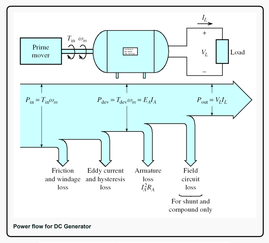
Electrical-Power

DC Generator types

- DC Generators types
  - DC separately generator:
  - DC shunt generator:
  - DC Compound Generator
  - DC Series Generator:



Power flow for DC Generator

- Principle operation of Generator
  - The amount of voltage generated depends on:
    - the strength of the magnetic field.
    - the angle at which the conductor cuts the magnetic field
    - the speed at which the conductor is moved
    - the length of the conductor within the magnetic field
- Separately Excited DC generator

$$E_A = K\phi\omega_m$$

EA = RA * IA + VL

$$V_f = (R_f)I_F \qquad T = K\emptyset I_a$$

$$\text{efficiency} = \frac{P_{out}}{P_{in}} \times 100\%$$

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

- Generator Losses
  - Rotor Copper Loss
  - Rotor Core Loss
  - Field Copper Loss
  - Friction
  - Windage
- Generator Efficiency

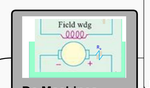
$$P_{in} = T.\omega = T.2\pi n_r/60$$

- **Pin= the input power in watts (W)**
- **T = the input shaft torque in (Nm)**
- **nr = the rotation speed of the shaft in revolutions per minute(rpm)**

$$\eta = P_{out} / P_{in} = V_t I_t / (T.n_r / 7.04)$$

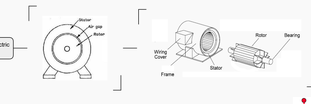
- **η = the efficiency (dimensionless)**
- **Vt = the generator terminal voltage (V)**
- **It = the generator output current (A)**

Dc Machines



- **Fundamentals**
  - Generator action: An emf (voltage) is induced in a conductor if it moves through a magnetic field
  - Motor action: A force is induced in a conductor that has a current going through it and placed in a magnetic field.

  Any DC machine can act either as a generator or as a motor.
- **Construction of DC machine**
  - Rotor (coils / Commutator): Rotating part of the machine, carries a distributed winding where the emf is induced in. Also known as the armature.
  - Stator (Poles): Stationary part of the machine, carries afield winding that is used to produce the required magnetic field by DC excitation. Often known as the field
  - Commutator: behaves as a reversing switch - used to convert the alternating current (AC) into direct current (DC)
- **DC Machine Equivalent Circuit Dc Generator**
  - **The magnetic field produced by the stator poles induces a voltage in the rotor (or armature) coils when the generator is rotated.**
  - **This induced voltage is represented by a voltage source.**
  - **The stator coil has resistance(connected in series)**
  - **The pole flux is produced by the DC excitation/field current**
  - **The field circuit has resistance and a source**
  - **The voltage drop on the brushes represented by a battery**
- **General principles of rotating machines**
  - Electric generators: Electrical Energy ← Generator ← Mechanical Energy; Field
  - Electric motors: Electrical Energy → Motor → Mechanical Energy; Field
- General construction of electric rotating machines



- Electric machines consists of two members; one is stationary and called stator and a rotating member called rotor.
- Air gap must exist between stator and rotor to allow the rotor to rotate.
- Both of stator and rotor are made from magnetic materials and laminated to decrease the eddy current losses

Either the stator or the rotor carry armature windings(emf + torque) and the other member carry the field windings (Flux)

Induction machines

- **Equivalent circuit of I.M**

$$I_r = \frac{E_r}{R_r + jX_r} \qquad I_r = \frac{SE_{r0}}{R_r + jSX_{r0}} = \frac{E_{r0}}{\frac{R_r}{s} + jX_{r0}}$$

KVL at the rotor circuit:

- Power and torque equations

$$P_{g\,p} = 3V_1 I_r \cos(\theta) \rightarrow input\ power$$

$$P_{scu} = 3I_1^2 R_1 \rightarrow stator\ copper\ losses$$

$$P_{core} = \frac{3V_1^2}{R_c} \rightarrow core\ losses$$

$$P_{rcu} = 3I_r^2 R_r \rightarrow rotor\ copper\ losses$$

$$P_{rcu} = 3I_r^2 R_r \rightarrow rotor\ copper\ losses$$

$$P_{mech} = P_{conv} + P_{mcu} \rightarrow mechanical\ losses$$

$$P_g = 3I_r^2 \frac{R_r}{s} \rightarrow air\ gap\ power$$

$$P = 3I_r^2 \frac{R_r^2}{s}(1-s) \rightarrow developed\ power$$

$$P_d = (1-s)P_g,\ P_{rcu} = sP_g$$

$$T_d = \frac{P_d}{\omega_m} = \frac{(1-s)P_g}{(1-s)\omega_s} = \frac{P_g}{\omega_s} \rightarrow Developed\ torque$$

$$T_{out} = \frac{P_{out}}{\omega_m} \rightarrow output\ torque$$

- **Rotor speed and voltage:**

$$N_r = (1-s)N_s$$

$$\omega_r = (1-s)\omega_s$$

At stand still, Nr=0 and the slip s=1.
The mechanical speed of the rotor, in terms of slip and synchronous speed: ==> Er = Er0 (rotor emf at standstill)

$$E_r = SE_{r0}$$

$$f_r = Sf_s$$

==> rotor emf at running

The rotor's EMF is maximum at the starting of the Induction Motor and then starts to decrease with the increase of the rotor speed.

If the rotor attains the synchronous speed, Nr=Ns, so that the slip s = 0:
No induction takes place because there is no relative speed between the flux and the rotor conductors.
No induced EMF in the rotor and hence there is no current induced in the rotor's conductors.
Therefore, there is no torque produced on the rotor and rotor starts to slow down to a speed a little bit lower than the synchronous speed.
The induction motor cannot run at synchronous speed.

- **Induction motor speed**
  - **The difference between the motor speed and the synchronous speed is called the Slip**

$$n_{slip} = n_{sync} - n_m$$

n(slip)= slip speed.
n(sync)= speed of the magnetic field.
n(m)= mechanical shaft speed

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{n_s - n_m}{n_s}$$

$$\omega_{slip} = s\omega$$

if the rotor runs at synchronous speed
s = 0
if the rotor is stationary
s = 1

  - **Synchronous speed: depends on the current frequency (fs) and number of poles(p)**

$$\omega_s = \frac{2\pi}{p} f_s \rightarrow electrical\ angular\ speed\ (synchronous)$$

$$\omega_m = \frac{\omega_s}{p} = \frac{2\pi}{p} f_s \rightarrow mechanical\ angular\ speed\ (synchronous)$$

$$\cdot N = \frac{60}{2\pi}\omega$$

$$\therefore N_s = \frac{60 f_s}{P}$$

==> mechanical synchronous speed

- **Construction**
  - Induction motor (I.M.) consists of stator and rotor separated by an air gap
    - Stator
      - **==Made of high permeability steel.**
      - **==Laminated to decrease eddy Losses.**
      - **==Cylindrical shape with slots.**
      - **==Carry three or single phase armature windings**
    - Rotor
      - Wound rotor: **Cylindrical and slotted.** **Carry poly phase windings.** **The ends of each phase are connected to a slip ring.** **The terminals of all field windings are short circuited**
      - Squirrel cage rotor: **Laminated Iron core with slots** **Aluminum bars are molded in the slots** **Two rings are used to short circuit the bars** **The bars perform the same task of the winding**

Slip Ring Rotor	Squirrel Cage Rotor
Construction is complicated due to presence of slip ring and brushes.	Construction is very simple.
The rotor winding is similar to the stator winding	The rotor consists of rotor bars which are permanently shorted with the help of end rings
We can easily add rotor resistance by using slip ring and brushes	The rotor bars are permanently shorted, its not possible to add external resistance.
Due to presence of external resistance high starting torque can be obtained	Slip ring and brushes are absent

This motor is rarely used only 10% industry uses slip ring induction motor.	Less rotor copper losses and hence high efficiency.
Slip ring induction motor are used where high starting torque is required. i.e in hoists, cranes, elevator etc.	Squirrel cage induction motor is used in lathes, drilling machine, fan, blower, printing machines etc.

