LECTURE NOTES

ON

ELECTRICAL MACHINE (Chapter 1,2)

BRANCH- ELECTRONICS AND TELLECOMMUNICATION

4th Semester

Department of Electrical Engineering

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ROURKELA 12

COURSE CONTENT:

1. ELECTRICAL MATERIAL

1.1 Properties & uses of different conducting material.

1.2 Properties & use of various insulating materials used electrical engineering.

1.3 Various magnetic materials & their uses.

2. DC GENERATOR

2.1Construction, Principle & application of DC Generator.

2.2 Classify DC generator including voltage equation.

2.3 Derive EMF equation & simple problems.

2.4 Define parallel operation of DC generators.

MODULE 1

ELECTRICAL MATERIAL

CONDUCTOR MATERIALS

Resistivity- Resistivity or specific resistance of a material may be defined as the resistance offered between the opposite faces of a metre cube of that material. The unit of resistivity is ohm metre (Ω-m). We have according to law of resistance: The resistance of a material (R) depends-

- directly to its length (L)

-inversely to the X-sectional area (A)

So $R \alpha L / A$

Or $R= \rho L/A$ (where ρ is known as resistivity of material)

Therefore $\rho = A R/L$

When R= Resistance in Ohms (Ω)

L= Length in m

A= Area of cross section in m^2

ρ = resistivity or Specific resistance in Ω-m

Temperature Coefficient of Resistance.

Based on temperature effect, electrical materials can be classified into two groups (i) positive temperature coefficient materials and (ii) negative temperature coefficient materials.

(i) Positive temperature coefficient means that the resistance of some of the metals and alloys increases when their temperature is raised.

(ii) Negative temperature coefficient means that the resistance of some of the materials, i.e., carbon and insulators and electrolytes, decreases when their temperature is raised.

If the resistance of a conductor is R_0 at 0^0 C, then its resistance at t^0C is given by the equation $R_t = R_0 \alpha t$ where α is the temperature coefficient of resistance at 0^0C and t is the difference in temperature.

Properties of Conductors

While selecting a material for a specific purpose in electrical engineering, its electrical, mechanical and economical properties are to be considered.

A. Electrical Properties

1. The conductivity must be good.
2. Electrical energy displayed in the form of heat must be low.
3. Resistivity must be low.
4. Temperature resistance ratio must be low.

B. Mechanical Properties

1. Ductility: It has that property of a material which allows it to be drawn into a wire.
2. Solderability: The joint should have minimum contact resistance.
3. Resistance to corrosion: Should not get rusted when used in outdoors.
4. Withstand stress and strain.
5. Easy to fabricate.

C. Economical Factors

1. Low Cost
2. Easily Available.

PROPERTIES AND USES OF DIFFERENTCONDUCTING MATERIAL

- **COPPER**

  Properties:

  1. Pure copper is one of the best conductors of electricity and its conductivity is highly sensitive to impurities.
  2. It is reddish-brown in colour.
  3. It is malleable and ductile.
  4. It can be welded at red heat.
  5. It is highly resistant to corrosion.
  6. Melting point is $108^{4}0$C.
  7. Specific gravity of copper is 8.9.
  8. Electrical resistivity is 1.682 micro ohm cm.

9. Its tensile strength varies from 3 to 4.7 tonnes/cm^2.

10. It forms important alloys like bronze and gun-metal.

Uses : Wires, cables, windings of generators and transformers, overhead conductors, busbar etc.

Hard drawn (cold-drawn) copper conductor is mechanically strong with tensile strength of 40 Kg/mm^2. It is obtained by drawing cold copper bars into conductor length. It is used for overhead line conductors and busbars.

Annealed Copper (Soft Copper) Conductor. It is mechanically weak, tensile strength 20 Kg/mm^2, easily shaped into any form.

Low-resistivity Hard Copper. It is used in power cables, windings and coils as an insulated conductor. It has high flexibility and high conductivity.

- **SILVER**

It is best known electrical conductor.

Properties

1. It is very costly.
2. It is not affected by weather changes.
3. It is highly ductile and malleable.
4. Its resistivity is 165 micro ohm cm.

Uses : Used in special contact, high rupturing capacity fuses, radio frequency conducting bodies, leads in valves and instruments.

- **ALUMINIUM**

Properties:

1. Pure aluminium has silvery colour and lustre. It offers high resistance to corrosion. Its electrical conductivity is next to that of copper.
2. It is ductile and malleable.
3. Its electrical resistivity is 2.669 micro ohms cm at 20^0C.
4. It is good conductor of heat and electricity.
5. Its specific gravity is 2.7.
6. Its melting point is 658^0C.

7. It forms useful alloys with iron, copper, zinc and other metals.

8. It cannot be soldered or welded easily.

Uses : Overhead transmission line conductor, busbars, ACSR conductors. Well suited for cold climate.

- **STEEL**.

Steel contains iron with a small percentage of carbon added to it. Iron itself is not strong but when carbon is added to it, it assumes very good mechanical properties. The tensile strength of steel is higher than that of iron. The resistivity of steel is 8-9 times higher than that of copper. Hence, steel is not generally used as conductor material. Galvanised steel wires are used as overhead telephone wires and as earth wires. Aluminium conductors are steel-reinforced to increase their tensile strength.

