AC Machines: Synchronous Machine

Construction and EMF Equation of AC Generator/Alternator

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Synchronous Machine: Generator

- A synchronous generator is a synchronous machine which converts mechanical power into AC electric power through the process of electromagnetic induction.
- Synchronous generators are also referred to as alternators or AC generators.
- The term "alternator" is used since it produces AC power.
- It is called synchronous generator because it must be driven at synchronous speed to produce AC power of the desired frequency.
- An alternator or synchronous generator works on the principle of electromagnetic induction, i.e., when the flux linking a conductor changes, an EMF is induced in the conductor.
- When the armature winding of alternator subjected to the rotating magnetic field, the voltage will be generated in the armature winding.

- Synchronous generators are used to generate bulk power at thermal, hydro and nuclear stations.
- Typical ratings: 3.3 kV to 33 kV, 500 MVA
- Practically, most of the synchronous generators or alternators have stationary armature and rotating field.
- A stationary armature-rotating field alternator has several advantages over a rotating armature type alternator, as given below:
- Advantages of stationary armature and rotating field:
  - ✓ When a stationary armature is used in the alternator, the output current can be taken directly from the fixed terminals on the stationary armature without using slip rings, brushes, etc.
  - ✓ The armature windings of the rotating field alternator, being stationary, are not subjected to vibration and centrifugal forces.
  - ✓ A stationary armature can be easily insulated for the high voltage for which the alternator is designed. This generated voltage may be as high as 33 kV.

- ✓ When the stationary armature is used, the armature windings can be braced better mechanically against the high electromagnetic forces due to large short circuit currents.
- ✓ The rotating field is supplied with the direct current. Thus, only two slip rings are required to provide direct current for the rotating field Generally, the field voltage is between 100 to 500 volts and hence the insulation of the low voltage slip rings from the shaft can be provided easily.
- ✓ The weight of the armature windings is greater than the windings of the rotating field poles. Therefore, the rotating field type alternator has smaller size than a rotating armature type alternator.
- ✓ A stationary armature may be cooled easily because the size of the armature can be increased to provide more cooling ducts.
- ✓ Since the rotating field is comparatively light, it can be constructed for high speed rotation.
- ✓ The forced cooling with gas or liquids can be easily provided in stationary armature type alternators.
- ✓ The cost of the rotating field type alternator is low as compared to the rotating armature type alternator.

Construction of Synchronous Generator

Similar to other rotating machines, an alternator consists of two main parts namely, the stator and the rotor. The **stator** is the stationary part of the machine. **It carries the armature winding in which the voltage is generated.** The output of the machine is taken from the stator. The **rotor** is the rotating part of the machine. **The rotor produces the main field flux.**

