\ \frac{W_a}{W_{tw}} = \frac{2(N_1I_1 - N_2I_1)}{2(N_1I_1)}$$

$$= \frac{N_1I_1 - N_2I_1}{N_1I_1} = 1 - \frac{N_2I_1}{N_1I_1}$$

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

$$\therefore W_a = W_{tw}(1 - k)$$

$$\Rightarrow W_a = W_{tw} - kW_{tw}$$

∴ Saving of copper in auto transformer compared to two winding transformer,
$\Rightarrow W_{tw} - W_a = kW_{tw}$

Auto transformer employs only single winding per phase as against two distinctly separate windings in a conventional transformer.

Advantages of using Auto Transformers

The advantages of an auto transformer include:

1. For transformation ratio = 2, the size of the **auto transformer** would be approximately 50% of the corresponding size of two winding transformer. For transformation ratio say 20 however the size would be 95 %. The saving in cost of the material is of coursenot in the same proportion. The saving of cost is appreciable when the ratio of transformer is low, that is lower than 2. Thus auto transformer is smaller in size and cheaper.
2. An auto transformer has higher efficiency than two winding transformer. This is because of less ohmic loss and core loss due to reduction of transformer material.
3. Auto transformer has better voltage regulation as voltage drop in resistance and reactance of the single winding is less.

Disadvantages of Using Auto Transformer

The disadvantages of an auto transformer include:

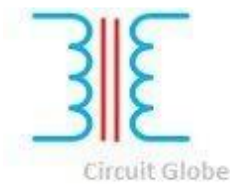
1. Because of electrical conductivity of the primary and secondary windings the lower voltage circuit is liable to be impressed upon by higher voltage. To avoid breakdown in the lower voltage circuit, it becomes necessary to design the low voltage circuit to withstand higher voltage.
2. The leakage flux between the primary and secondary windings is small and hence the impedance is low. This results into severer short circuit currents under fault conditions.
3. The connections on primary and secondary sides have necessarily needs to be same, except when using interconnected starring connections. This introduces complications due to changing primary and secondary phase angle particularly in the case of delta/delta connection.
4. Because of common neutral in a star/star connected auto transformer it is not possible to earth neutral of one side only. Both their sides should have their neutrality either earth or isolated.
5. It is more difficult to maintain the electromagnetic balance of the winding when voltage adjustment tappings are provided. It should be known that the provision of tapping on an auto transformer increases considerably the frame size of the transformer. If the range of tapping is very large, the advantages gained in initial cost is lost to a great event.

Applications of Auto Transformers

The applications of an auto transformer include:

1. Compensating voltage drops by boosting supply voltage in distribution systems.
2. Auto transformers with a number of tapping are used for starting induction and synchronous motors.
3. **Auto transformer** is used as variac in laboratory or where continuous variable over broad ranges are required.

4.14 Applications & Comparison With Two Winding Transformer

Basis For Differences	Autortransformer	Conventional transformer
Definition	A transformer, having only one winding a part of which acts as a primary and the other as a secondary.	It is a static machine which transfers electrical energy from one end to another without changing frequency.
Number of Windings	Auto-transformer has only one winding wound on a laminated core	It has two separate winding, i.e., primary and secondary winding.
Symbol		

Basis For Differences	Autortransformer	Conventional transformer
Insulation	The primary and secondary winding are not electrically insulated.	The primary and secondary winding are electrically insulated from each other.
Induction	Self Induction	Mutual Induction
Size	Small	Large
Power Transfer	Partly by transformation and partly by direct electrical connection.	Through transformation
Voltage Regulation	Better	Good
WindingMaterial	Less requires	More requires
Circuit	The primary and secondary winding circuits are connected magnetically.	The primary and secondary winding circuits are connected both electrically and magnetically.
Connection	Depends upon the tapping	Connect directly to the load.
Startingcurrent	Decreases	Decreases by 1/3 times.
Excitationcurrent	Small	Large
Economical	More	Less
Cost	Less costly	More costly
Efficient	More	Less
Leakage flux and resistance	Low	High
Impedance	Less	High
Cost	Cheap	Very costly
Losses	Low	High
Outputvoltage	Variable	Constant.

Basis For Differences	Autortransformer	Conventional transformer
Applications	Use as a starter in an induction motor, as a voltage regulator, in railways, in a laboratory.	Use in power system for step up and step down the voltage.

Key Differences Between Autotransformer and Transformer

1. An autotransformer has only one winding which acts both as a primary and the secondary whereas the conventional transformer has a two separate windings, i.e., the primary and the secondary winding.
2. The auto-transformer works on the principle of self-induction i.e. induce the electromagnetic force in the circuit due to variation in current. The conventional transformer works on the principle of mutual induction in which the emf induces in the coil by changing the current in the adjacent coil.
3. The auto-transformer is smaller in size, whereas the conventional transformer is larger in size.
4. The autotransformer is more economical as compared to a conventional transformer.
5. In an autotransformer, electrical power is transferred from primary to secondary partly by the process of transformation and partly by the direct current. The conventional transformer transfers the electrical power through the electric transformation due to which power loss occurs.
6. The voltage regulation of an auto-transformer is much better than the conventional transformer
    - The voltage regulation is the change in the secondary terminal voltage from no load to full load.
7. The autotransformer has only one winding. Thus, less conductor is required for winding as compared to the conventional transformer.
8. The primary and secondary windings of the autotransformer are not electrically insulated whereas the windings of the conventional transformer are electrically insulated from each other.
9. The starting current of the auto-transformer is less than the actual current, whereas the starting current of the conventional transformer is one-third of the main current.
10. The auto-transformer is more efficient as compared to the conventional transformer.
11. The leakage flux and resistance of an auto-transformer are low because it has only one winding whereas it is high in the conventional transformer.
12. The autotransformer has less impedance as compared to conventional current. The smaller impedance results in the large short circuit current.
13. The cost of the autotransformer is very less whereas the conventional current is very costly.
14. The losses in the auto-transformer are less as compared to the conventional transformer.

15. The output voltage of the secondary transformer varies when the sliding contacts are used in the secondary winding whereas the output voltage of the conventional transformer always remains constant.
16. The autotransformer is used as a voltage regulator, in the laboratory, in the railway stations, as a stator in an induction motor, etc., whereas the conventional transformer is used to step-up and step-down the voltage in the power grid.

Similarities: The autotransformer and the conventional transformer both work on the principle of electromagnetic induction. They used copper conductor for making the windings. The cores of both the transformers are made up of CRGO steel. The primary and the secondary of both the transforms are magnetically connected to each other.

9. PRACTICE QUIZ

1. The open circuit test in a transformer is used to measure

a) Copper loss
b) Winding loss
c) Total loss
d) Core loss

2. The leakage flux in a transformer depends upon the value of

a) Frequency
b) Mutual Flux
c) Load current
d) Applied Voltage

3. Lamination of transformer core is made of

a) Cast Iron
b) Silicon Steel
c) Aluminium
d) Cast Steel

4. Breather is provided in a transformer to

a) Absorb moisture of air during breathing
b) provide cold air in the transformer
c) The filter of transformer oil
d) None of above

5. Which of the following losses varies with the load in the transformer?

a) Core loss
b) Copper loss
c) Both core & copper loss
d) None of the above

6. Transformer core are laminated in order to

a) reduce hysteresis loss

b) reduce hysteresis & eddy current loss
c) minimize eddy current loss
d) Copper loss

7. Generator transformers are _______________
a) Step-up transformers
b) Step-down transformers
c) Auto-transformers
d) One-one transformers

8. What is the no-load current drawn by transformer?
a) 0.2 to 0.5 per cent
b) 2 to 5 per cent
c) 12 to 15 per cent
d) 20 to 30 per cent

9. Purpose of no-load test on a transformer is ___________
a) Copper loss
b) Magnetising current
c) Magnetising current and CORE loss
d) Efficiency of the transformer

10. No-load current in a transformer _______________
a) Lags behind the voltage by about 75°
b) Leads the voltage by about 75°
c) Lags behind the voltage by about 15°
d) Leads the voltage by about 15°

11. Which of the following statement is true for no-load current of the transformer?
a) has high magnitude and low power factor
b) has high magnitude and high power factor
c) has small magnitude and high power factor
d) has small magnitude and low power factor

12. In no-load test we keep secondary terminals __________
a) Shorted
b) Shorted via fixed resistor
c) Open
d) Shorted via variable resistors

13. Maximum value of flux established in a transformer on load is equal to _________
a) $E1/(4.44*f*N_1)$
b) $E1/(4.44*f*N_2)$
c) $E2/(4.44*f*N_1)$
d) Cannot define