- **TUNGSTEN**

Properties :

1. It is grayish in colour when in metallic form.
2. It has a very high melting point (3300^0C)
3. It is a very hard metal and does not become brittle at high temperature.
4. It can be drawn into very thin wires for making filaments.
5. Its resistivity is about twice that of aluminium.
6. In its thinnest form, it has very high tensile strength.
7. It oxidizes very quickly in the presence of oxygen even at a temperature of a few hundred degrees centigrade.
8. In the atmosphere of an inert gas like nitrogen or argon, or in vacuum, it will reliably work up to 2000^0C.

Uses : It is used as filaments of electric lamps and as a heater in electron tubes. It is also used in thermionic valves, radars. Grids of electronic valves, sparking and contact points.

- **CARBON**.

Carbon is mostly available as graphite which contains about 90% of carbon. Amorphous carbon is found in the form of coal, coke, charcoal, petroleum, etc.

Electrical carbon is obtained by grinding the raw carbon materials, mixing with binding agents, moulding and baking it.

Properties :

1. Carbon has very high resistivity (about 4600 micro ohm cm).
2. It has negative temperature coefficient of resistance.
3. It has a pressure-sensitive reistance material and has low surface friction.
4. The current density is 55 to 65 A/cm^2.
5. This oxidizes at about 300^{0}C and is very weak.
6. It has very good abrasive resistance.
7. It withstands arcing and maintains its properties at high temperature.

- **PLATINUM**

Properties :

1. It is a grayish-white metal.
2. It is non-corroding.
3. It is resistant to most chemicals.
4. It can be drawn into thin wires and strips.
5. Its melting point is 1775^{0}C.
6. Its resistivity is 10.5 micro ohm cm.
7. It is not oxidized even at high temperature. **Applications**:

1. It is used as heating element in laboratory ovens and furnaces.
2. It is used as electrical contact material and as a material for grids in special- purpose vacuum tubes.
3. Platinum-rhodium thermocouple is used for measurement of temperatures up to 1600^{0}C.

- **MERCURY**

Properties:

1. It is good conductor of heat and electricity.
2. It is a heavy silver-white metal.
3. It is the only metal which is liquid at room temperature.
4. Its electrical resistivity is 95.8 micro hom cm.
5. Oxidation takes place if heated beyond 300^{0}C in contact with air or oxygen.

6. It expands and contracts in regular degrees when temperature changes.

Uses : Mercury vapour lamps, mercury arc rectifiers, gas filled tubes; for making and breaking contacts; used in valves, tubes, liquid switch.

INSULATING MATERIALS

INSULATING MATERIALS FOR ELECTRICAL ENGINEERING

The insulating materials used for various applications in electrical engineering are classified in three categories:

- Insulating gases
- Liquid insulating material
- Solid insulating material

INSULATING GAS: PROPERTIES AND APPLICATIONS

Air: Air provides insulation between the over-head transmission lines. It is the best insulating material when voltages are not very high. It is also used in air capacitor, switches and various electrical equipments.

It is easily available, non-inflammable, non-explosive, small dielectric strength (nearly 3to 5 kV/m) and reliable at low voltage.

Hydrogen: It is commonly used for cooling purpose in electrical machine due to its lightness. Its high thermal conductivity helps to transmit heat from windings of high capacity alternator. Thus it reduces windage losses and increases efficiency.

Nitrogen: Nitrogen is used in place of air, to prevent oxidation due to its chemically inert property. It is generally used in transformers, gas pressure cable and capacitors.

Carbon Dioxide: Carbon dioxide is used in certain fixed type capacitor, and is used as a pre-impregnate for oil filled high voltage apparatus, such as cables and transformers. The relative permittivity of carbon oxide is 1.000985 at 0^0 C.

Sulphur Hexafluoride (SF_6): The electromagnetic gases have high dielectric strength compared to other traditional dielectric gases like nitrogen and air. The dielectric strength of SF_6 is 2.35 times more than air. The electronegative gases are non-inflammable and non-explosive. The most important gas under this category is sulphur Hexafluoride, while others are Freon gases.

SF_6 is mostly used in high voltage application and its use is most satisfactory in dielectric machines, like X-ray apparatus, Van de Graff generators, voltage stabilizers, high-voltage switch gears, gas lasers etc. SF_6 bears some special properties as follows:

- SF_6 is colourless, nontoxic and non-inflammable gas. It is the heaviest gas and has low solubility in water. The gas can be liquefied by compression. Its cooling characteristic is better than air and nitrogen.
- Under normal temperature conditions it is chemically inert and completely stable with high dielectric strength.
- This gas has very good electronegative property. Its relatively large molecules have a great affinity for free electrons, with which they combine making the gas-filled break much more resistant to dielectric breakdown.

LIQUID INSULATING MATERIAL: PROPERTIES AND APPLICATIONS

Mineral oils: The operating temperature range of mineral oil is 50-110^{0}C. These hydrocarbon oils are used as insulating oils in transformers, circuit breakers, switch gears, capacitors etc.

In transformers, light fraction oil, such as transil oil is used to allow convection cooling. Its high flash point is 130^{0}C, so it is able to prevent fire hazard. Highly purified oil has a dielectric strength of 180 kv/mm and if the oil contains polar and ionizing material its dielectric loss increases. The dielectric Constant is about 2.3 and therefore it is capable of dissolving only very few substances in it and produce the conducting ions. The TRANSIL oil undergoes oxidation, particularly in the presence of catalysts such as copper, to form sludge and acids.

Light oils having viscosity of 100 seconds at 40^{0}C, have been used under pressure in oil filled high voltage cables.

More viscous or tacky oils with viscosity of 2000 seconds at 40^{0}C, are generally to impregnate the paper in solid type cable.