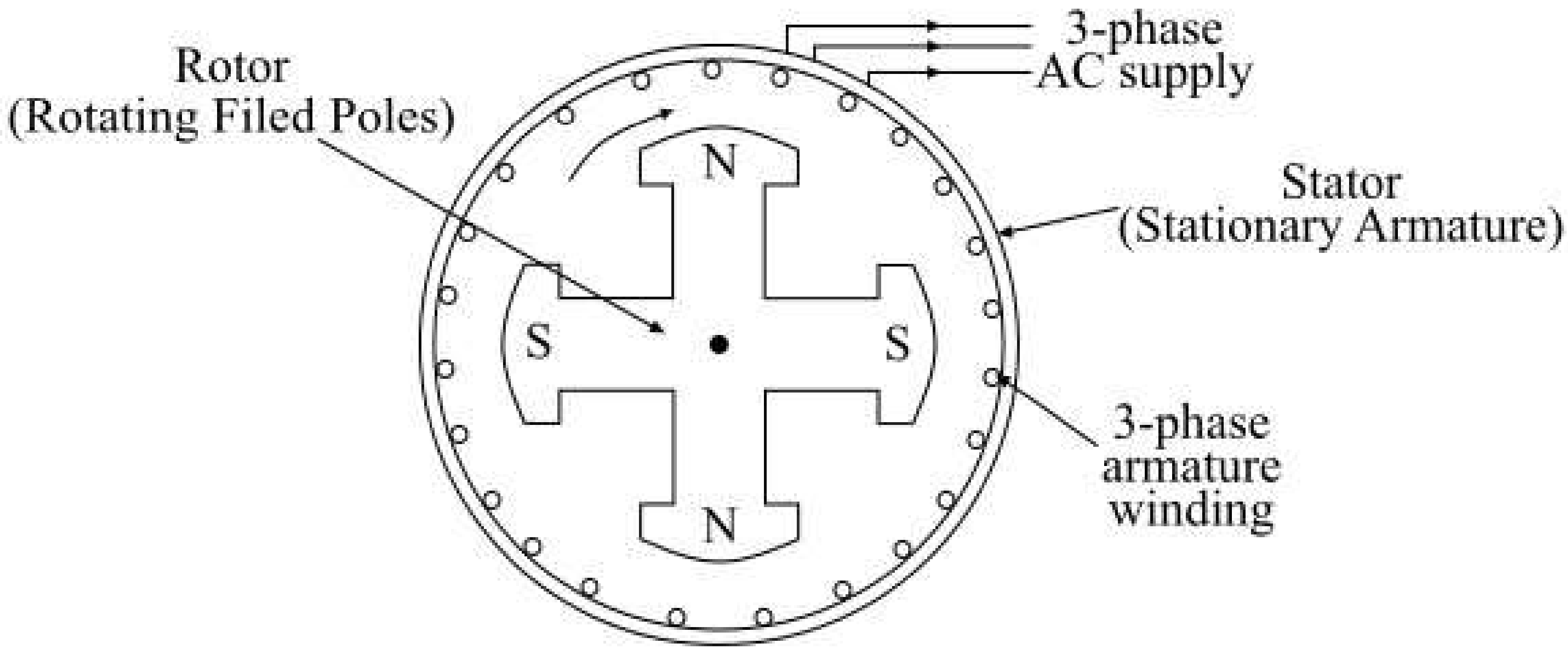


Figure 1: *Schematic diagram of a 4-pole Synchronous Machine*

Stator Construction

❖ The stator of the alternator includes several parts, viz. the frame, stator core, stator or armature windings, and cooling arrangement.

✓ The stator frame may be made up of cast iron for small-size machines and of welded steel for large-size machines.