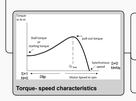
$$f_r = \frac{P \times n}{120}$$

The frequency of the voltage induced in the rotor is given by

$$f_r = \frac{P \times (n_s - n_m)}{120} = \frac{P \times sn_s}{120} = sf_e$$

fr = the rotor frequency (Hz)
P = number of stator poles
n = slip speed (rpm)

- **When the rotor is blocked (s=1) , the frequency of the induced voltage is equal to the supply frequency**
- **On the other hand, if the rotor runs at synchronous speed (s = 0), the frequency will be zero**



Torque- speed characteristics

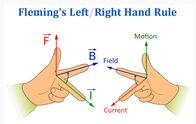
$$\tau_{load} = \frac{P_{out}}{\omega_m}\ N.m \qquad \omega_m = \frac{2\pi n_m}{60}\ rad//s$$

Another unit used to measure mechanical power is the horse power

refer to the mechanical output power of the motor

$$hp = 746\ watts$$

Fleming's Left / Right Hand Rule



Single-phase transformer

الّلَهُمَّ انْفَعْنِي بما علمتني، وعلمني ما ينفعني، وَارْزُقْنِي علما ينفعني

$$e = N\frac{d\phi}{dt}$$

faraday's law

ZL will be seen from the primary side as follows

$$\therefore Z_{L1} = Z_{L2}\left(\frac{N_1}{N_2}\right)^2$$

$$\frac{N_1}{N_2} = a = turns\ ratio$$

$$\therefore Z_1 = Z_2 a^2$$

$$Z_{L2} = \frac{V_2}{I_2}$$

The referred impedance of the transformer

$$\frac{e_1}{e_2} = \frac{N_1}{N_2} \approx \frac{V_1}{V_2} \approx \frac{I_2}{I_1}$$

Power input = power output

Ideal Transformer (no losses)

Note that the emf leads the flux by 90°.

$$e_1(t) = \omega N_1 \varphi_{max} \sin(\omega t + 90)$$

$$e_1 = N_1\frac{d\phi}{dt} \qquad e_2 = N_2\frac{d\phi}{dt}$$

then the induced voltages are given by:

$$\varphi(t) = \varphi_{max}\sin\omega t$$

If the flux varies sinusoidally, such that:

$$E_{1rms} = 4.44 f N_1 \varphi_{max}$$

$$E_{2rms} = 4.44 f N_2 \varphi_{max}$$

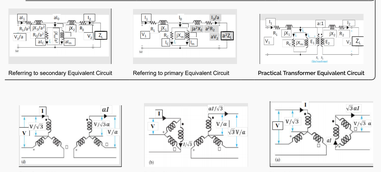
The RMS values of the emf's are given by:

$$e(t) = E_{max}\sin(\omega t)$$

$$E_{1max} = \omega N_1 \varphi_{max}$$

$$e_{rms} = \frac{E_{max}}{\sqrt{2}}$$

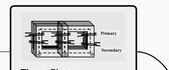
RMS values of EMF's



Referring to secondary Equivalent Circuit | Referring to primary Equivalent Circuit | Practical Transformer Equivalent Circuit

Delta-delta : Δ Δ | Star-Star : Y Y | Delta- Star: ΔY | Star-delta : Y Δ

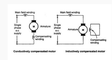
Three-Phase Transformers



- Construction: Core type:

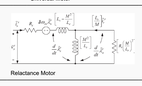
AC Series Motor

- Disadvantages of AC Series Motor
  - Because of the high eddy currents produced due to the alternating flux, the efficiency of the motor is considerably reduced
  - As the inductance in the field and armature circuits is high , power factor is low.
  - Starting torque is very less due to low power factor.
  - Due to high voltage and current induced in the short circuited armature coils in the commutation period, sparking takes place at the brushes.
- The motor is simple, less expensive and generally used for lower ratings
  It is used where high starting torque is required.
- Advantages of AC Series Motor
- High-speed vacuum cleaner
  Sewing machines
  Used in drills and power tools
  Electric shavers
- Application
- The magnetic circuit must be laminated.
  Field circuit must be designed for much lower reactance than dc motor field in order to reduce the reactance voltage drop of field and improve power factor.
  Distributed compensation winding is required to minimize the reactance of armature winding
- Construction of AC series Motor



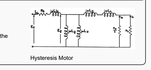
Universal Motor

- Types
  - Non-Compensated Type
  - Compensated Type through Distributed Field
- Disadvantages of a universal motor:
  - Brushes and commutator wear out.
  - It is not easy to reverse the motor.
  - Speed control is lousy.
  - High maintenance cost and short life commutator caused by the commutator.
  - Produce more noise and vibration than the induction motor.
- Advantages of a universal motor:
  - It is a cheap motor.
  - It can run from AC or DC supplies.
  - It has good torque at low speed.
- Applications of Universal Motor
  - Drills
  - Electric shavers
  - Sewing machines
  - High speed vacuum cleaners
  - Machine tools, etc.
- Construction of Universal Motor
  - laminated stator
  - rotor or armature.