Askarels: These are non-inflammable, synthetic insulating liquids, used in temperature range of 50 – 110^{0}C. Chlorinated hydrocarbons are the most widely used among the askarels because of high dielectric strength, low dielectric constant (4 to 6) and small dielectric loss. They do not decompose under the influence of electric arc and have good thermal, chemical and electrical stability.

Chlorinated hydrocarbons as askarels are used as transformer fluids to reduce fire hazards. Chlorinated diphenyl, penta chloro diphenyl, trichloro diphenyl, hexa chloro diphenyl, trichloro benzene, etc., are the most widely used hydrocarbons or askarels. Askarels are generally used to impregnate a cellulose insulating material, such as paper or press board etc., for its high breakdown strength.

Silicon Fluids: It is used in the temperature range of 90-220^{0}C and it is clear, water like liquid. It is available in wide range of viscosity and stable in high temperature. They are non-corrosive to metal upto 200^{0}C and bear excellent dielectric properties in wide range of temperature. So it is used as coolants in radio pulse and aircraft transformers.

Fluorinated Liquids: These are non inflammable, chemically stable oils used in temperature range of 50-200^{0}C. They provide efficient heat transfer from the winding and magnetic circuits in comparison to hydrocarbon oils and used in small electric and radio devices, transformers etc. In presence of moisture electrical properties are deteriorated.

Synthetic Hydrocarbon oils: Polybutylene, Polypropylene is the example of synthetic hydrocarbon oils. They have similar dielectric strength; thermal stability and susceptibility to oxidation properties are similar as that of mineral oils. The operating temperature range is 50-110^{0}C. These are used in high pressure gas filled cables and dc voltage capacitors.

Organic Esters: These organic fluids are used in the temperature range of 50-110^{0}C. They have dielectric constant and very low dielectric losses. The dielectric constant ranges from 2 to 3.5. The higher range of is obtained in tetra hydro-furyloxalate. These fluids are well suited for use in high frequency capacitors.

Vegetable Oils: These insulating liquids have temperature range of 20-100^{0}C. Drying oils are generally suitable in the formation of insulating varnishes, while non-drying oils are used as plasticisers in insulating resin compositions.

Varnish: It is the liquid form of resinous matter in oil or a volatile liquid. Hence by applying, it dries out by evaporation or chemical action to form hard, lustrous coating, which is resistant to air and water.

It is used to improve the insulation properties, mechanical strength and to reduce degradation caused by oxidation and adverse atmospheric condition.

SOLID INSULATING MATERIALS: PROPERTIES AND APPLICATIONS

Mica: two kind of mica are used as neutral insulating material in electrical engineering. Those are Muscovite mica and Phlogophite mica.

1.Muscovite Mica: The chemical composition of muscovite mica is $KAI_3SiO_3O_{10}(OH)_2$. It is translucent green, ruby, silver or brown and is strong, tough and flexible. It exhibits good corrosion resistance and is not affected by alkalis. It is used in capacitors and commutators.

2. ***Phlogophite Mica:*** The chemical composition of this is, $KMg_3AlSiO_3O_{10}(OH)_2$. It possesses less flexibility. It is amber, yellow, green or grey in colour. It is more stable, but electrical properties are poorer compared to Muscovite Mica. It is used in thermal stability requirements, such as in domestic appliances like iron, hotplates etc.

Polyethylene: It is obtained by polymerization of ethylene. The polymerization is performed in the presence of catalyst at atmospheric temperature and pressure around 100^0C. To obtain heat resistance property polythene is subjected to ionizing radiation.

Polyethylene exhibits good electrical and mechanical properties, moisture resistant and not soluble in many solvents except benzene and petroleum at high temperature. The dielectric constant and power factor remains steady over a wide range of temperature.

It is used as general purpose insulation, insulations of wires and cable conductors, in high frequency cables and television circuits, jacketing material of cables. Polyurethane films are also used as dielectric material in capacitors.

Teflon: The chemical name of Teflon is Polytetra fluoro-ethylene. This is synthesized by polymerization of tetra fluro ethylene. It bears good electrical, mechanical and thermal properties. Its dielectric constant is 2 to 2.2, which does not change with time, frequency and temperature. Its insulation resistance is very high and water resistant.

It is used as dielectric materials in capacitors, covering of conductors and cables, as base material for PCBs.

Polyvinyl Chloride (PVC): It is obtained by polymerization of vinyl chloride in the presence of a catalyst at 50^0C. PVC exhibits good electrical and mechanical properties. It is hard, brittle, and non-hygroscopic and can resist flame and sun light.

PVC used as insulation material for dry batteries, jacketing material for wires and cables.

Epoxy Glass: Epoxy glass is made by bonding two or more layer of material. The layers used reinforcing glass fibers impregnated with an epoxy rasin. It is water resistant and not affected by alkalis and acids.

It is used as base material for copper-clad sheets used for PCBs, terminal port, instrument case etc.

Bakelite: It is hard, dark colored thermosetting material, which is a type of phenol formaldehyde. It is widely used for manufacture of lamp holders, switches, plug socket and bases and small panel boards.

MAGNETIC MATERIALS

Materials in which a state of magnetization can be induced are called magnetic materials when magnetized such materials create a magnetic field in the surrounding space.

The property of a material by virtue of which it allows itself to be magnetized is called permeability. The permeability of free space is denoted by μ_o. Its value $\mu_o = 4\pi \times 10^{-7}$.