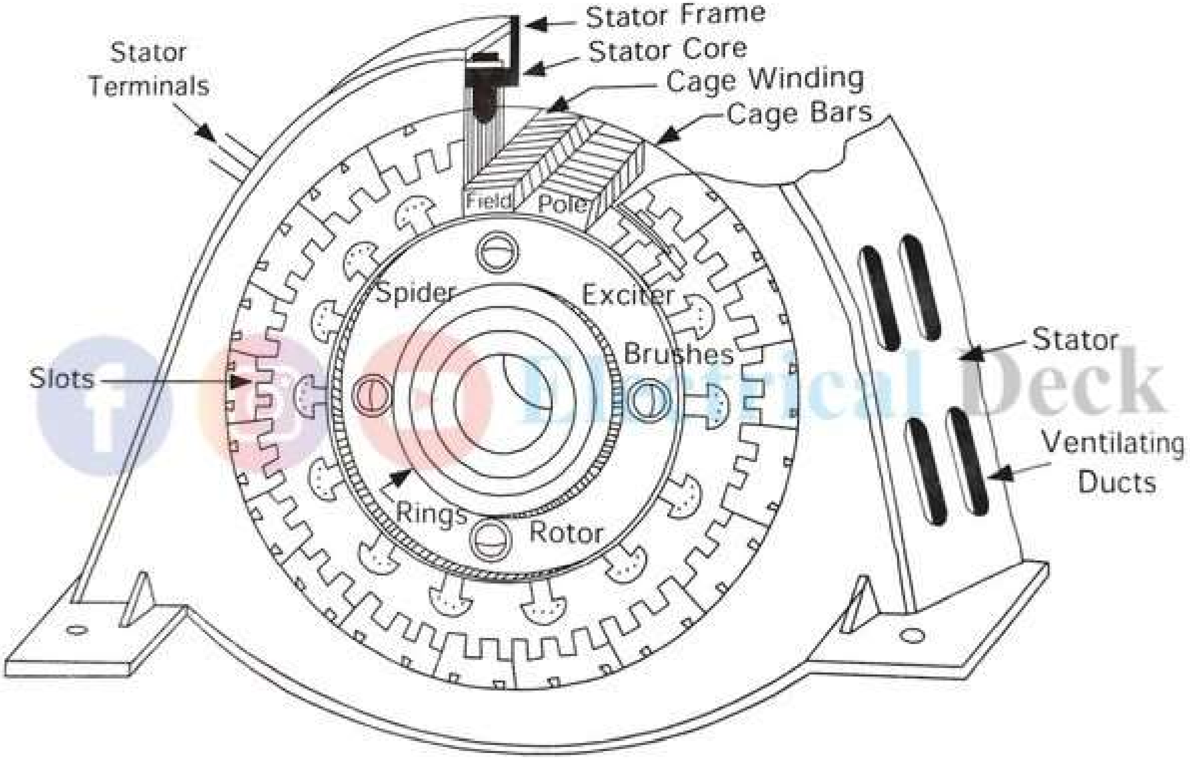
✓ The stator core is assembled with high-grade silicon content steel laminations. These silicon steel laminations reduce the hysteresis and eddy-current losses in the stator core.

✓ The slots are cut on the inner periphery of the stator core. A 3-phase armature winding is put in these slots.

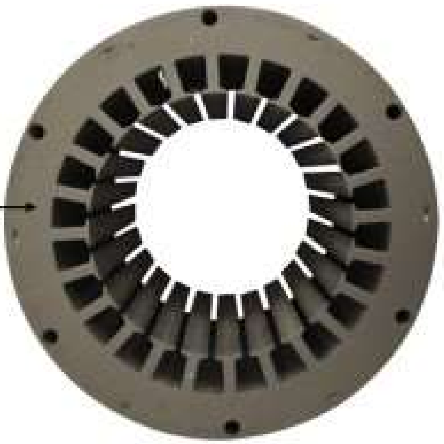
✓ The armature winding of the alternator is star connected. The winding of each phase is distributed over several slots.

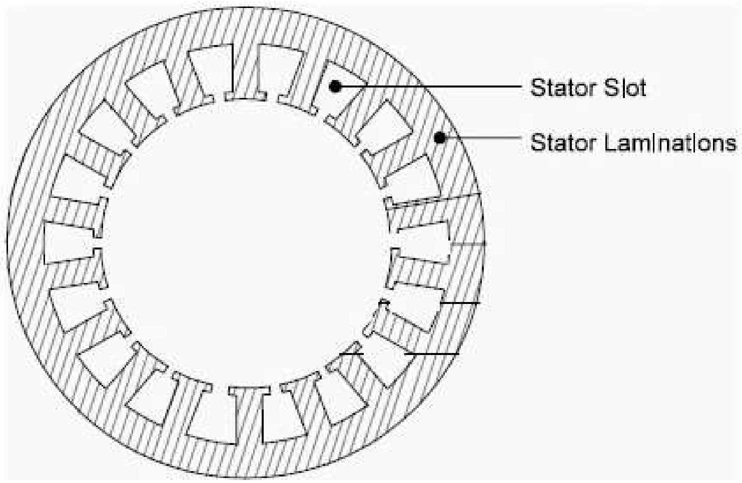
✓ When current flows through the distributed armature winding, it produces an essential sinusoidal space distribution of EMF.

