**Electric Machinery Fundamentals**

- An electrical machine is a device that can convert either mechanical energy to electrical energy (**generator**) or electrical energy to mechanical energy (**motor**). Since any given electrical machine can convert power in either direction, any machine can be used as either a generator or a motor.

- **The transformer** is an electrical device that is closely related to electrical machines. It converts AC electrical energy at one voltage level to AC electrical energy at another voltage level.

- **Magnetic fields** are the fundamental mechanism by which energy is converted from one form to another in motors, generators, and transformers.

- Four basic principles describe how magnetic fields are used in these devices:
  1. A current-carrying wire produces a magnetic field in the area around it.
  2. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. (This is the basis of **transformer action**.)
  3. A moving wire in the presence of a magnetic field has a voltage induced in it. (This is the basis of **generator action**.)
  4. A current-carrying wire in the presence of a magnetic field has a force induced on it. (This is the basis of **motor action**.)
I. Magnetic Field Sources

A current-carrying wire produces a magnetic field in the area around it.
The basic law governing the production of a magnetic field is given by a current is **Ampere's law**:

\[ \oint H \, dl = NI \]

- \( H \): magnetic field intensity (Amp. Turns/m)
- \( I \): Current passing through coil.
- \( N \): Number of coil turns.
- \( dl \): differential element of length along the path of integration (m).

If the core is composed of iron or certain other similar metals with high magnetic permeability (collectively called ferromagnetic materials), essentially all the magnetic field produced by the current will remain inside the core, so the path of integration in Ampere's law is the mean path length of the core \( l_c \). Ampere's law thus becomes

\[ NI = H l_c \]

The strength of the magnetic field flux produced in the core also depends on the material of the core. The relationship between the magnetic field intensity \( H \) and the resulting magnetic flux density \( B \) produced within a material is given by

\[ H = \frac{B}{\mu} \]

- \( B \): magnetic field density (tesla)
- \( \mu \): magnetic field permeability of material (H/m)

Permeability of space is \( \mu_0 = 4\pi \times 10^{-7} \) (H/m), while permeability of any other material compared to that of free space is called relative permeability \( (\mu_r) \)

\[ \mu_r = \frac{\mu}{\mu_0} \]

Since

\[ \beta = \frac{\Phi}{A} \]

Hence,

\[ NI = H l = \frac{B l}{\mu} = \phi A \mu = \phi R \]

- \( NI \): magneto motive force (Amp. Turns)
- \( \Phi \): flux lines (weber)
- \( A \): Core cross sectional area (m²)
- \( R \): Material reluctance (Amp. Turn/weber)
Example

\[ NI = \phi_R c + \phi_R \text{airgap} \]

\[ 400 NI = \phi \frac{I_c}{\mu_c} + \phi \frac{0.0005}{A_{\text{airgap}}} \]

\[ \phi = B_c \frac{l_c}{\mu_c} + \frac{B_{\text{airgap}}}{\mu_0} l_{\text{airgap}} = H_c l_c + H_{\text{airgap}} l_{\text{airgap}} \]
II. Basis of Transformer Action (Faraday Law of Induced Voltage from a Time-Changing Magnetic Field)

Faraday’s law states that if a flux passes through a turn of a coil of wire, a voltage will be induced in the turn of wire that is directly proportional to the rate of change in the flux with respect to time.

\[ e_{\text{induced}} = -N \frac{d\Phi}{dt} \]

- \( e_{\text{induced}} \): Induced voltage at coil terminal
- \( N \): Number of turns of wire in a coil
- \( \Phi \): Flux passing through the coil

The minus sign in the equations is an expression of Lenz’s law. Lenz’s law states that the direction of the voltage buildup in the coil is such that if the coil ends were short circuited, it would produce current that would cause a flux opposing the original flux change.

Instead of the moving magnet, if a time varying current is passed through a coil, a time-changing flux is produced which when transferred to another coil, induces a voltage across its terminals. This is the basis of the transformer action which transforms the voltage level according to the number of turns in each coil.
III. Basis of Generator Action

A wire, moving through a magnetic field, has a voltage induced in it. If the wire circuit is closed, a current is induced with a direction determined according to Fleming’s right hand rule. This is basis of generator action (mechanical energy + magnetic field → electrical energy)
IV. Basis of Motor Action

A force is induced on a current-carrying wire placed within a magnetic field. The direction of the force is given by Fleming’s left-hand rule: If the index finger of the left hand points in the direction of the current vector and the middle finger points in the direction of the flux density vector $B$, then the thumb points in the direction of the resultant force on the wire.

$$\vec{F} = L \vec{I} \times \vec{B}$$

- $\vec{F}$: Force induced in a wire
- $L$: Length of wire
- $\vec{I}$: Current vector passing through the wire
- $\vec{B}$: Magnetic field density
If a current carrying loop is placed in a magnetic field, a torque is produced which causes a rotational movement of the loop which is the basis of motor action (electrical energy + magnetic field → mechanical energy).