14. Induced emf in the primary of transformer is equal to terminal voltage applied at primary.
a) **True** b) False

15. **For a linear B-H relationship, which option is correct?**
    a) The exciting current is equal to core loss current
    b) The exciting current is equal to magnetizing current
    c) The exciting current is equal to de-magnetizing current
    d) The exciting current is equal to cross-magnetizing current
16. **A transformer transforms _______________**
    a) voltage b) current **c) power** d) frequency
17. **In a given transformer for given applied voltage, which of the following losses remain constant irrespective of load changes?**
    a) Friction and windage losses
    b) Copper losses
    c) Hysteresis and eddy current losses
    d) Cannot be determined
18. **Variations in a hysteresis loss in a transformer (Bmax) ____________**
    a) Bmax
    b) $Bmax^{1.6}$
    c) $Bmax^{3.83}$
    d) Bmax/2
19. **The full-load copper loss is 1600 W. At half-load, the copper loss will be _______**
    a) 6400 W
    b) 1600 W
    c) 800 W
    d) 400 W
20. **If the supply frequency to the transformer is increased, the iron loss will ___________**
    a) Not change
    b) Decrease
    c) Increase
    d) Cannot be determined

10. Assignments

S.No	Question	BL	CO
1	Explain the constructional details and types of single-phase transformers	2	5
2	What are the conditions required for the parallel operation of two transformers?	2	5
3	Explain the procedure to conduct back to back test on two identical single-phase transformers.	2	5
4	**Explain the principle of operation of an Auto transformer in detail.**	2	5
5	Explain the procedure for conducting OC and SC tests with neat diagrams.	3	5
6	Explain the principle of operation of a single-phase transformer when it supplies lagging power factor load. Draw the phasor diagram under this condition.	3	5

11. Part A- Question & Answers

S.No	Question& Answers	BL	CO
1	**Define a transformer?** A transformer is a static device that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field and without a change in frequency.	1	5
2	**Give the Emf equation of a transformer and define each term** Emf induced in primary coil E1 = 4.44 fømN1 volt Emf induced in secondary coil E2 = 4.44fømN2 volt Where f is the frequency of AC input øm is the maximum value of flux in the core N1, N2 are the number of primary and secondary turns.	1	5
3	**Define voltage regulation of a transformer** When a transformer is loaded with a constant primary voltage, the secondary voltage decreases for lagging power factor load, and increases for leading pf load because of its internal resistance and leakage reactance. The change in secondary terminal voltage from no load to full load expressed as a percentage of no load or full load voltage is termed as regulation. % regulation down = (0V2-V2) x 100/0V2 % regulation up = (0V2-V2) x 100/V2	1	5
4	**Why transformers are rated in KVA?** Copper loss of a transformer depends on current and iron loss on voltage. Hence total losses depend on Volt- Ampere and not on the power factor. That is why the rating of transformers is in kVA and not in kW.	1	5
5	**What are the applications of a step-up and step-down transformers?** Step-up transformers are used in generating stations. Normally the generated voltage will be either 11 kV. This voltage(11 KV) is stepped up to 110 kV or 220 kV or 400 kV and transmitted through transmission lines. (In short it may Be called as sending end). Step-down transformers are used in receiving stations. The voltage are again stepped down to 11 kV or 22 kV and transmitted through feeders.(In short it may be called as receiving end). Further these 11 kV or 22kV are stepped down to 3 phase 400 V by means of a distribution transformer and made available at consumer premises. The transformers used at generating stations and receiving stations are called power transformers.	1	5
6	**Briefly explain the principle of operation of transformers.** A transformer consists of two coils which are in mutual inductance. When AC supply is given to one of the coils, an alternating flux is set up, which is linked with the second coil. Due to this	1	5

	alternating flux there is a mutually induced emf produced in the second coil. If the second coil is closed, current flows in it and so electric energy is transferred magnetically from the first coil to the second coil.		
7	**Why are breathers used in transformers?** Breathers are used to entrap the atmospheric moisture and thereby not allowing it to pass on to the transformer oil. Also to permit the oil inside the tank to expand and contract as its temperature increases and decreases. Also to avoid sledging of oil i.e. decomposition of oil. Addition of 8 parts of water in 1000000 reduces the insulations quantity of oil. Normally silica gel is filled in the breather having pink color. This color will be changed to white due to continuous use, which is an indication of bad silica gel, it is normally heated and reused.	2	5
8	**A 1100/400 V, 50 Hz single phase transformer has 100 turns on the secondary winding. Calculate the number of turns on its primary.** We know V1 / V2 = k = N2 / N1 Substituting 400/1100 = 100/N1 N1 = 100/400 x 1100 = 275 turns.	2	5
9	**What is meant by Sumpner's test?** 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 can not 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.	2	5
10	List any two Comparison of auto Transformer with Two Winding Transformer Autotransformer Two Winding Transformer Autotransformer has only one winding wound on a laminated core. Two winding transformer has two separate winding, i.e., primary and secondary winding. Autotransformer primary and secondary share same winding. In two winding transformer primary and secondary have separate windings.	2	5

12. Part B- Questions

S.No	Question	BL	CO
1	(a) Explain the procedure for conducting OC and SC tests with neat diagrams. (b) A 20 kVA, 2500/250 V, 50 Hz, Single phase transformer gave the following test results: OC test (LV side): 250 V, 1.6 A, 110 W; SC test (HV side): 90 V, 7 A, 300 W. Compute the parameters of the approximate equivalent circuit referred to LV side.	3	5
2	Explain the principle of operation of a single-phase transformer when it supplies lagging power factor load. Draw the phasor diagram under this condition.	2	5
3	(a) What are the conditions required for the parallel operation of two transformers? (b) A 300 kVA, 11000/440 V, single phase, 50 Hz transformer gave the following test results. Open circuit test on LV side a normal voltage and frequency, input 1300 W, 4amps; short circuit test HV side with voltage 600 V, input 2800 W, 150 amps.Calculate regulation for full load at 0.8 p.f lagging and what isthe p.f on short circuit?	2	5
4	Explain the procedure to conduct back to back test on two identical single-phase transformers.	3	5
5	Explain the principle of operation of an Auto transformer in detail.	2	5
6	a) Derive an emf equation of a single phase transformer. b) A transformer with an output voltage of 4000V is supplied at 220V. If the secondary has 2000 turns, calculate the no. of primary turns.	2	5
7	a) Explain the working principle of operation of single-phase transformer. b)) Explain the constructional details and types of single-phase transformers	3	5
8	A 30 KVA, 2400/120 V, 50 Hz transformer has a high voltage winding resistance of 0.1 ohm and a leakage reactance of 0.22 ohm. The low voltage winding resistance is 0.035 ohm and the leakage reactance is 0.012 ohms. Find the equivalent winding resistance, reactance and impedance referred to the (i) high voltage side (ii) low voltage side.	3	5

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DC MACHINES & TRANSFORMERS (20A02302T)

UNIT-V

Three Phase Transformers

LECTURE NOTES

1. Course Objectives

The objectives of this course is to

1. The constructional features of DC machines and different types of windings employed in DC machines.
2. Characteristics of generators and parallel operation of generators.
3. Methods for speed control of DC motors and application of DC machines.
4. The Constructional Features of transformers, Predetermination of regulation and efficiency of transformers.
5. Various tests on single phase and three phase transformers and parallel operation of transformers.

2. Prerequisites

Students should have knowledge on

1. Engineering Physics
2. Basic Electrical Circuits

3. Syllabus

UNIT 5

Three Phase Transformers

Three-phase transformer – construction, types of connection and their comparative features, Phase conversion - Scott connection, Tap-changing transformers - No-load and on-load tap- changing of transformers, Three-winding transformers- Cooling of transformers.

4. Course outcomes

1. **Apply** the knowledge of magnetic material properties and fundamentals of energy conversion principles.
2. **Identify** the working principle of Dc machines & Transformers with mechanism and various operations performed
3. **Illustrate** the characteristics of various DC machines & Transformers with various operational conditions to determine efficiency & regulation.
4. **Evaluate** the performance & losses of Machines with help of various testing methods like OCC, speed control and OC & SC test.
5. **Explain**&**analyse** the parallel operation of DC machines & Transformers, Scott connections and phase conversions of transformers.