Stator Construction



Laminated & sloted Stator core





Rotor Construction

- The rotor of the alternator carries the field winding which is supplied with direct current through two slip rings by a separate DC source (also called exciter).
- The exciter is generally a small DC shunt generator mounted on the shaft of the alternator.
- For the alternator, there are two types of rotor constructions are used viz. the salient-pole type and the cylindrical rotor type.

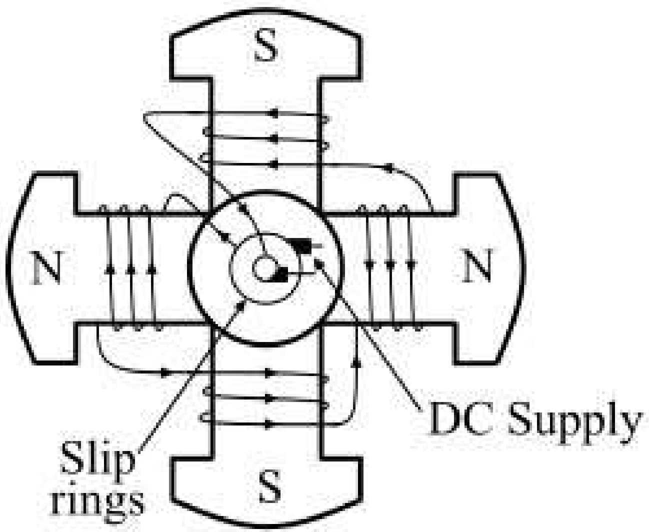


Fig. - Salient Pole Rotor

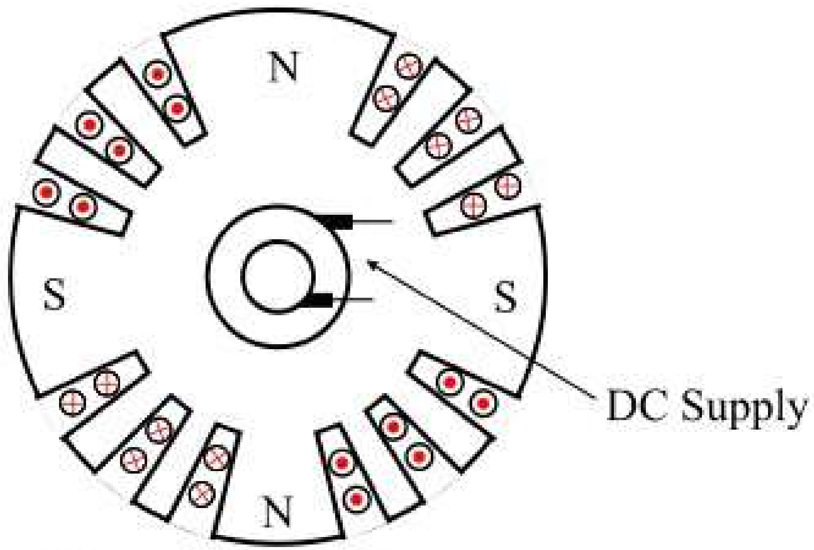


Fig. - Cylindrical Rotor

Salient Pole Rotor

- ❖ The term salient means projecting.
- ❖ Hence, a salient pole rotor consists of poles projecting out from the surface of the rotor core.
- ❖ This whole arrangement is fixed to the shaft of the alternator as shown in the figure.
- ❖ The individual field pole windings are connected in series such that when the field winding is energised by the DC exciter, the adjacent poles have opposite polarities.
- ❖ The salient pole type rotor is used in the low and medium speed (from 120 to 400 RPM) alternators such as those driven by the diesel engines or water turbines.
- ❖ Low speed rotors of the alternators possess a large diameter to provide the necessary space for the poles.
- ❖ As a result, the salient pole type rotors have large diameter and short axial length.