The torque on an object is defined as the product of the force applied to the object and the distance from object’s axis of rotation to the line of action of the force.

\[ \vec{T} = r \times \vec{F} \]  
\( (Nm) \)

Analogy between rotational movement and linear movement

\[ \theta: \text{angular displacement (radians or degrees)} \]
\[ \omega: \text{angular velocity} = \frac{d\theta}{dt} \text{ (rad/sec)} \]
\[ T: \text{Torque applied to rotate the object (Nm)} \]
\[ W: \text{Work applied} = T\theta \text{ (Joule), for constant torque} \]
\[ P: \text{Power developed} = \frac{dW}{dt} = T\omega \text{ (Watt), for constant torque} \]

\[ F: \text{Force applied to move the object linearly (N)} \]
\[ W: \text{Work applied} = FS \text{ (Joule), for constant force} \]
\[ P: \text{Power developed} = \frac{dW}{dt} = Fv \text{ (Watt), for constant force} \]
DC Generator
An electrical DC machine can convert mechanical energy into **direct current electricity (DC generator)** or vice versa (**DC motor**) without any constructional changes. Thus, a DC generator or a DC motor can be broadly termed as a **DC machine**.
I. Construction of DC machine
The DC machine mainly consists of two parts; stator and rotor

I. **STATOR**: that houses the field winding which is the source of magnetic flux in the DC machine;

- **Yoke**: An outer frame made up of cast iron or steel to provide mechanical strength and protective covering to the whole machine and also carries the magnetic flux produced by the field winding.

- **Poles**: The magnetic poles are made of thin laminations of silicon steel structures fitted onto the inner wall of the yoke with screws or welding. The pole core carries field winding.

- **Field winding**: Usually made of copper wire and wound over the pole slots and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles, hence producing magnetic flux.

- **Eye Bolt**: It helps to shift the machine from one place to another or for level change.
II. Rotor: which contains slots to carry armature windings and provides the rotating element in the DC machine

- **Armature core:** It is cylindrical in shape with slots to carry armature winding. The armature core is built up of thin laminated circular silicon steel disks for reducing eddy current losses.

- **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.

- **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement;

  The commutator is made of a set of hard drawn copper segments 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.

  Its main function, in a DC generator, is to collect the current generated in armature conductors and change it from internal AC to DC output. Whereas, in case of a DC motor, commutator helps in providing current to the armature conductors that can produce a rotating torque in them.

  Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping same physical contact.
Need of Commutator

Using a semicircular commutating segments, whenever current reversal occurs at the armature conductors, the sliding commutator segment reverses connection to the brushes. And therefore, the output at the fixed contacts (brushes) is always built up in the same way resulting in unidirectional DC output current.
Armature conductors arrangements

Most of the armature windings consist of diamond-shaped preformed coils which are inserted into the armature slots as a unit. Each coil consists of a number of turns (loops) of wire, and each side of a turn is called a conductor. Hence, the number of conductors on a machine's armature is given by

\[ Z = 2CN_c \]

where:
- \( Z \) = number of conductors on rotor
- \( C \) = number of coils on rotor
- \( N_c \) = number of turns per coil

Finally, there are two basic sequences of armature winding connections to the Commutator; lap windings and wave windings.

In lap winding, the number of parallel paths (A) = Number of poles (P).

In wave winding, the number of parallel paths is two (A=2).

Lap winding is suitable when requirement is: Large DC currents and low voltage.

Wave winding is suitable when requirement is: Low DC current and high voltage.
II. Operation Principle of DC generator

According to Faraday’s laws of electromagnetic induction, whenever a conductor is moved in a magnetic field, an emf (electromotive force) gets induced in the conductor. If the conductor is provided with the 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. The magnitude of induced emf can be calculated from the emf equation of dc generator.