5. Lecture Notes

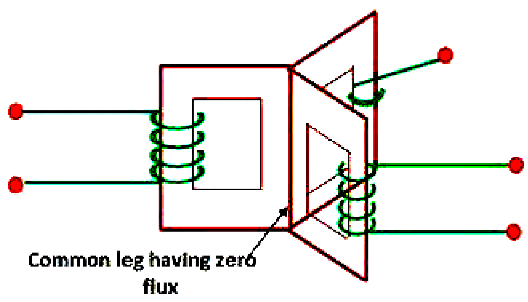
1.1 INTRODUCTION

Three-Phase Transformer Construction

A three phase transformer is used to transfer a large amount of power. The three phase transformer is required to step-up and step-down the voltages at various stages of a power system network. The three phase transformer is constructed in two ways. 1. Three separate single phase transformer is suitably connected for three phase operation. 2. A single three-phase transformer in which the cores and windings for all the three phases are merged into a single structure. The three single-phase transformers can be used as a three-phase transformer when their primary and secondary winding are connected to each other. The three phase transformer supply has many advantages as compared to three single phase units like it requires very less space and also very lighter smaller and cheaper in size.

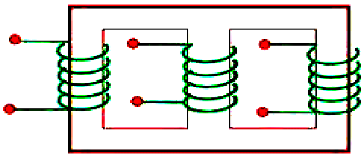
The three phase transformer is mainly classified into two types, i.e., the core type transformer and the shell type transformer.

1.2 Construction Core Type Three Phase Transformer Consider a three single phase core type transformer positioned at 120° to each other as shown in the figure below. If the balanced three-phase sinusoidal voltages are applied to the windings, the fluxes φa, φb and φc will also be sinusoidal and balanced. If the three legs carrying these fluxes are combined, the total flux in the merged leg becomes zero. This leg can, therefore, be removed because it carries the no flux. This structure is not convenient for the core. The core of the three phase transformer is usually made up of three limbs in the same plane.



Three Single Phase Core in
Contact With Another

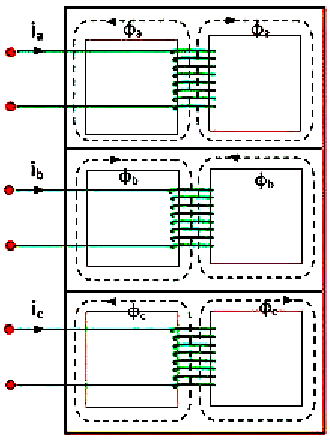
This can be built using stack lamination. The each leg of this core carries the low voltage and high voltage winding. The low voltage windings are insulated from the core than the high voltage windings.



Core Structure Using Stacked Lamination

The low windings are placed next to the core with suitable insulation between the core and the low voltage windings. The high voltage windings are placed over the low voltage windings with suitable insulation between them. The magnetic paths of the leg a and c are greater than that of leg b, the construction is not symmetrical, and there is a resultant imbalance in the magnetizing current.

Shell type Three Phase Transformer The shell type 3-phase transformer can be constructed by stacking three single phase shell transformer as shown in the figure below. The winding direction of the central unit b is made opposite to that of units a and c. If the system is balanced with phase sequence a-b-c, the flux will also be balanced The magnitude of this combined flux is equal to the magnitude of each of its components. The cross section area of the combined yoke is same as that of the outer leg and top and bottom section of the yoke. The imbalance in the magnetic path has very little effect on the performance of the three shell-type transformers. The windings of the shell type three phase transformer are either connected in delta or star as desired.



3-Phase Shell Type Transformer

1.3 Three-Phase Transformer Connections

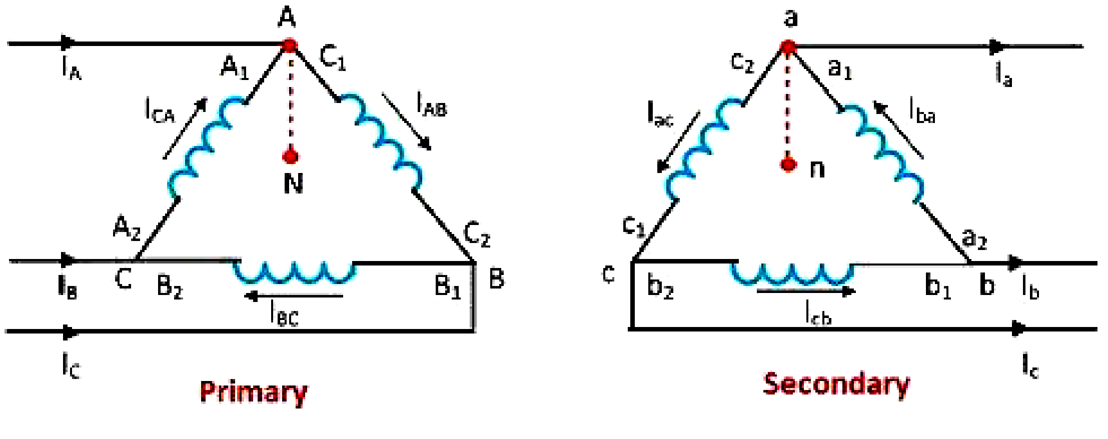
The three phase transformer consists three transformers either separate or combined with one core. The primary and secondary of the transformer can be independently connected either in star or delta. There are four possible connections for a 3-phase transformer bank.

1. Δ – Δ (Delta – Delta) Connection
2. Y – Y (Star – Star) Connection
3. Δ – Y (Delta – Star) Connection
4. Y – Δ (Star – Delta) Connection

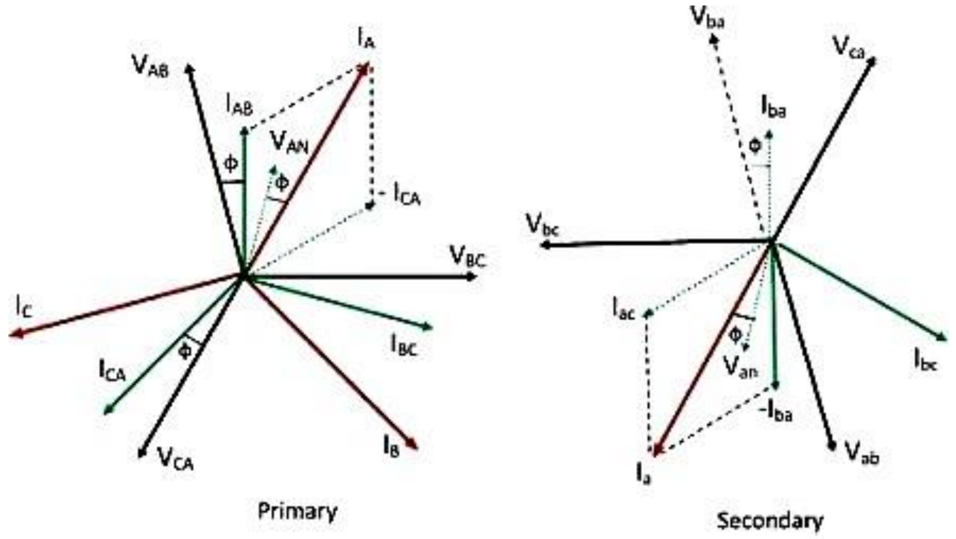
The choice of connection of three phase transformer depends on the various factors likes the availability of a neutral connection for grounding protection or load connections, insulation to ground and voltage stress, availability of a path for the flow of third harmonics, etc. The various types of connections are explained below in details.

1.4.1. Delta-Delta (Δ -Δ) Connection

The delta-delta connection of three identical single phase transformer is shown in the figure below. The secondary winding a1a2 is corresponding to the primary winding A1A2, and they have the same polarity. The polarity of the terminal **a** connecting **a1** and **c2** is same as that connecting **A1** and **C2**. The figure below shows the phasor diagram for lagging power factor **cosφ**.



Delta-Delta Connection of Transformer



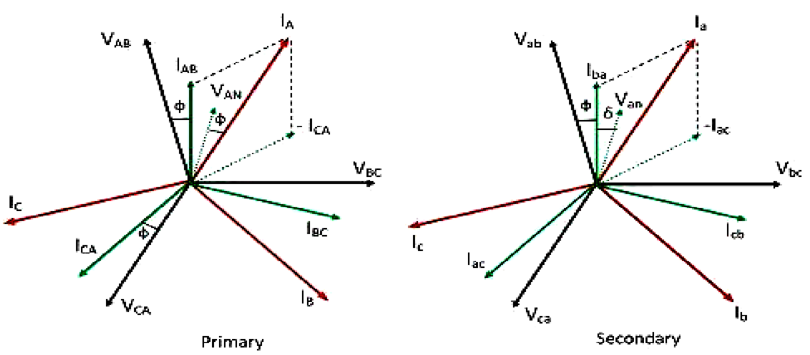
180 Phase Shift of Delt Delta Connection of Transformer

The magnetizing current and voltage drops in impedances have been neglected. Under the balanced condition, the line current is √3 times the phase winding current. In this configuration, the corresponding line and phase voltage are identical in magnitude on both primary and secondary sides.