Smooth Cylinerical Rotor

- The cylindrical rotors are made from solid forgings of high-grade nickel-chrome-molybdenum steel.
- In about two-third of the outer periphery of the cylindrical rotor, slots are cut at regular intervals and parallel to the rotor shaft.
- The field windings are placed in these slots and is excited by DC supply. The field winding is of distributed type.
- The unslotted portion of the rotor forms the pole faces.
- The cylindrical rotor that the poles formed are non-salient, i.e., they do not project out from the rotor surface.
- The cylindrical type rotor construction is used in the high-speed (1500 to 3000 RPM) alternators such as those driven by steam turbines.
- A cylindrical rotor alternator has a comparatively small diameter and long axial length.
- The cylindrical rotor alternators are called turbo-alternators or turbo-generators.

Speed-Frequency Relationship

- The frequency of the generated voltage by the alternator depends upon the number of field poles and the speed at which the field poles are rotated.
- One complete cycle of the voltage being generated in an armature coil when a pair of field poles i.e. one north pole and one south pole passes over the coil.

Let,

P = Number of rotor field poles

N = Speed of rotor or field poles in RPM

f = Frequency of the generated voltage in Hz

- In one revolution of the rotor, an armature coil is cut by (P/2) north poles and (P/2) south poles.

Speed-Frequency Relationship

- Since one cycle of the voltage is generated in the armature coil when a pair of field poles passes over the coil.
- Thus, the number of cycles generated in one revolution of the rotor will be equal to the number of pairs of poles
- Number of cycles/Revolution=Number of pole pairs=P/2
- Number of revolutions/second=N/60
- Number of cycles/second=P/2×N/60
- The frequency is defined as the number of cycles per seconds. Therefore, Frequency, f=Number of cycles second=PN/120…(1)

Calculate the highest speed at which a 50 Hz synchronous generator can be operated.

EMF Equation

- Let,

  P = Number of poles

  ϕ = Flux per pole in Webers

  N = Speed in revolution per minute (r.p.m)

  f = Frequency in Hertz

  Z_{ph} = Number of conductors connected in series per phase

  T_{ph} = the number of turns connected in series per phase

- Flux cut by each conductor during one revolution = $P\phi$ Weber.
- N revolution in 1 min or 60 sec
- One revolution =60/N sec
- Time taken to complete one revolution = 60/N sec

EMF Equation

- Average EMF induced per conductor =flux cut by one conductor in one complete revolution /time taken for one complete revolution $= P\phi/(60/N) = P\phi N/60$ Volt
- Average EMF induced per phase = $Z_{ph} (P\phi N/60)$
- $T_{ph}=Z_{ph}/2$ i.e. $2T_{ph}=Z_{ph}$
- Average EMF induced per phase = $P\phi NZ_{ph}/60 = 2P\phi NT_{ph}/60$
- Average EMF induced per phase = $2\phi Z_{ph}(PN/120) = 2\phi Z_{ph} f$
- Root mean square (R.M.S) value of the EMF induced per phase is given by: E_{ph} = Average value x form factor (form factor=1.1)
- $E_{ph} = 2.22\phi Z_{ph} f = 4.44\phi T_{ph} f$ Volts
- If the alternator is star connected $E_L = \sqrt{3}\, E_{ph}$

EMF Equation: Problems

- P1: A 3-phase, 6-pole star connected alternator revolves at 1000 rpm. The stator has 90 slots and 8 conductors per slot. The flux per pole is 0.05 Wb. Calculate the generated voltage.

  ($E_L = \sqrt{3}\ E_{ph} 2.22 \phi f Z_{ph} = 1.732 x 2.22 x 0.05 x 50 x 240 = 2307.024$ V)

- P1: A 3-phase, 16-pole synchronous generator has a resultant air-gap flux of 0.06 Wb per pole. The stator has 2 slots per pole per phase and 4 concoctors per slot in 2 layers. Calculate the line voltage when the machine runs at 375 rpm.