The material permeability $\mu = \mu_o \times \mu_r$

When μ_r = Relative permeability

Classification of Magnetic materials :

Magnetic materials classified as :

a. Diamagnetic material
b. Para-magnetic material
c. Ferro-magnetic material

DIAMAGNETIC MATERIAL:

The materials which are repelled by a magnet are known as diamagnetic materials. Eg. Zinc, Mercury, lead, Sulphur, Copper, Silver. Their permeability is slightly less than one. They are slightly magnetized when placed in a strong magnetic field and act in the direction opposite to that of applied magnetic field.

PARAMAGNETIC MATERIALS:

The materials which are not strongly attracted by a magnet are known as paramagnetic materials. Eg. Aluminium, Tin, Platinum, Magnesium, Manganese, etc. Their relative permeability‟s is small but positive. Such materials are slightly magnetized when placed in a strong magnetic field and act in the direction of the magnetic field.

In paramagnetic materials the individual atomic dipoles are oriented in a random fashion. So the resultant magnetic field is negligible. When an external magnetic field is applied. The permanent magnetic dipoles orient themselves parallel to the applied magnetic field and give rise to a positive magnetization.

FERRO-MAGNETIC MATERIALS

The materials which are strongly attracted by a magnet are known as ferro-magnetic materials. Their permeability is very high. Eg. Iron, Nikel, Cobalt, etc.

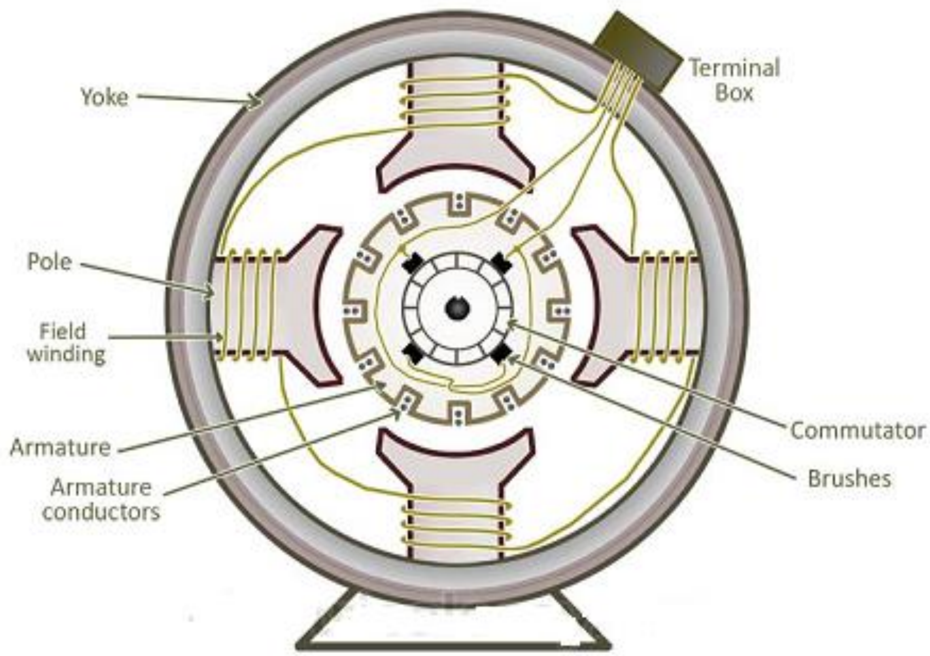
The opposing magnetic effects of electron orbital motion and electron spin do not eliminate each other in an atom of such a material.

MODULE II - DC GENERATORS

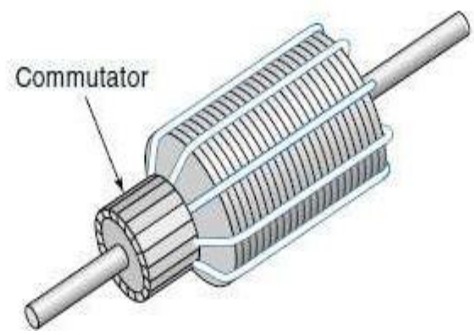
Constructional Features

A dc generator is an electrical machine which converts mechanical energy into direct current electricity**.** This energy conversion is based on the principle of production of dynamically induced emf.

The figure shown below shows constructional details of a simple **4-pole DC machine**. A DC machine consists of two basic parts; stator and rotor. Basic constructional parts of a DC machine are described below.



Cross sectional view of DC Machine



Armature of DC Machine

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.

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 approximately 0.5 mm 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.

It function is to provide a path of very low reluctance to the flux through the armature from a N- pole to a S-pole.

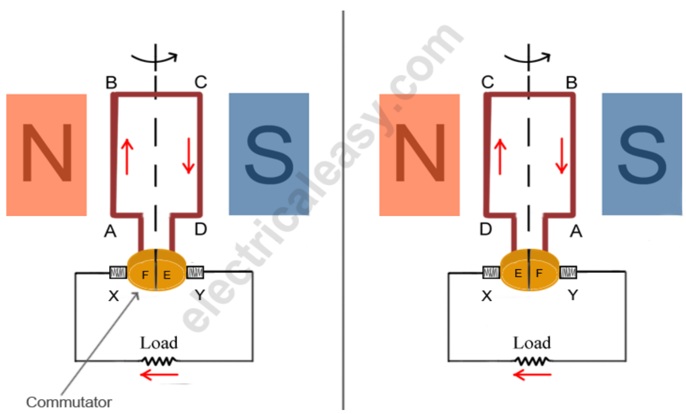
5. **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings 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.