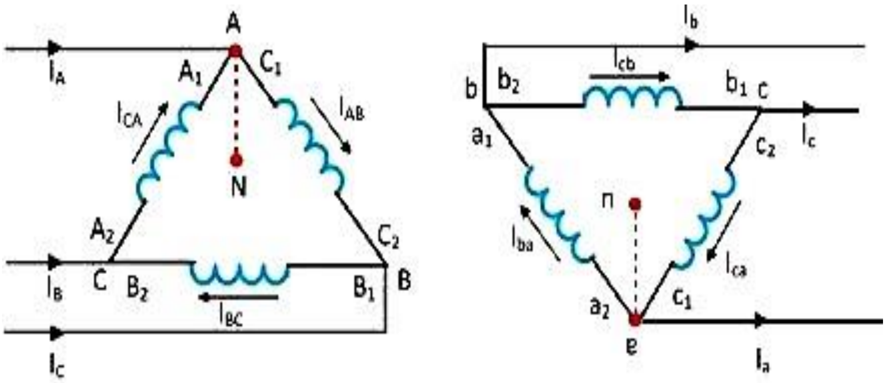
The secondary line-to-line voltage is in phase with the primary line-to-line voltage with a voltage ratio equal to the turns ratio.

If the connection of the phase windings is reversed on either side, the phase difference of 180° is obtained between the primary and the secondary system. Such a connection is known as an 180º connection.

The delta-delta connection with 180º phase shift is shown in the figure below. The Phasor diagram of a three phase transformer shown that the secondary voltage is in phase opposition with the primary voltage.



Phasor Diagram of Delta-Delta Connection of Transformer



180° Phase Shift of Delta-Delta Connection of Transformer

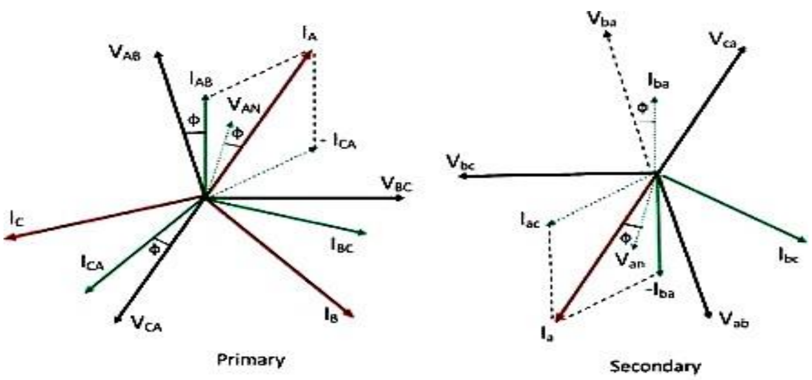
The delta-delta transformer has no phase shift associated with it and problems with unbalanced loads or harmonics.

Advantages of delta–delta connection of transformer

The following are the advantages of the delta-delta configuration of transformers.

1. The delta-delta transformer is satisfactory for a balanced and unbalanced load.
2. If one transformer fails, the remaining two transformers will continue to supply the three-phase power. This is called an open delta connection.
3. If third harmonics present, then it circulates in a closed path and therefore does not appear in the output voltage wave.

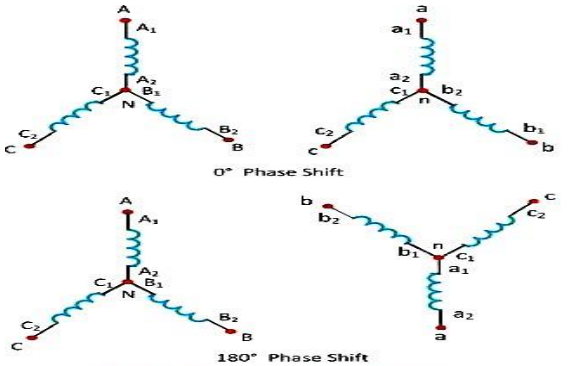
The only disadvantage of the delta-delta connection is that there is no neutral. This connection is useful when neither primary nor secondary requires a neutral andthe voltage are low and moderate.



180 Phase Shift of Delt Delta Connection of Transformer

2. Star-Star (Y -Y) Connection of Transformer

The star-star connection of three identical single phase transformer on each of the primary and secondary of the transformer is shown in the figure below. The Phasor diagram is similar as in delta-delta connection.



Star-Star Connection of Transformer

The phase current is equal to the line current, and they are in phase. The line voltage is three times the phase voltage. There is a phase separation of 30º betweenthe line and phase voltage. The 180º phase shift between the primary and secondary of the transformer is shown in the figure above.

Problems Associated With Star-Star Connection

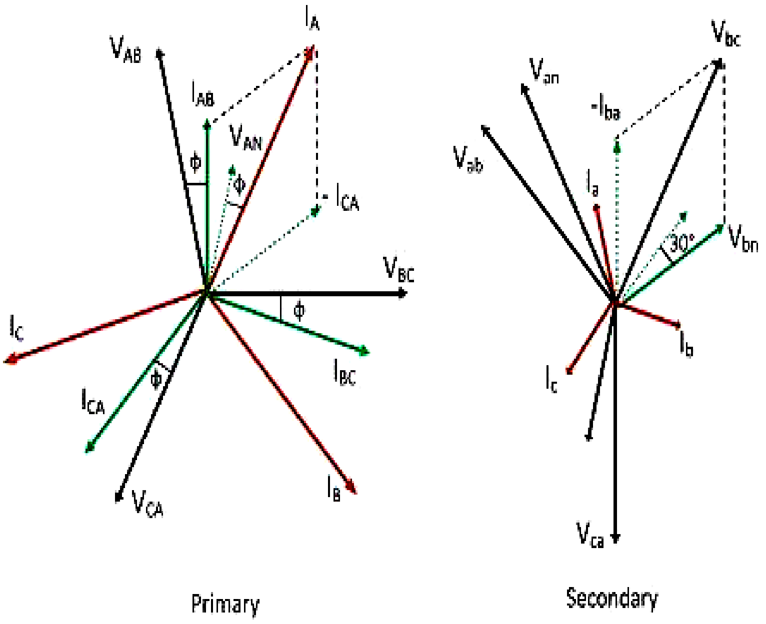
The star-star connection has two very serious problems. They are

1. The Y-Y connection is not satisfactory for the unbalance load in the absence of a neutral connection. If the neutral is not provided, then the phase voltages become severely unbalance when the load is unbalanced.
2. The Y-Y connection contains a third harmonics, and in balanced conditions, these harmonics are equal in magnitude and phase with the magnetizing current. Their sum at the neutral of star connection is not zero, and hence it will distort the flux wave which will produce a voltage having a harmonics in each of the transformers

The unbalanced and third harmonics problems of Y-Y connection can be solved by using the solid ground of neutral and by providing tertiary windings.

3. Delta-Star (Δ -Y) Connection

The Δ-Y connection of the three winding transformer is shown in the figure below. The primary line voltage is equal to the secondary phase voltage. The relation between the secondary voltages is $V_{LS} = \sqrt{3}\, V_{PS}$.



Phasor Diagram of Delta-Star Connection of Transformer

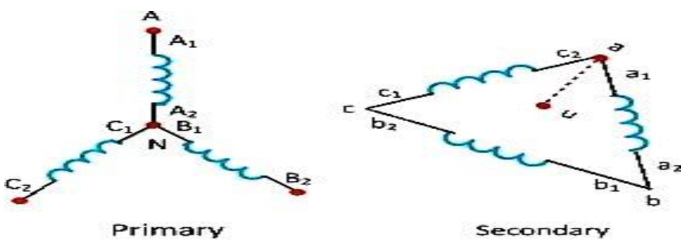
By reversing the connection on either side, the secondary system voltage can be made to lag the primary system by 30°. Thus, the connection is called -30° connection.

4. Star-Delta (Y -Δ) Connection

The star-delta connection of three phase transformer is shown in the figure above. The primary line voltage is √3 times the primary phase voltage. The secondary line voltage is equal to the secondary phase voltage. The voltage ratio of each phase is

Therefore line-to-line voltage ratio of Y-Δ connection is

$$\frac{V_{pP}}{V_{pS}} = a$$



Star-Delta Connetion of a transformer

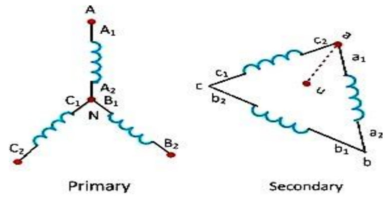
$$\frac{V_{lP}}{V_{LS}} = \frac{\sqrt{3}V_{pP}}{V_{pS}} = \sqrt{3}a$$

The Phasor diagram of the configuration is shown in the figure above. There is a phase shift of

30 lead exists between respective phase voltages. Similarly, 30° leads exist between

respective phase voltages. Thus the connection is called +30 º connections.