EMF Equation

\[ P = \text{number of field poles} \]
\[ \Phi = \text{flux produced per pole in Wb (weber)} \]
\[ Z = \text{total no. of armature conductors} \]
\[ A = \text{no. of parallel paths in armature} \]
\[ n_m = \text{rotational speed of armature in revolutions per min (rpm)} \]

Induced armature voltage (emf) per conductor depends on \( \frac{d\Phi}{dt} \),

Flux cut per conductor in one revolution = \( \Phi P \),

Number of revolutions per second \( (f_m) = \frac{n_m}{60} \),

and time for one revolution = \( \frac{1}{f_m} = \frac{60}{n_m} \),

Hence, generated emf/conductor = \( \Phi P \frac{n_m}{60} \)

Since, generated emf for parallel paths is equal;

Hence, total induced e.m.f \( (E_A) = \frac{Z}{A} \Phi P \frac{n_m}{60} \)

Since \( \omega_m = \frac{2\pi n_m}{60} \), \( E_A = \frac{ZP}{2\pi A} \Phi \omega_m \) (volts)

\[ E_A = K\Phi \omega_m \], where \( K = \frac{ZP}{2\pi A} \)
Adding more armature coils smooth out induced voltage fluctuation and changes the direct current from pulsating to regular DC.
III. Power flow diagram

DC generators take in mechanical power and produce electric power. The efficiency of a DC machine is defined by

\[ \eta = \frac{P_{out}}{P_{in}} \times 100\% \]

\[ \eta = \frac{P_{in} - P_{loss}}{P_{in}} \times 100\% \]

\[ P_{in} = T_{app} \cdot \omega_m \]

\[ P_{developed} = T_{dev} \cdot \omega_m = E_A I_A \]

\[ P_{out} = V_T I_L \]

Input mechanical power

Copper losses

Stray losses

Rotational losses

Total losses

Output electrical power

\[ P_{out} = P_{in} - \text{total losses} \]

\[ P_{dev} = P_{in} - \text{stray losses-rotational losses} = P_{out} + \text{copper losses} \]
The Losses in DC Machines

The losses that occur in DC machines can be divided into four basic categories:

1. Electrical or copper losses
2. Core losses
3. Mechanical losses
4. Stray load losses

**ELECTRICAL OR COPPER LOSSES.** Copper losses are the losses that occur in the armature and field windings of the machine.

\[
\begin{align*}
\text{Armature loss:} & \quad P_A = I_A^2 R_A \\
\text{Field loss:} & \quad P_F = I_F^2 R_F
\end{align*}
\]

**CORE (or MAGNETIC) LOSSES.** The core losses are losses encountered in the magnetic core of the machine which include the hysteresis losses and circulating eddy current losses.

**MECHANICAL LOSSES** There are two basic types of mechanical losses: *friction* and *windage*. Friction losses are caused by the friction of the bearings in the machine with the shaft and friction between brushes and commutator, while windage losses are caused by the friction between the moving parts of the machine and the air inside the motor's casing.

**STRAY LOAD LOSSES**

Stray losses are losses that cannot be placed in one of the previous categories such as losses due to distorted flux and short circuit currents in coils.
DC generators can be classified in two main categories, (i) Separately excited and (ii) Self-excited.

i. **Separately excited**: In this type, field coils are energized from an separate external DC source. That is, field winding is electrically separated from the armature circuit.

ii. **Self excited**: In this type, field coils are energized from the current produced by the generator itself. Initial emf generation is due to residual flux in field poles. This generated emf causes a part of current to flow in the field coils, thus strengthening the field flux and thereby increasing emf generation.

Field winding and armature winding are interconnected in various ways to achieve wide range of performance characteristics. Depending on that, self-excited DC generators can be further classified divided into two main types

(a) **Shunt wound** - , field flux is derived by connecting the field winding in parallel with the armature winding. Shunt winding is made with large number of turns and the resistance is kept very high (about 100 Ohm). It takes only small current which is less than 5% of the rated armature current.