Working principle of a DC generator:

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with a closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors. The direction of induced current is given by Fleming's right hand rule.

Need of a Split ring commutator:



According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating. If you look at the above figure, you will know how the direction of the induced current is alternating in an armature conductor. But with a split ring commutator, connections of the armature conductors also gets reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

Classification of DC Generator:

DC generators are classified based on how their fields are excited (i.e. produced). There are thwo methods of excitation:

1. **Separately Excited DC Generators** – Field coils excited by some external source
2. **Self Excited DC Generators** – Field coils excited by the generator itself

Self-excited DC generators can further be classified depending on the position of their field coils. The three types of self-excited DC generators are:

1. Series Wound Generators
2. Shunt Wound Generators
3. Compound Wound Generators

Compound Wound Generators is again classified in to two type

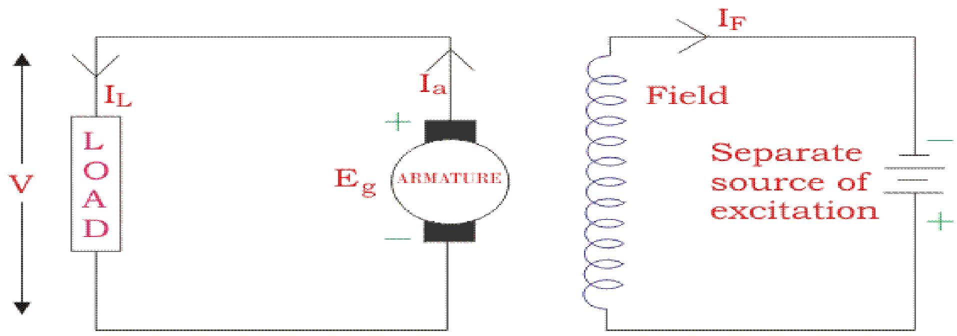
1. Long Shunt

2. Short shunt

Separately Excited DC Generator

These are the generators whose field magnets are energized by some external DC source, such as a battery. A circuit diagram of separately excited DC generator is shown in the figure below. The symbols below are:

- I_a = Armature current
- I_L = Load current
- V = Terminal voltage
- E_g = Generated EMF (Electromagnetic Force)



Separately Excited DC Generator

Voltage drop in the armature = $I_a \times R_a$ (Ra is the armature resistance)

Let,

$$I_a = I_L = I\ (say)$$

Then,

$$voltage\ across\ the\ load, V = IR_a$$

Power generated is equal to

$$P_g = E_g \times I$$

And power delivered to the external load is equal to

$$P_L = V \times I$$

Self Excited DC Generators

Self-excited DC generators are generators whose field magnets are energized by the current supplied by themselves. In these type of machines, field coils are internally connected with the armature.

Due to residual magnetism, some flux is always present in the poles. When the armature is rotated, some EMF is induced. Hence some induced current is produced. This small current flows through the field coil as well as the load and thereby strengthening the pole flux.

As the pole flux strengthened, it will produce more armature EMF, which cause the further increase of current through the field. This increased field current further raises armature EMF, and this cumulative phenomenon continues until the excitation reaches the rated value.

According to the position of the field coils, self-excited DC generators may be classified as:

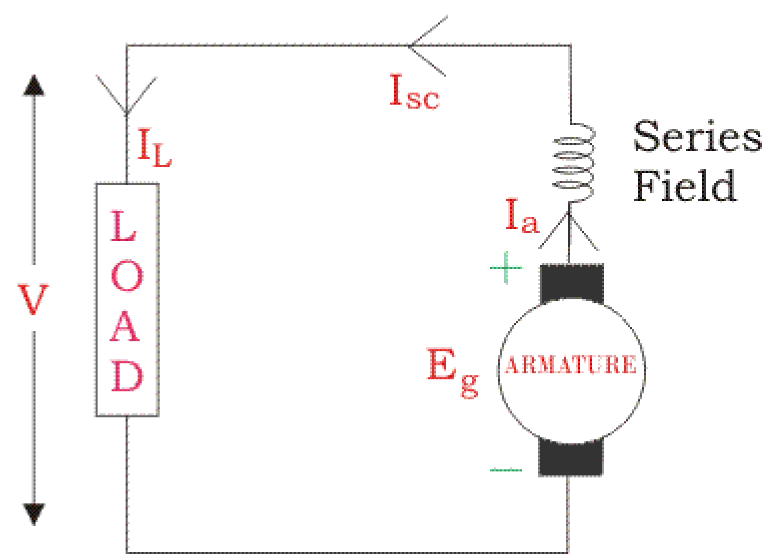
1. Series Wound Generators
2. Shunt Wound Generators
3. Compound Wound Generators

Series Wound Generator

In these type of generators, the field windings are connected in series with armature conductors, as shown in the figure below.