The phase shows the star-delta connection of transformer for a phase shift of 30° lag. This connection is called – 30° connection. This connection has no problem with the unbalanced load and thirds harmonics. The delta connection provided balancedphase on the Y side and provided a balanced path for the circulation of third harmonics without the use of the neutral wire.



Star-Delta Connetion of a transformer

Open delta or V-V Connection

If one transformer of delta-delta connection is damaged or accidentally opened,then the defective transformer is removed, and the remaining transformer continues to work as a three phase bank. The rating of the transformer bank is reduced to 58% of thatof the actual bank. This is known as the open delta or V-V delta. Thus, in open winding transformer, two transformers are used instead of three for the 3-phase operation.

Let the V_{ab}, V_{bc} and V_{ca} be the voltage applied to the primary winding of the transformer. The voltage induced in the transformer secondary or on winding one is V_{ab}. The voltage induced on the low voltage winding two is V_{bc}. There is no winding between points a and c. The voltage may be found by applying KVL around a closed path made up of point a, b, and c. Thus,

$$V_{ab} + V_{bc} + V_{ca} = 0$$

$$V_{ca} = -V_{ab} - V_{bc}$$

$$V_{BC} = V_p < -120°$$

$$V_{BC} = V_p < -120°$$

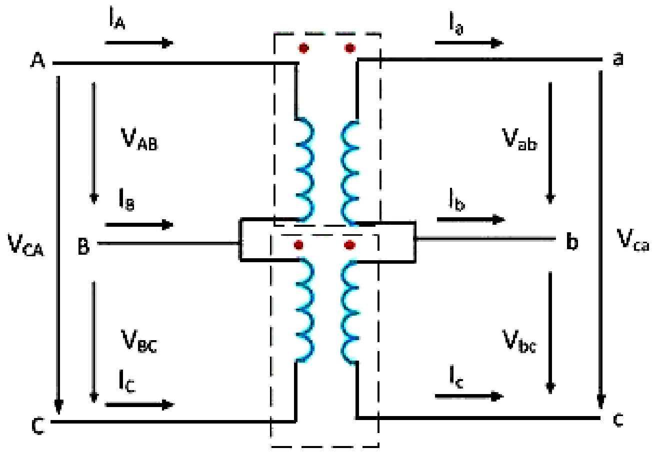
Let ,

$$V_{CA} = V_p < +120°$$

Where Vp is the magnitude of the line on the primary side.

$$V_{ab} = V_s < 0°$$

$$V_{bc} = V_s < -120°$$



Open Delta (V - V Connection) of Transformer

On substituting the value of Vab and Vbc in equation,
we get

$$V_{ca} = -V_s - (-0.5V_s - j0.866V_s)$$
$$= -0.5V_s + j0.866V_s$$
$$= V_s < +120°$$

The Vca is equal in magnitude from the secondary terminal voltage and 120º apart in time from both of them. The balanced three phase line voltage produced balanced 3-phase voltage on the secondary side.

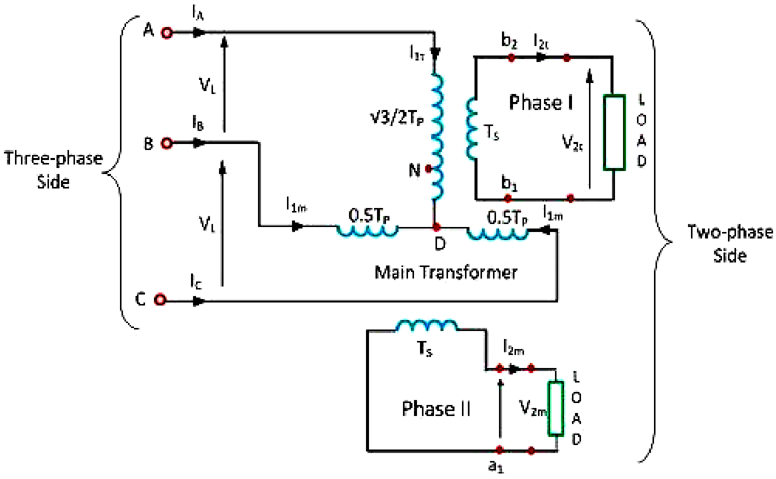
If the three transformers are connected in delta-delta configuration and are supplying rated load and if the connection becomes V-V transformer, the current in each phase winding is increased by √3 times. The full line current flows in each of the two phase windings of the transformer. Thus the each transformer in the V-V system is overloaded by 73.2%.

It should be noticed that the load should be reduced by √3 times in case of an open delta
connected transformer. Otherwise, serious overheating and breakdown of the two transformers may take place.

1.5 Scott-T Transformer Connection

Definition: The Scott-T Connection is the method of connecting two single phase transformer to perform the 3-phase to 2-phase conversion and vice-versa. The two transformers are connected electrically but not magnetically. One of the transformers is called the main transformer, and the other is called the auxiliary or teaser transformer.

The figure below shows the Scott-T transformer connection. The main transformer is centre tapped at D and is connected to the line B and C of the 3-phase side. It has primary BC and secondary a1a2. The teaser transformer is connected to the line terminal A and the centre tapping D. It has primary AD and the secondary b1b2



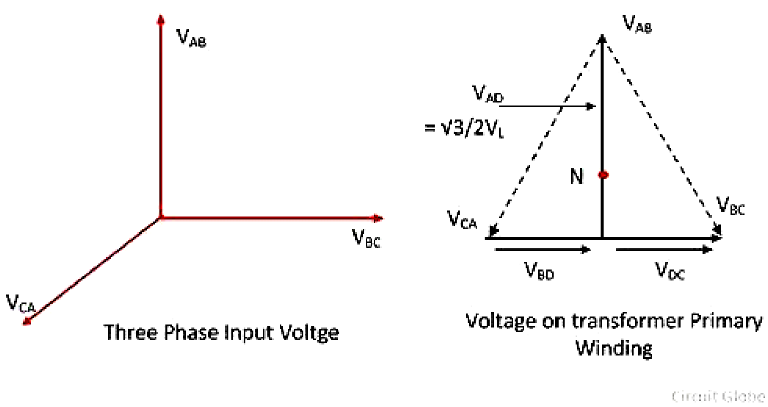
Scott connection Transformers

The identical, interchangeable transformers are used for Scott-T connection in which each transformer has a primary winding of Tp turns and is provided with tapping at 0.289Tp , 0.5Tpand 0.866 Tp.

Phasor Diagram of Scott Connection Transformer

The line voltages of the 3-phase system VAB, VBC, and VCA which are balanced are shown in the figure below. The same voltage is shown as a closed equilateral triangle.The figure below shows the primary windings of the main and the teaser transformer.

$$|V_{AB}| = |V_{BC}| = |V_{CA}| = |V_L|$$



The D divides the primary BC of the main transformers into two halves and hence the number of turns in portion BD = the number of turns in portion DC = Tp/2.The voltage VBD and VDC are equal, and they are in phase with VBC.

$$V_{BD} = V_{DC} = \frac{1}{2}V_{BC} = \frac{1}{2}V_L < 0°$$

The voltage between A and D is

$$V_{BD} = V_{DC} = \frac{1}{2}V_{BC} = \frac{1}{2}V_L < 0°$$

$$V_{AD} = V_{AB} + V_{BD}$$

$$V_{AD} = V_L\left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) + \frac{1}{2}V_L$$

$$V_{AD} = V_L\left(j\frac{\sqrt{3}}{2}\right) = 0.866V_L < 90°$$

The teaser transformer has the primary voltage rating that is √3/2 or 0.866 of the voltage ratings of the main transformer. Voltage VAD is applied to the primary of the teaser transformer and therefore the secondary of the voltage V2t of the teaser transformer will lead the secondary terminal voltage V2m of the main transformer by 90º as shownin the figure below.

Then,

$$\frac{V_{S_1}}{V_{AD}} = \frac{T_S}{T_{AD}}$$

$$V_{2t} = \frac{T_S}{T_{AD}}V_{AD} = \frac{T_S}{\frac{\sqrt{3}}{2}T_P} \times \frac{\sqrt{3}V_t}{2}$$

$$\frac{T_S}{T_P}V_L = v_{2m}$$

For keeping the voltage per turn same in the primary of the main transformer and the primary of the teaser transformer, the number of turns in the primary of the teaser transformer should be equal to √3/2Tp.