(b) **Series wound** - field flux is derived by connecting field winding in series with the armature winding. Therefore, the field winding carries whole load current (armature current). That is why series winding is designed with few turns of thick wire and the resistance is kept very low (about 0.5 Ohm).
Separately excited

\[ V_T = E_A - I_A R_A \]
\[ I_L = I_A \]
\[ I_F = \frac{V_F}{R_F} \]

Voltage regulation (VR): \[ VR\% = \frac{V_{Tnl} - V_{Tfl}}{V_{Tfl}} \times 100 \]

where

\( V_{Tnl} \) : No-load terminal voltage of the generator

\( V_{Tfl} \) : Full-load terminal voltage of the generator

Shunt

\[ V_T = E_A - I_A R_A \]
\[ I_A = I_F + I_L \]
\[ I_F = \frac{V_T}{R_F} \]

Series

\[ V_T = E_A - I_A (R_A + R_S) \]
\[ I_A = I_S = I_L \]
V. DC generator characteristics

Generally, the following three characteristics of DC generators are taken into considerations:

1. Open Circuit Characteristic (O.C.C.) \((E_A/I_f)\)

Open circuit characteristic is also known as magnetization curve. This characteristic shows the relation between generator induced e.m.f. \(E_A\) and the field current \(I_f\) at a given speed. The magnetization curve at no-load is almost similar for all type of generators.

2. Loading characteristics \((V_T/I_L)\)

The load characteristic curve shows the relation between the terminal voltage \(V_T\) and load current \(I_L\). The terminal voltage \(V_T\) is less than generated emf \(E_A\) due to voltage drop in the armature circuit in addition to the armature reaction effect.

Armature reaction: The effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator which demagnetizes or weakens the main flux.

Loading characteristic curves differ according to each type of generator as follows;
At no load, the terminal voltage is the internal induced voltage whose characteristic is a straight line as it is independent of load current. When the load is supplied by the generator, increasing the load current \((I_L)\), increases the armature current increasing \(I_A R_A\) drop, thus \(V_T\) decreases. Moreover, due to demagnetizing effect of armature reaction, flux weakens decreasing \((E_A)\), thus causing further decrease in \(V_T\).

To control the generator terminal voltage, either increasing \(\omega_m\) or \(\Phi\) increases \(E_A\), hence increasing \(V_T\). However, in many applications, the speed range of the prime mover is quite limited, so the terminal voltage is most commonly controlled by changing the field current, by changing the field resistance.

Separately excited generators operate in a stable condition with any variation in field excitation. Hence, they are used as supply source of DC motors, whose speeds are to be controlled for various applications.
Shunt generator

\[ V_T = E_A - I_A R_A \]

\[ I_A = I_F + I_L \]

\[ I_F = \frac{V_T}{R_F} \]

\[ E_A = K \Phi \omega_m \]

As the load is increased, \( I_L \) increases, increasing \( I_A \) so the voltage drop \( I_A R_A \) increases as well as the armature reaction effect, decreasing \( V_T \). The latter causes decrease in the field current decreasing flux which in turn decreases \( E_A \) causing further decrease in \( V_T \). That’s why the voltage drop in the shunt generator is steeper than the separately excited generator.

As with the separately excited generator, to control the generator terminal voltage in the shunt generator, either increasing \( \omega_m \) or \( \Phi \) increases \( E_A \), hence increasing \( V_T \). Changing \( I_F \), by changing the field resistance is the main principle to control \( V_T \).

The application of shunt generators are restricted for its dropping voltage characteristic. They are used to supply power to the apparatus situated very close to its position, as lighting, battery charge, for small power supplies
In DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current. Thus, the loading characteristic curve is close to the machine magnetization curve. At no load, there is no field current, so $V_T$ is reduced to a small level given by the residual flux in the machine.

As the load increases, the field current rises, so $E_A$ rises rapidly. The $I_A (R_A + R_s)$ drop goes up too, but at first the increase in $E_A$ goes up more rapidly than the drop rise, so $V_T$ increases.

After a while, the machine approaches saturation, and $E_A$ becomes almost constant. At that point, the resistive drop is the predominant effect, and $V_T$ starts to fall.

This machine gives constant current in the dropping portion of the characteristic curve. For this property they can be used as constant current source and employed for applications as arc welding and for supplying field excitation current in DC locomotives.

\[
V_T = E_A - I_A (R_A + R_s)
\]

\[
I_A = I_S = I_L
\]

\[
E_A = K \Phi \omega_m
\]
Questions

- Discuss the construction of DC machine

- Discuss the theory of operation of DC generator

- What is the need of commutator?

- How to smooth out the DC generator induced voltage?

- What are the losses experienced in the DC machine?

- What are different DC generator types?
  
  Draw their equivalent circuits
  
  Draw their open circuit characteristics
  
  Draw their loading characteristics
  
  How to control their terminal voltage?

State their applications