Whole current flows through the field coils as well as the load. As series field winding carries full load current it is designed with relatively few turns of thick wire. The electrical resistance of series field winding is therefore very low (nearly 0.5Ω).
Here:

- R_{sc} = Series winding resistance
- I_{sc} = Current flowing through the series field
- R_a = Armature resistance
- I_a = Armature current
- I_L = Load current
- V = Terminal voltage
- E_g = Generated EMF



Series Wound Generator

Then,

$$I_a = I_{sc} = I_L = I\ (say)$$

Voltage across the load is equal to,

$$V = E_g - I(I_a \times R_a)$$

Power generated is equal to,

$$P_g = E_g \times I$$

Power delivered to the load is equal to,

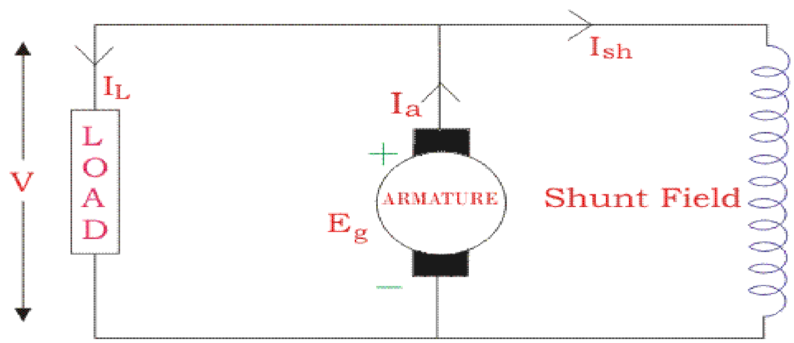
$$P_L = V \times I$$

Shunt Wound DC Generators

In these type of DC generators, the field windings are connected in parallel with armature conductors, as shown in the figure below. In shunt wound generators the voltage in the field winding is same as the voltage across the terminal.

Here:

- R_{sh} = Shunt winding resistance
- I_{sh} = Current flowing through the shunt field
- R_a = Armature resistance
- I_a = Armature current
- I_L = Load current
- V = Terminal voltage
- E_g = Generated EMF



Shunt Wound Generator

Here armature current I_a is dividing in two parts – one is shunt field current I_{sh}, and another is load current I_L.

So,

$$I_a = I_{sh} + I_L$$

The effective power across the load will be maximum when I_L will be maximum. So, it is required to keep shunt field current as small as possible. For this purpose the resistance of the shunt field winding generally kept high (100 Ω) and large no of turns are used for the desired EMF.
Shunt field current is equal to,

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

Voltage across the load is equal to,

$$V = E_g - I_a R_a$$

Power generated is equal to,

$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

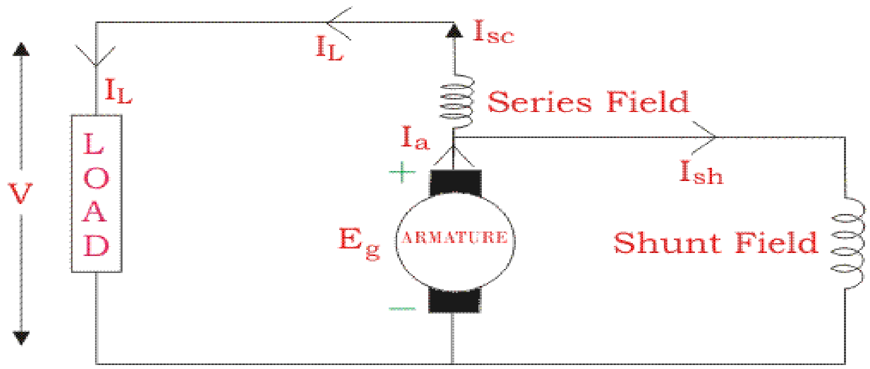
Compound Wound DC Generator

In series wound generators, the output voltage is directly proportional with load current. In shunt wound generators, the output voltage is inversely proportional with load current.
A combination of these two types of generators can overcome the disadvantages of both. This combination of windings is called compound wound DC generator.

Compound wound generators have both series field winding and shunt field winding. One winding is placed in series with the armature, and the other is placed in parallel with the armature. This type of DC generators may be of two types- short shunt compound-wound generator and long shunt compound-wound generator.

Short Shunt Compound Wound DC Generator

Short Shunt Compound Wound DC Generators are generators where only the shunt field winding is in parallel with the armature winding, as shown in the figure below.



Short Shunt Compound Wound Generator

Series field current is equal to,

$$I_{sc} = I_L$$

Shunt field current is equal to,

$$I_{sh} = \frac{(V + I_{sc}R_{sc})}{R_{sh}}$$

Armature current is equal to,

$$I_a = I_{sh} + I_L$$

Voltage across the load is equal to,

$$V = E_g - I_aR_a - I_{sc}R_{sc}$$

Power generated is equal to,

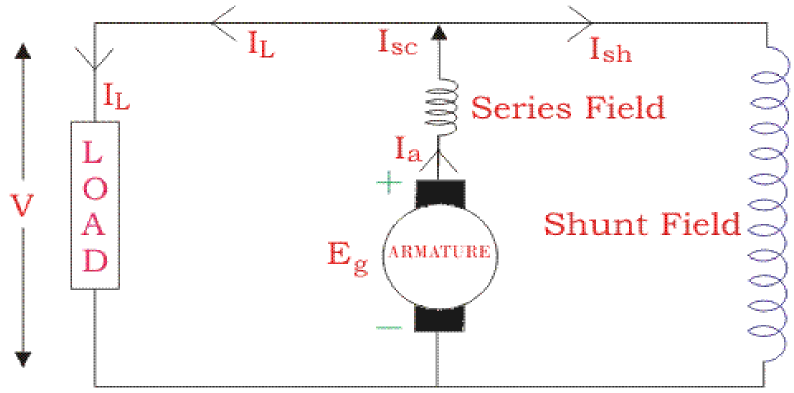
$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

Long Shunt Compound Wound DC Generator

Long Shunt Compound Wound DC Generator are generators where the shunt field winding is in parallel with both series field and armature winding, as shown in the figure below.