Thus, the secondary of both transformers should have equal voltage ratings. The V2t and V2m are equal in magnitude and 90º apart in time; they result in the balanced 2-phase system.

Position of Neutral Point N

The primary of the two transformers may have a four wire connection to a 3-phase supply if the tapping N is provided on the primary of the teaser transformer such that

The voltage across AN = VAN = phase voltage = Vl/√3.

Since the voltage across the portion AD.

$$V_{AD} = \frac{\sqrt{3}}{2}V_L$$

The voltage across the portion ND

$$V_{ND} = V_{AD} - V_{AN} = \frac{\sqrt{3}}{2}V_L - \frac{V_L}{\sqrt{3}} = \frac{V_L}{2\sqrt{3}}$$

The same voltage turn in portion AN, ND and AD are shown by the equations,

$$T_{AN} = \frac{T_P}{\sqrt{3}} = 0.577T_P$$

$$T_{ND} = \frac{T_P}{2\sqrt{3}} = 0.288T_P$$

$$T_{ND} = \frac{\sqrt{3}T_P}{2} = 0.866T_P$$

$$\frac{T_{AN}}{T_{ND}} = \frac{T_P}{\sqrt{3}} + \left(\frac{T_P}{2\sqrt{3}}\right) = 2$$

The equation above shows that the neutral point N divides the primary of the teaser transformer in ratio.

AN : ND = 2 : 1

Applications of Scott Connection

The following are the applications of the Scott-T connection.

1. The Scott-T connection is used in an electric furnace installation where it is desired to operate two single-phase together and draw the balanced load from the three-phase supply.
2. It is used to supply the single phase loads such as electric train which are so scheduled as to keep the load on the three phase system as nearly as possible.
3. The Scott-T connection is used to link a 3-phase system with a two–phase system with the flow of power in either direction.

The Scott-T connection permits conversions of a 3-phase system to a two-phase system and vice versa. But since 2-phase generators are not available, the converters from two phases to three phases are not used in practice.

1.6 Tap changing in Transformers

It is a normal fact that increase in load lead to decrease in the supply voltage. Hence the voltage supplied by the transformer to the load must be maintained within the prescribed limits. This can be done by changing the transformer turns ratio.

The taps are leads or connections provided at various points on the winding. The turns ratio differ from one tap to another and hence different voltages can be obtained at each tap.

Need for system voltage control

System voltage control is essential for:

1. Adjusting the terminal voltage of consumer within the prescribed limits

2. Adjustment of voltage based on change in load.

3. In order to control the real and reactive power.

4. For varying the secondary voltage based on the requirement.

Types of taps
Taps may be principal, positive or negative. Principal tap is one at which rated secondary voltage can be obtained for the rated primary voltage. As the name states positive and negative taps are those at which secondary voltage is more or less than the principle tap.

Taps are provided at the HV windings of the transformer because of the following reasons.

1. The number of turns in the High voltage winging is large and hence a fine voltage variation can be obtained.

2. The current on the low voltage winding of large transformers are high. Therefore interruption of high currents is a difficult task.

3. LV winding is placed nearer to the core and HV winding is placed outside. Therefore providing taps on the HV winding is comparatively easier than that of the LV winding.

Location of Taps
The taps can be provided at the phase ends, at the neutral point, or in the middle of the winding. The number of bushing insulators can be reduced by providing taps at the phase ends. When the taps are provided at the neutral point the insulation between various parts will be reduced. This arrangement is economical particularly important for the large transformer.

1.7 Tap changing methods

Tap changing causes change in leakage reactance, core loss, copper loss and perhaps some problems in the parallel operation of dissimilar transformer. There are two methods of tap changing.

1. Off load tap changing

2. On load tap changing

1. Off load (No load or off circuit) tap changing
As the name indicates, in this method tap changing is done after disconnecting the load from the transformer. Off load tap changing is normally provided in low power, low voltage transformers. It is the cheapest method of tap changing. The tap changing is done manually though hand wheel provided in the cover. In some transformers arrangements to change the taps by simply operating the mechanical switches are also provided.
The winding is tapped at various points. Since the taps are provided at various points in the winding single tap must be connected at a time otherwise it will lead to short circuit. Hence the selector switch is operated after disconnecting the load .To prevent unauthorized operation of an off load tap changer, mechanical lock is provided. To prevent inadvertent operation, electromechanical latching devices are provided to

operate the circuit breakers and de-energize the transformer as soon as the tap changer handle is moved.

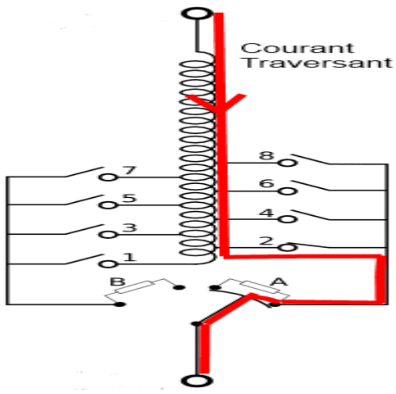
2. On load tap changing

On load tap changers are used to change the turns ratio without disconnecting the load from it. Tap changing can be done even when the transformer is delivering load. On load tap changers considerable increases the efficiency of the system. Nowadays almost all the large power transformers are provided with on load tap changers. The reason for providing On load tap changer in power transformers are1. During the operation of on load tap changers the main circuit remains unaffected.2. Dangerous sparking is prevented. The taps on the windings are brought to a separate oil filled compartment in which the on load tap changer switch is housed. The tap changer is a form of mechanical selector switch which is operated by a motor by local or remote control.

A handle fitted for manual operation in case of emergency. The selector switch is a form of make before break switch and during the transition of the tap changers from one tap to another; momentary connection must be made between the adjacent taps. This results in short circuit between the adjacent taps. The short circuit current must be limited by including resistor or reactor. Hence all forms of on load tap changer are provided with an impedance to limit short circuit current during tap changing operation. The impedance may be resistance or a center tapped reactance. In modern designs it is invariably carried out by a pair of resistors.

Procedure

Consider a high speed resistor type on load tap changers provided at neutral end of each phase as shown. The load is now supplied from the tap 1. The selector switches 1 and 2 are in contact with the taps 1 and 2. Now to switch over to the tap 2, the selector switch follows the following steps:



Tap changing switch Animation

1. Contacts a and b are closed. The load current flows from tap 1 through contact b.

2. The external mechanism moves the diverter switch S3 from b, now load is supplied from contact a through resistor R_1.

3. When diverters switch moves further it closes the contact d and both R1 and R2 are connected across taps 1 and 2 and the load current flows through these resistances to its mid point.

4. When S_3 moves further to the left, contact a is opened and the load current flows from tap 2 through resistor R_2 and d.

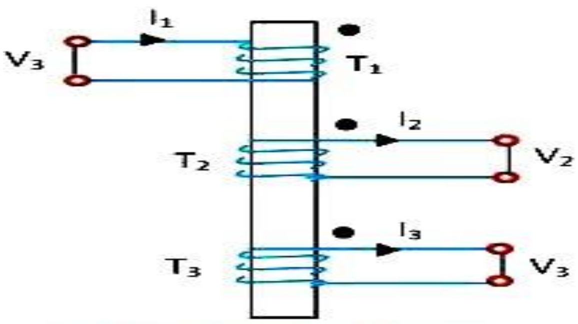
5. Finally the contact reaches the contact c and resistor R_2 is short circuited. The load current flows from tap 2 through contact c.
Now to change the tap from 2 to 3, the selector switch S_1 is first moved to tap 3 and the above steps are reverse. In order to limit the power loss it is necessary that the transformers are kept in the circuit for as minimum time as possible.
More compact tap changers with high reliability and performance are being made by employing vacuum switches in the diverter switch.

1.9 Three-winding Transformer

Definition: Sometimes in high rating transformer, the third winding is constructed in addition to the primary and the secondary windings. **The third winding is called the tertiary winding, and because of the three windings, the transformer is called the three winding transformer.**

The voltage ratings of all the three windings of the transformer are usually unequal. The primary winding has the highest voltage rating; the tertiary has the lowest voltage rating, and the secondary has the intermediate voltage rating.

The chief advantages of the three winding transformers are an economy of construction and their great efficiency. The schematic diagram of a three-phase transformer is shown in the figure below.