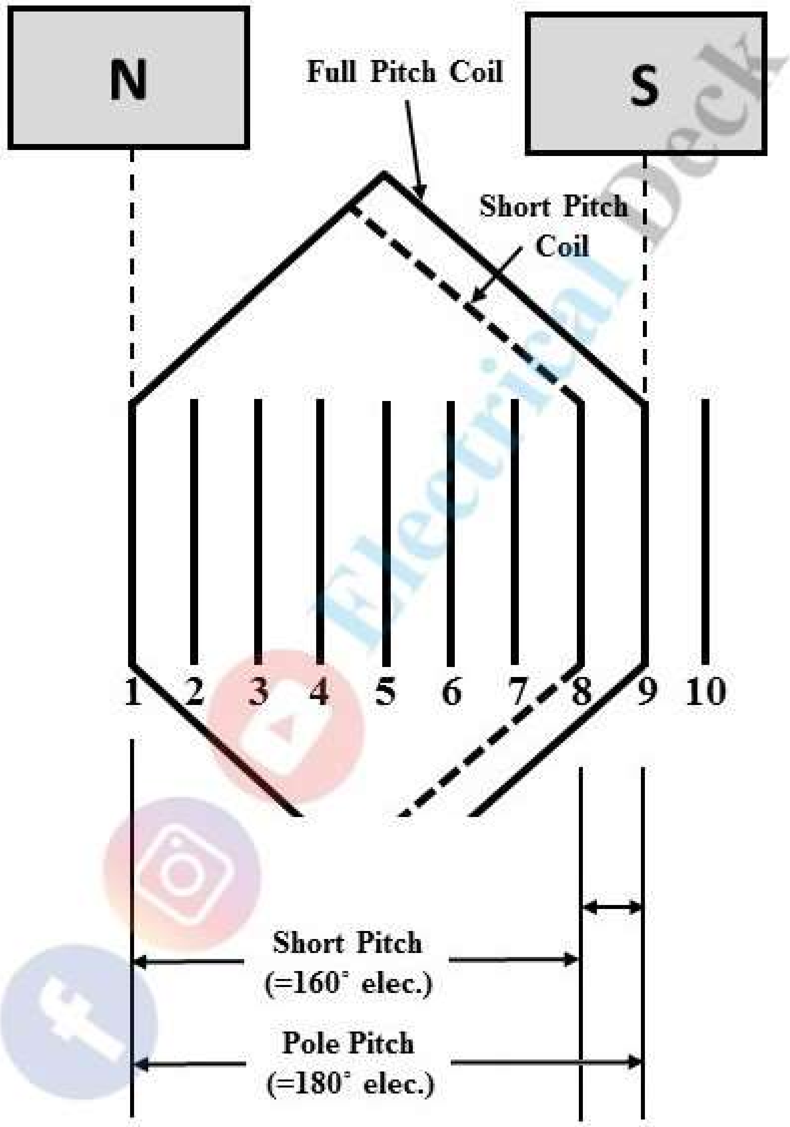
  ($E_L = \sqrt{3}\ E_{ph} 2.22 \phi f Z_{ph} = 1.732 x 2.22 x 0.06 x 50 x 128 = 1476.495$ V)

- P3: A 3-phase, 50 Hz, 2-pole star connected synchronous generator has 54 slots with 4 conductors per slot. If the machine gives 3300 V line voltage, calculate the useful flux per pole.

  Φ=3300/(sqrt(3)*2.22*50*72= .23839 Wb)

Full Pitch and Fractional Pitch Winding

- A coil when placed in a slot, the distance between two coil sides of a coil is equal to the distance between the center of one pole to the center of an adjacent pole (i.e., pole-pitch) is known as 'Full Pitch'. The coil span of a full pitch coil is always 180° electrical.
- if the distance between two coils sides of a coil placed in the slot is less than the pole pitch (i.e., less than 180° electrical), it is known as 'Fractional Pitch', 'Short Pitch' or Chorded'