Long Shunt Compound Wound Generator

Shunt field current is equal to,

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

Armature current, I_a = series field current,

$$I_{sc} = I_L + I_{sh}$$

Voltage across the load is equal to,

$$V = E_g - I_a R_a - I_{sc} R_{sc} = E_g - I_a (R_a + R_{sc}) \ [\therefore I_a = I_{cs}]$$

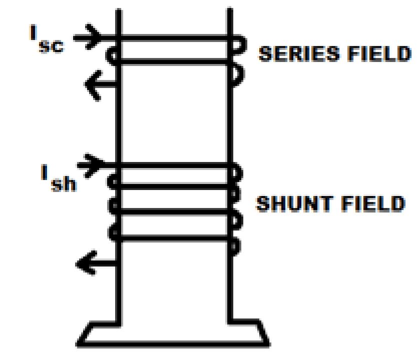
Power generated is equal to,

$$P_g = E_g \times I_a$$

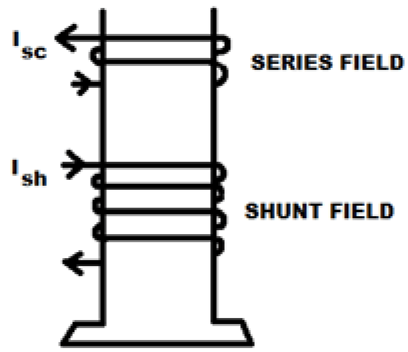
Power delivered to the load is equal to,

$$P_L = V \times I_L$$

In a compound wound generator, the shunt field is stronger than the series field. When the series field assists the shunt field, generator is said to be **commutatively compound wound**.



CUMULATIVE COMPOUNDING



DIFFERENTIAL COMPOUNDING

On the other hand, if the series field opposes the shunt field, the generator is said to be **differentially compound wound**.

1.20 E.M.F. EQUATION OF A D.C. GENERATOR

We shall now derive an expression for the e.m.f. generated in a d.c. generator.

Let ϕ = flux/pole in Wb

Z = total number of armature conductors

P = number of poles

A = number of parallel paths = 2 .... for wave winding

= P .... for lap winding

N = speed of armature in r.p.m.

E_g = e.m.f. of the generator = e.m.f./parallel path

Flux cut by one conductor in one revolution of the armature,

$$d\phi = P\phi \text{ webers}$$

Time taken to complete one revolution,

$$dt = 60/N \text{ second}$$

$$\text{e.m.f. generated/conductor} = \frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60} \text{ volts}$$

e.m.f. of generator, E_g = e.m.f. per parallel path

= (e.m.f./conductor) × No. of conductors in series per parallel path

$$= \frac{P\phi N}{60} \times \frac{Z}{A}$$

$$\therefore \quad E_g = \frac{P\phi Z N}{60\, A}$$

where $A = 2$ ... *for wave winding*

$= P$ ... *for lap winding*

Parallel Operation of DC Generator

Advantages of DC generator operating in parallel

In a dc power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large generator. This is due to the following reasons:

a. 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.

b. Efficiency:
Generators run most efficiently when loaded to their rated capacity. Therefore, when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

c. 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 load is being supplied by other units. This leads to both safety and economy.

d. 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.

e. 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.

Connection of Parallel DC Generators

1. The generators in a power plant, connected by heavy thick copper bars, called bus-bars which act as positive and negative terminals. To connect the generators in parallel, Positive terminal of the generators are connected to the positive terminal of the bus-bars and negative terminals of generators are connected to negative terminal of the bus-bars, as shown in the figure.

2. To connect the 2 generators with the 1 existing working generators, first we have to bring the speed of the prime mover of the 2nd generator to the rated speed. At this point switch S_4 is closed.

3. The circuit breaker V_2 (voltmeter) connected across the open switch S_2 is closed to complete the circuit. The excitation of the generator 2 is increased with the help of field rheostat till it generates voltage equal to the voltage of bus-bars.

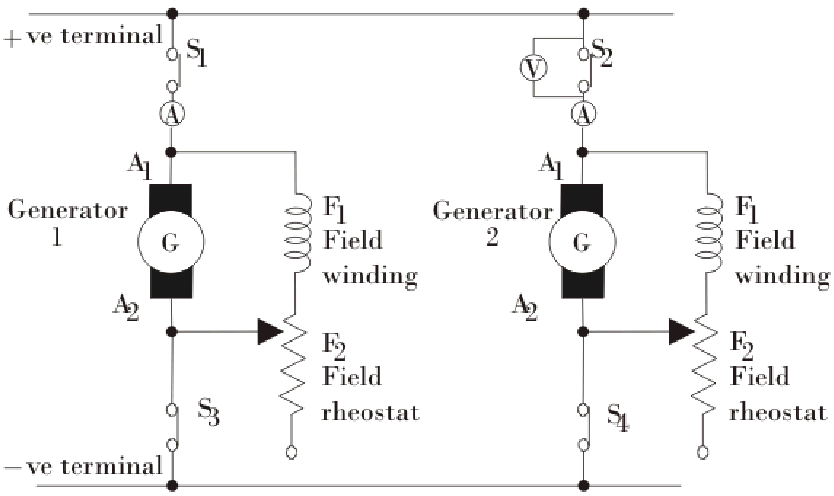
4. The main switch S_2 is then closed and the generator 2 is ready to be paralleled with existing generator. But at this point of time generator 2 is not taking any load as its induced e.m.f. is equal to bus-bar voltage. The present condition is called floating, that means ready for supply but not supplying current to the load.