3-Winding Transformer

Foran ideal transformer,

$$\frac{V_2}{V_1} = \frac{T_2}{T_1}$$

$$\frac{V_3}{V_1} = \frac{T_3}{T_1}$$

$$I_1 T_1 = I_2 T_2 = I_3 T_3$$

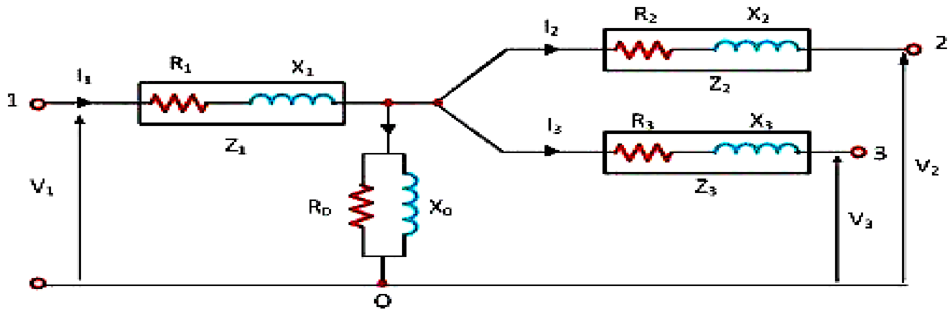
The most significant advantage of the third winding is are that the harmonic generated by the primary and secondary winding extinguish by the third winding. The third winding is connected in delta.

The voltage of the tertiary winding differs than the primary and secondary winding. Thus, it is used for supplying the power to the auxiliary appliances like the fan, tube light, etc. of the substations. The tertiary winding is used for following applications.

- The reactive power is supplied to the substations with the help of the tertiary winding.
- The tertiary winding reduces the impedance of the circuit so that the fault current easily passes to the ground.
- It is used for testing the high rating transformer.

Equivalent Circuit of a Three Winding Transformer

The equivalent circuit diagram of the three-phase transformer is shown in the figure. Consider the R1, R2 and R3 are the resistance and the X1, X2 and X3 are the impedance of their windings.



Equivalent Diagram of a 3-Winding Transformer

The V1, V2, V3 are the voltages and the I1, I2, I3 are current flows through their windings. Determination of Parameters of Three-Winding Transformers

The parameters of the equivalent circuit can be determined from the open circuit and the three short-circuit tests.

Short Circuit Test

Consider the Z1, Z2 and Z3 are the impedances of the three winding transformers. These impedances are considered as the base for performing the short circuit test. For the short-circuit test, the two winding is short circuit and the third winding is kept open. In the first step, consider the winding 1 and 2 are short-circuited. The low voltage

winding is applied to the winding 1 due to which the full load current flows through the winding 2. The Z12 indicates the impedance of winding 1 and 2 and it measuredas Equivalent resistance,

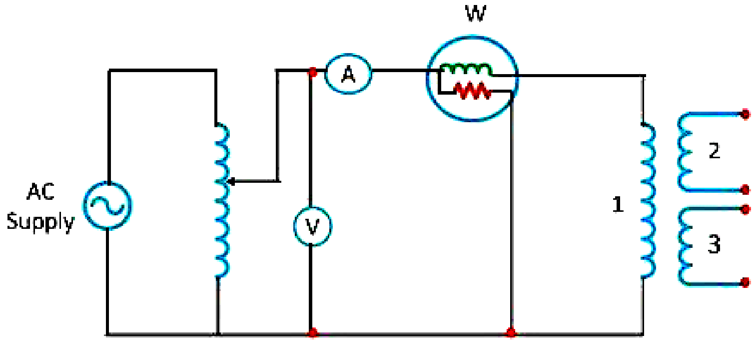
$$R_{12} = \frac{P_1}{I_1^2}$$

Equivalent leakage reactance,

$$X_{12} = \sqrt{Z_{12}^2 - R_{12}^2}$$

The Z_{12} is the series combination of Z_1 and Z_2 respectively,

$$Z_{12} = R_{12} + jX_{12} = Z_1 + Z_2$$

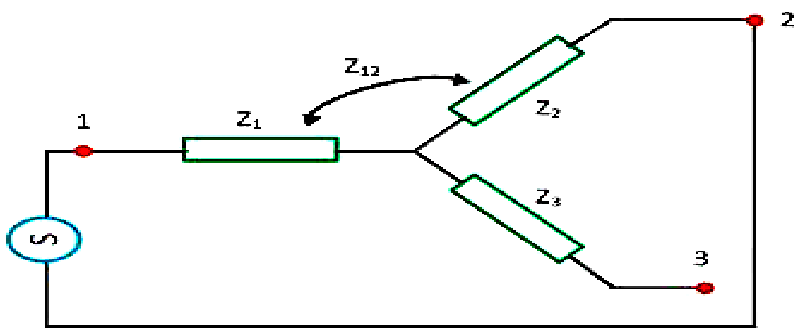


Connection Diagram of Short Circuit Test on Three Winding Transformer

In the second step, the third winding is short-circuited with the second winding and the first winding is kept open. The low voltage source is applied across the third winding so that the full load current flows through the second winding. The Z_{23} represents the impedance of the winding 2 and 3 and the below equation expresses it

$$Z_{23} = Z_2 + Z_3$$

In the third step, the second winding is opened and first and third winding are short-circuited. The low voltage is supplied to the third winding, and full load current flows through the first windings. The Z_{13} is the impedance of the first and third winding.



Solving equation (1), (2) and (3) we get the leakage impedance Z_1, Z_2 and Z_3all referred to as primary,

$$Z_1 = \frac{1}{2}(Z_{12} + Z_{13} - Z_{23})$$
$$Z_1 = \frac{1}{2}(Z_{23} + Z_{12} - Z_{13})$$
$$Z_1 = \frac{1}{2}(Z_{13} + Z_{23} - Z_{12})$$

Open-Circuit Test

The open circuit test is carried out to determine the core loss, magnetizing impedance and turn ratios. In open circuit test the voltmeter, ammeter and wattmeter are connected in low voltage winding. The secondary side is kept open, and the voltmeter is connected.

Since the high voltage side is opened the current drawn by the primary is no load current and I0 measured by the ammeter A. The magnetizing impedance may be found by exciting current winding 1 with both winding 2 and 3 be open circuit. Then we have,

$$a_{12} = \frac{V_1}{V_3}, a_{13} = \frac{V_1}{V_3}$$
$$a_{23} = \frac{V_2}{V_3} = \frac{a_{23}}{a_{12}}$$

The voltage regulation of a three-winding transformer is defined as the ratio of the magnitude of the actual kVA loading of the winding to the base kVA used in determining the network parameters.

Separation of No Load Losses

The no load losses are the constant losses which include core loss and friction and windage loss. The separation between the two can be carried out by the no load test conducted from variable voltage, rated frequency supply. When the voltage is decreased below the rated value, the core loss reduces as nearly square of voltage. The slip does not increase significantly the friction and windbag loss almost remains constant. The voltage is continuously decreased, till the machine slip suddenly begins to increase and the motor tends to stall. At no load this takes place at a sufficiently reduced voltage. The graph showing no load losses versus voltage is extrapolated to V =0 which gives friction and windage loss as iron or core loss is zero at zero voltage.

1.10 Cooling Methods Of A Transformer

No transformer is truly an 'ideal transformer' and hence each will incur some losses, most of which get converted into heat. If this heat is not dissipated properly, the excess temperature in transformer may cause serious problems like insulation failure. It is obvious that transformer needs a cooling system. Transformers can be divided in two types as (i) dry type transformers and (ii) oil immersed transformers. Different **cooling methods of transformers** are -

- For dry type transformers
  - Air Natural (AN)
  - Air Blast
- For oil immersed transformers
  - Oil Natural Air Natural (ONAN)
  - Oil Natural Air Forced (ONAF)
  - Oil Forced Air Forced (OFAF)
  - Oil Forced Water Forced (OFWF)

Cooling Methods For Dry Type Transformers

Air Natural Or Self Air Cooled Transformer

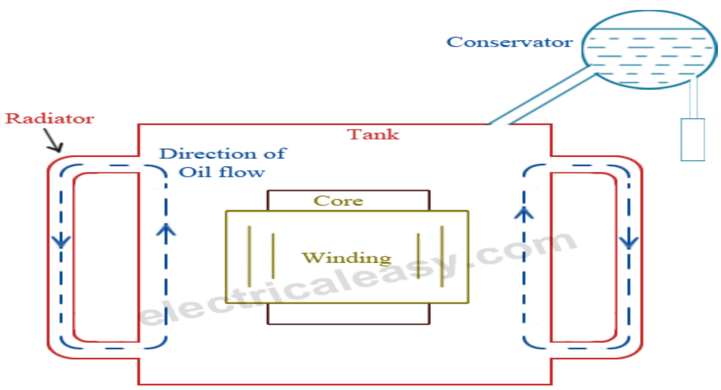
This method of transformer cooling is generally used in small transformers (upto 3 MVA). In this method the transformer is allowed to cool by natural air flow surrounding it.