Reluctance Motor

- Types of Reluctance Motor
  - Synchronous Reluctance Motor
  - Switched Reluctance Motor
- The applications
  - Signaling Devices
  - Control Devices
  - Automatic regulators
  - Recording Devices
  - Clocks
- The disadvantages
  - Efficiency is less
  - Power factor is poor
  - Frequency control
  - The capacity of these motors is less to drive the loads
  - Less inertia rotor is required.
- The advantages.
  - It doesn't require DC supply.
  - Stable characteristics
  - Maintenance is less
  - Less heat
  - No magnets
  - Speed control
- The reluctance motor consists of
  - Stator
  - squirrel-cage rotor.



Hysteresis Motor

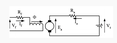
- Applications
  - Record players
  - Electric clocks
  - Timing devices, etc.
- The following are the disadvantages of hysteresis motor
  - The output obtained is ¼ times of induction motor
  - Small in size
  - Torque is less
- The following are the advantages of the hysteresis motor
  - Absence of mechanical vibrations
  - It operates noiselessly
  - Mainly suitable for accelerating inertia loads
- Types of hysteresis motor
  - Cylindrical type
  - Disk type
  - Circumferential-Field type
  - Axial-Field type
- The main parts of hysteresis motor are stator and rotor, the stator is classified into two types
  - shaded pole type
  - permanent split capacity type.

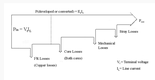
DC motors

- **1- DC separately motor:**

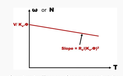
$$V_t = E_a + I_a R_a$$

$$Vf = I_f R_f$$

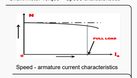




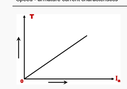
DC motor power flow



Shunt motor Torque – Speed characteristics



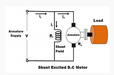
Speed - armature current characteristics



Torque - armature current characteristics

Ta= Pa/w= Ea* Ia /w , Pa= Ka . Φ.w. Ia
= Ka . Φ.w. Ia/w
Ta = Ka . Φ . Ia
Ta α Φ . Ia

In this case the torque of DC motor can be changed by controlling the field and flux



Shunt wound DC motor:

$$\omega_m = \frac{V}{K_a\varphi} - \frac{R_a}{(K_a\varphi)^2} I_a$$

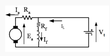
$$Y = C - m\ X$$

Torque /speed Characteristics of DC shunt motor
Eb = Ka . Φ . Wm = V – Ia . Ra

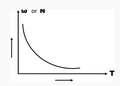
$$V_t = E_a + I_a R_a$$

$$v_t = I_f R_f$$

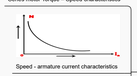
$$I_f = I_a + I_f$$



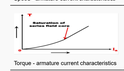
- **2- DC shunt motor:**



Series motor Torque – Speed characteristics



Speed - armature current characteristics



Torque - armature current characteristics

$$Ta = Ka\ .\ \Phi\ .\ Ia$$

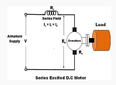
$$Ta\ \alpha\ (Ia):$$

torque and speed of DC motor can be changed by controlling the [armature supply]

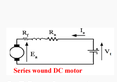
$$V_t = E_a + I_a(R_a + R_f)$$

$$I_t = I_a = I_f$$

Eb = K . Φ . Wm= V – Ia (Ra +Rs)
Eb α Ia . N

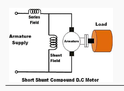


series wound self excited DC motor

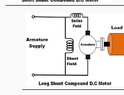


Series wound DC motor

- **3- DC series motor:**



shunt field winding is only parallel to the armature winding winding then its known as ==> short shunt DC motor.

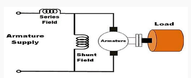


shunt field winding is parallel to both the armature winding and the series field winding ==> long shunt

compound and differential compound DC motors can either be of short shunt or long shunt type depending on the nature of arrangement.