5. In order to deliver current from generator 2, it is necessary that its induced e.m.f. E should be greater than the bus-bars voltage V. By strengthening the field current, the induced e.m.f. of generator 2 could be improved and the current supply will get started. To maintain bus-bar voltage, the field of generator 1 is weakened so that value remains constant.

Field current I given by

$$I = \frac{E - V}{R_a}$$

Where, R_a is resistance of armature winding.



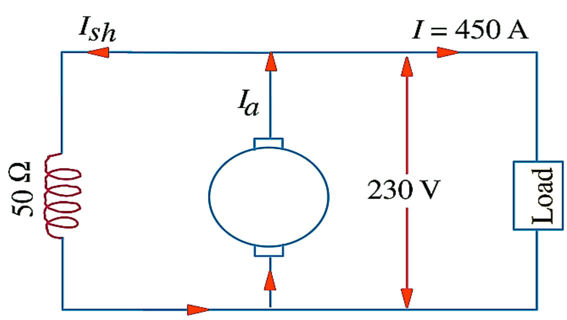
Example1: A four pole generator, having lap wound armature winding has 51 slot containing 20 conductors. What will be the voltage generated in the machine when driven at 1500 rpm assuming the flux per pole to be 7.0 mWb?

Solution: $Eg = \frac{P\phi ZN}{60A}$ volt

$\Phi = 7\text{x } 10^{-3}$ Wb, Z = 51 x 20= 1020, A=P= 4, N= 1500 rpm

$\therefore Eg = \frac{4\times7\times10^{-3}\times1020\times1500}{60\times4}$ volt= 1785 volt

Example2. 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:

$$\begin{aligned}
&\textit{Current through shunt field winding is,}\\
I_{sh} &= 230/50 = 4.6\ A\\
\textit{Load current, } I &= 450\ A\\
\therefore \textit{Armature Current } I_a &= I + I_{sh}\\
&= 450 + 4.6 = 454.6\ A\\
\textit{Armature Voltage Drop, } I_a R_a &= 454.6 \times 0.03\\
&= 13.6\ V\\
\textit{Now, Generated Emf, } E_g &= \textit{terminal voltage} + \textit{armature drop}\\
&= V + I_a R_a\\
&\therefore \textit{Emf generated in armature}\\
E_g &= 230 + 13.6\\
&= 243.6\ V
\end{aligned}$$

<u>Example 3:</u> An 8-pole dc shunt generator with 778 wave-connected armature conductors and running at 500 rpm supplies a load of 12.5 ohm resistance at terminal voltage of 250 V. The armature resistance is 0.24 ohm and the field resistance is 250 ohm. Find the armature current, the induced emf and the flux per pole.

Solution:

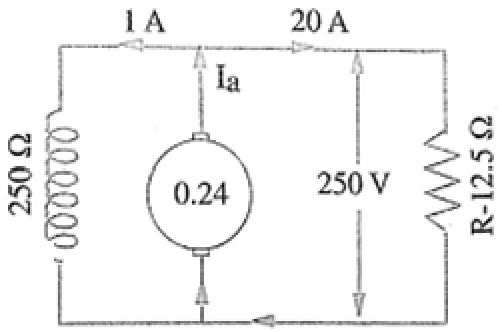
The circuit is shown

$$\begin{aligned}
\text{Load current} &= V/R = 250/12.5 = 20\text{ A}\\
\text{Shunt current} &= 250/250 = 1\text{ A}\\
\text{Armature current} &= 20 + 1 = 21\text{ A}\\
\text{Induced e.m.f.} &= 250 + (21 \times 0.24) = 255.04\text{ V}
\end{aligned}$$

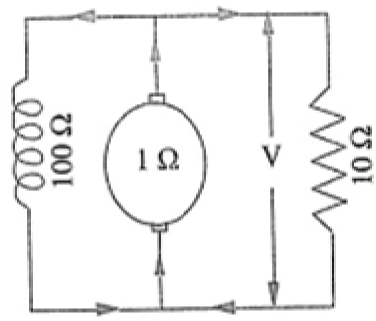
Now, $$E_g = \frac{\Phi Z N}{60} \times \left(\frac{P}{A}\right)$$

$$\therefore \quad 255.04 = \frac{\Phi \times 778 \times 500}{60}\left(\frac{8}{2}\right)$$

$$\therefore \quad \Phi = 9.83\text{ mWb}$$



<u>Example 4:</u> A 4- pole dc shunt generator with a shunt field resistance of 100 ohm and an armature resistance of 1 ohm has 378 wave connected conductors in its armature. The flux per pole is 0.02 Wb. If a load resistance of 10 ohm is connected across the armature terminals and the generator is driven at 1000 rpm, calculate the power absorbed by the load.



Solution:

Induced e.m.f. in the generator is

$$E_g = \frac{\Phi Z N}{60}\left(\frac{P}{A}\right) \text{ volt}$$

$$= \frac{0.02 \times 378 \times 1000}{60}\left(\frac{4}{2}\right) = 252 \text{ volt}$$

Now, let V be the terminal voltage *i.e.* the voltage available across the load as well as the shunt resistance

Load current = $V/10$ A and Shunt current = $V/100$ A

Armature current = $\frac{V}{10} + \frac{V}{100} = \frac{11\,V}{100}$

Now, $V = E_g$ – armature drop

$$\therefore \quad V = 252 - 1 \times \frac{11\,V}{100} \quad \therefore \quad V = 227 \text{ volt}$$

Load current = 227/10 = 22.7 A, Power absorbed by the load is = 227×22.7 = **5,153 W**