Air Blast

For transformers rated more than 3 MVA, cooling by natural air method is inadequate. In this method, air is forced on the core and windings with the help of fans or blowers. The air supply must be filtered to prevent the accumulation of dust particles in ventilation ducts. This method can be used for transformers upto 15 MVA.

Cooling Methods For Oil Immersed Transformers

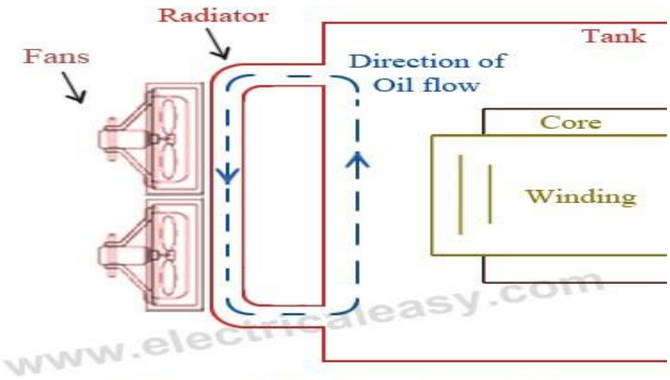
Oil Natural Air Natural (ONAN)



Oil Natural Air Natural (ONAN) - Cooling of Transformer

This method is used for oil immersed transformers. In this method, the heat generated in the core and winding is transferred to the oil. According to the principle of convection, the heated oil flows in the upward direction and then in the radiator. The vacant place is filled up by cooled oil from the radiator. The heat from the oil will dissipate in the atmosphere due to the natural air flow around the transformer. In this way, the oil in transformer keeps circulating due to natural convection and dissipating heat in atmosphere due to natural conduction. This method can be used for transformers upto about 30 MVA.

Oil Natural Air Forced (ONAF)



Oil Natural Air Forced (ONAF)
Cooling of Transformer

The heat dissipation can be improved further by applying forced air on the dissipating surface. Forced air provides faster heat dissipation than natural air flow. In this method, fans are mounted near the radiator and may be provided with an automatic starting arrangement, which turns on when temperature increases beyond certain value. This transformer cooling method is generally used for large transformers upto about 60 MVA.

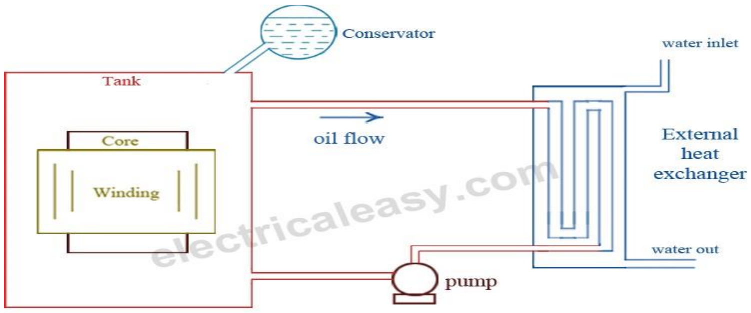
Oil Forced Air Forced (OFAF)

In this method, oil is circulated with the help of a pump. The oil circulation is forced through the heat exchangers. Then compressed air is forced to flow on the heat exchanger with the help of fans. The heat exchangers may be mounted separately from the transformer tank and connected through pipes at top and bottom as shown in the figure. This type of cooling is provided for higher rating transformers at substations or power stations.

Oil Forced Air Forced (OFAF) - Cooling of Transformer

Oil Forced Water Forced (OFWF)

This method is similar to OFAF method, but here forced water flow is used to dissipate hear from the heat exchangers. The oil is forced to flow through the heat exchanger with the help of a pump, where the heat is dissipated in the water which is also forced to flow. The heated water is taken away to cool in separate coolers. This type of cooling is used in very large transformers having rating of several hundreds MVA.



Oil Forced Water Forced (OFWF) - Cooling of Transformer

9.PRACTICE QUIZ

1. When does star/star transformers work satisfactorily?

a) Load is unbalanced only

b) Load is balanced only

c) On balanced as well as unbalanced loads

d) Independent of load type

2. Scott connection is used

a) To accomplish three phase to three phase transformation only
b) To accomplish three phase to two phase transformation only
c) To accomplish three phase to three phase and three phase to two phase transformation
d) None of the above

3. The efficiency of the transformer is independent of power factor.

a) true
b) false

4. The tapping in the transformer are always provided in the low voltage side

a) true
b) false

5. Under balanced load conditions, main transformer rating in the Scott connection is

a) 10% greater than teaser transformer
b) 15% greater than teaser transformer
c) 57.7% greater than teaser transformer
d) 66.6% greater than teaser transformer

6. If K is the transformation ratio of main transformer in the Scott connection then the transformation ratio of the teaser will be

a) K/√3
b) √(3/2K)
c) 2K/√3
d) √(K/2)

7. on-load tap-changers can be used as
a) resistor type
b) inductor type
c) capacitor type
d) impedance

8. Off –load tap changer has
a) 6 copper studs
b) 7 copper studs
c) 2 copper studs
d) 4 copper studs

10. Assignments

S.No	Question	BL	CO
1	With neat sketch, explain the construction and working principle of 3-Phase Transformer	2	5
2	Explain the phase connection	2	5
3	Draw the scott connection of transformer and mark the terminals and turns ratio	2	5
4	Explain the operation of no load and on load tap changing transformer	2	5
5	Explain briefly about the cooling transformer methods	3	5
6	Explain the types of three phase transformer	3	5

11. Part A- Question & Answers

S.No	Question& Answers	BL	CO
1	**What is a 3-Phase Transformer?** A 3-phase Transformer is that Transformer which is equivalent to three single phase transformer but wound on one core and enclosed with one common case	1	5

2	**What advantage has the star connection over the delta-connection?** Each star-connected transformer is wound for only 57.7% of line voltage .In Hv Transmission this admits of much smaller transformers being built for high voltage than possible with the delta connection because of less insulation	1	5
3	**What advantage is obtained with delta-connection?** When three transformers are connected in delta ,one may be removed and the two remaining units will carry 57.7% of the original three phase load and thus maintain the continuity of supply	1	5
4	**What is the angle by which no-load current will lag the ideal applied voltage?** In an ideal transformer, there are no copper & core loss i.e. loss free core. The no load current is only magnetizing current therefore the no load current lags behind by angle 900. However the winding possess resistance and leakage reactance and therefore the no load current lags the applied voltage slightly less than 90^0.	1	5
5	**List the arrangement of stepped core arrangement in a transformer?** 1. To reduce the space effectively 2. To obtain reduce length of mean turn of the winding 3. To reduce I^2R loss.	1	5
6	**Does the transformer draw any current when secondary is open? Why?** Yes, it (primary) will draw the current from the main supply in order to magnetize the core and to supply iron and copper losses on no load. There will not be any current in the secondary since secondary is open.	1	5
7	**How does transformer oil appear when it is new?** transformer oil appear clear light colour with a faint characteristic smell	2	5
8	**Is it possible to connect two single phase transformers to give a 3-phase output from a 3-phase input?** Yes,they would have to be connected in an open delta	2	5
9	**What is a Booster Transformer?** Booster Transformer is one which is often used toward the end of a power line in order to raise the voltage to its desired valve	2	5
10	**When connecting an ordinary transformer as a booster transformer what factors must be considered?** The HV side of the transformer must be able to with stand the voltage of the line in which it is to be connected the lv side must have a voltage of approximately the valve by which the line voltage is to be boosted up, and low voltage side must also have a current carrying capacity that is sufficient to carry the line current	2	5

12. Part B- Questions

S.No	Question	BL	CO
1	Explaintheconstructionaldetailsof3-phasetransformer, with diagrams	1	5
2	Draw the physical connection and Phasor diagrams of the following transformer connections	2	5
3	Draw the scott connection of transformer and mark the terminals and turns ratio	2	5
4	A 300 kVA, 11000/440 V, three phase, 50 Hz transformer gave the following test results. Open circuit test on LV side a normal voltage and frequency, input 1300 W, 4amps; short circuit test HV side with voltage 600 V, input 2800 W, 150 amps. Calculate regulation for full load at 0.8 p.f lagging and what is the p.f on short circuit?	3	5
5	Why are the tap-changing transformers required?	2	5
6	Explain the operation of no load and on load tap changing transformer	2	5
7	Explain the star-delta connection? with diagrams	3	5
8	Determine the number of turns per phase in each winding of a 3-phase transformer with ratio of 20000/2000v to work on a 50HZ network the HV winding is delta connected and the lowvoltage winding is star connected .each core has a net section of 504 cm^2 assume the flux density of 1.2 wb/m^2	3	5