- **shunt field flux assists the main field flux, produced by the main field connected in series to the armature winding then its called cumulative compound DC motor.**
  - Cumulative Compound DC Motor
- **The net flux produced in this case is less than the original flux and hence does not find much of a practical application.**
  - Differential Compound DC Motor

excitation of compound DC motor



Compound Wound DC Motor

Comparisons of D.C Motors

- D.C shunt motors
  - Applications : centrifugal pump, machine tools, blowers fans, … etc.
  - Constant speed motor. • Adjustable speed with medium starting torque.
- DC Series Motors
  - Applications : hoists, electric trains, conveyors, elevators, electric cars.
  - •Variable speed motor which changes speed fromone load condition to another.
  - • It has a high starting torque.
- DC Compound Motors
  - Applications : Rolling mills, sudden temporary loads, heavy machine tools, punches, etc.
  - • Variable speed motors.
  - •It has a high starting torque

Comparison

- single phase VS three phase Induction Motors

	Single Phase	Three Phase
Number of phases	1	3
Starting torque	Low	High
Power factor	Low	High
Power output	Low	High
Cost	Low	High
Efficiency	Low	High
Size	Small	Large
Weight	Light	Heavy
Maintenance	Low	High

- Squirrel-Cage Induction Motor VS Slip-Ring Induction Motor

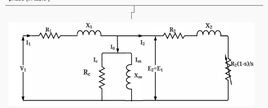
	Squirrel-Cage Induction Motor	Slip-Ring Induction Motor
Rotor construction	Solid, short circuited	Wound, externally fed
Speed control	Poor	Excellent
Starting torque	High	Low
Power factor	Low	High
Power output	Low to medium	High
Cost	Low	High
Efficiency	High	Low
Size	Small to medium	Large
Weight	Light to medium	Heavy
Maintenance	Low	High
Applications	Fans, pumps, compressors	Cranes, elevators, grinders

Applications of three-phase induction motors

Three-phase induction motors are used for commercial and industrial purposes, ideal for higher-power applications.

- Lifts
- Cranes
- Hoists
- Large exhaust fans
- Lathe machines
- Crushers
- Oil extracting mills
- Textiles
- Commercial electric and hybrid vehicles

Application of Three-phase induction motor and single phase (in table)



Circuit Equivalent of Three Phase Induction Motors

Advantages of Three Phase Induction Motor

Following are the chief advantages of a 3-phase induction motor –

- It has simple and rugged construction.
- It requires less maintenance.
- It has high efficiency and good power factor.
- It is less expensive.
- It has self-starting torque.

Disadvantages of Three Phase Induction Motor

The disadvantages of a 3-phase induction motor are given as follows –

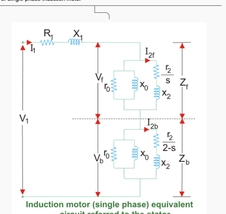
- The 3-phase induction motors are constant speed motors. hence their speed control is very difficult.
- 3-phase induction motors have poor starting torque and high inrush currents (about 4 to 8 times of the rated current).
- They always operate under lagging power factor and during light loads, they operate at very worst power factor (about 0.2 to 0.3 lagging).

Applications of single-phase induction motors

Single-phase induction motors are used more widely than the three-phase system for domestic, commercial, and sometimes industrial purposes. Single-phase induction motors are favoured because the single-phase system is more economical, and the power demand load is lower in these environments.

- Pumps
- Compressors
- Small fans
- Mixers
- Toys
- High-speed vacuums
- Electric shavers
- Drilling machines

Application of Single-phase induction motor



Induction motor (single phase) equivalent circuit referred to the stator

Circuit Equivalent of single Phase Induction Motors

Advantages of Single Phase Induction motor

- This induction motor is smaller in size and lighter in weight.
- It is also cheaper in cost.
- These motors are highly efficient.
- These motor also requires less maintenance.
- 1-phase induction motors have a longer life.
- Single-phase induction motors can be designed in a variety of sizes.

Disadvantages of Single Phase Induction motor

We know that these motors are used only for small outputs and not used for large powers as they suffer from many disadvantages and are never used in the case where three-phase machines can be adopted.

- **Low power factor and efficiency**
- For a given frame size and temperature, its output is only 50% of the three-phase induction motor.
- The single-phase induction motor is not self-starting.
- Power factor is low and hence poor.
- Efficiency is lower.
- These motors do not have a starting torque.
- For the same power output, these motors are more expensive than three-phase induction motors.

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