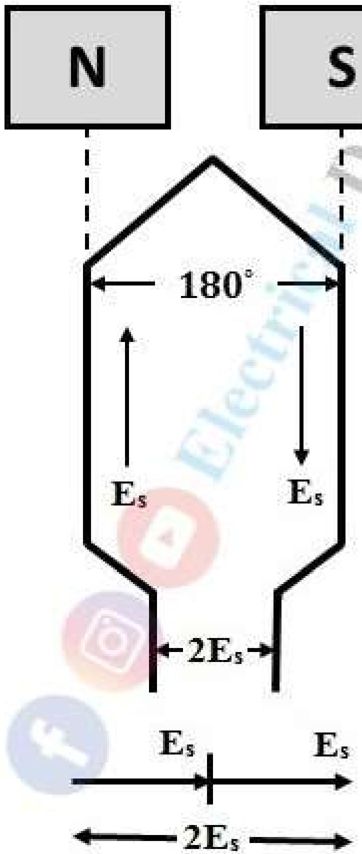


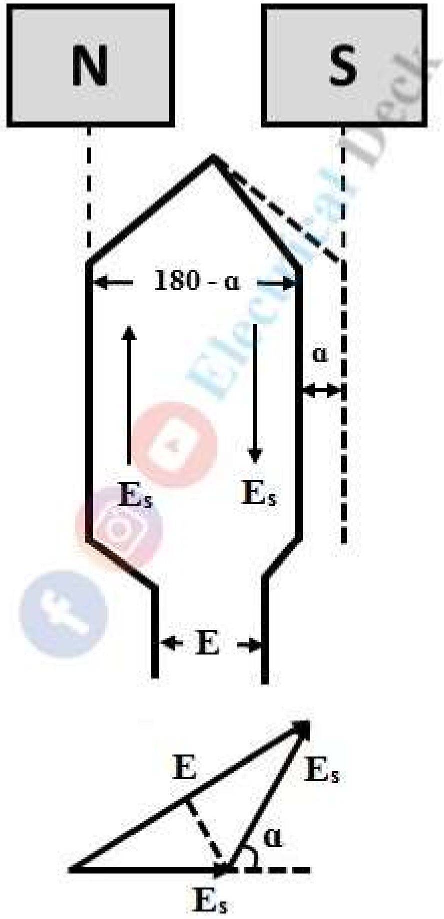
Full Pitch and Fractional Pitch Winding

- In practice, short-pitch coils are more preferred because of the following advantages:
- By using a short pitch coil copper is saved at the end connections.
- The effects of distorting harmonics are less compared to full pitch coil, thus improving the waveform of the induced emf i.e., more sinusoidal.
- The high-frequency harmonics are reduced. Since the hysteresis and eddy current loss depends upon frequency. Hence the losses are decreased, thereby increasing efficiency.
- When the coil is full pitched the net emf induced in the coil is the arithmetic sum of the emfs induced in two coil sides under adjacent poles.
- In fractional pitch, the phasor sum of emfs induced in the coil sides gives the net emf of the coil.
- Also, the amount of emf induced will be lesser compared to the full-pitched coil

Full Pitch and Fractional Pitch Winding

In a full pitch coil, the coil span is 180° electrical (equal to pole pitch)





In a short pitch coil, the coil span will be (180 - α)° electrical (α = angle by which coils are short-pitched and always less than pole pitch).

Coil Span Factor or Pitch Factor :

- The ratio of net emf induced in the coil when it is short-pitched to the net emf induced in the coil when it is full-pitched is defined as the 'Coil Span Factor or Pitch Factor or Chording Factor'.
- In general, it is the factor (Kp or Kc) by which reduction in induced emf in the short pitch coil compared to the full-pitch coil.
- It can be also defined as the ratio of the vector sum of the emfs induced per-coil to the arithmetic sum of the emfs induced per-coil.
- It is always less than unity (Kc < 1).

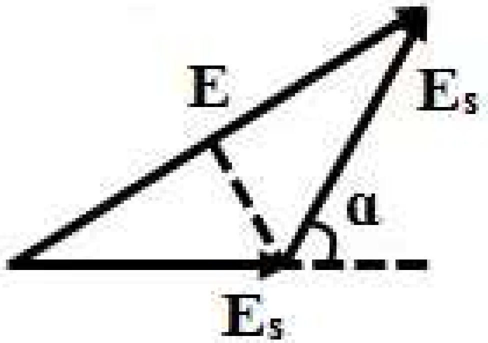
$$K_p \text{ or } K_c = \frac{EMF \text{ when coil is short pitched}}{EMF \text{ when coil is full pitched}}$$

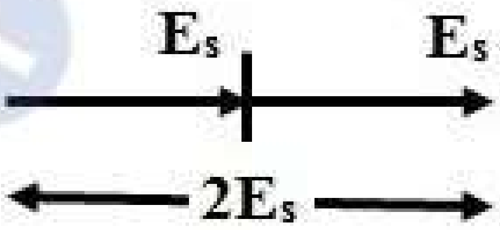
$$= \frac{Vector \text{ sum of } EMFs \text{ induced/coil}}{Arithmetic \text{ sum of } EMFs \text{ induced/coil}}$$

Vector sum=K_c x Arithmetic sum

Coil Span Factor or Pitch Factor :

- Let, Es = EMF induced in each coil side.
- α = Angle (electrical degree) by which the coil is short-pitched.





E = Vector sum = 2 Es cos α/2   Arithmetic sum=2Es

$$K_c = \frac{E}{2\,E_s} = \frac{2\,E_s\,\cos\frac{\alpha}{2}}{2\,E_s} = \cos\frac{\alpha}{2}$$

Calculate the pitch factor (A=slots per pole, Full pitch=1 to (1+A) slot

(a) 36 stator slots, 4-poles, coil-span=1 to 8, 36/4=9 slots =180^0

for full pitch=1 to 10, 1 to 8 is short by 2 slots, α =2x180^0/9=40^0

(a) 72 stator slots, 6-poles, coil-span=1 to 10

(b) 96 stator slots, 6-poles, coil-span=1 to 12

Distribution Factor Breadth Factor Spread factor

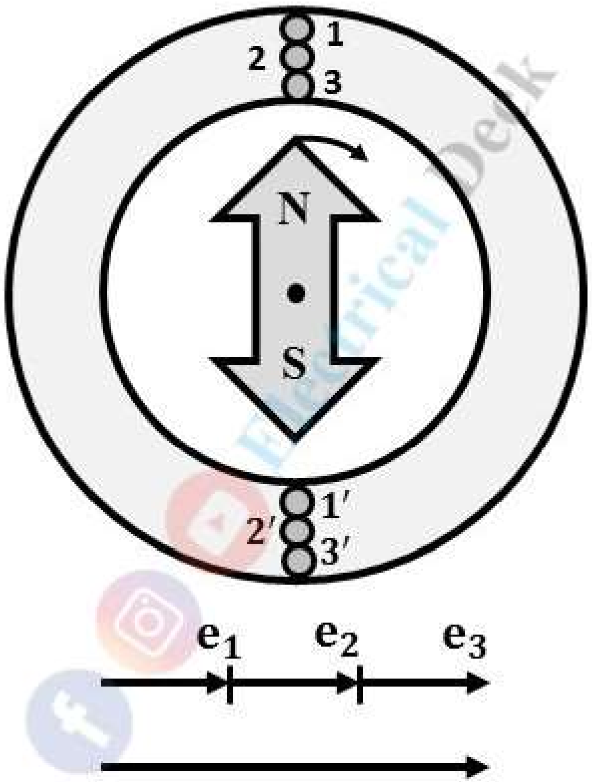
- In a concentrated winding, each phase of a coil is concentrated in a single slot.
- In actual practice, in each phase, coils are not concentrated in a single slot.
- They are distributed in a number of slots in space to form a polar group under each pole.
- The voltages induced in coil sides are not in phase, but they differ by an angle β which is known as the angular displacement of the slots.

$$K_d = \frac{\text{Phasor Sum of the coil volatges per phase}}{\text{Arithmetic sum of coil voltages per phase}}$$

Vector sum=K_d x Arithmetic sum

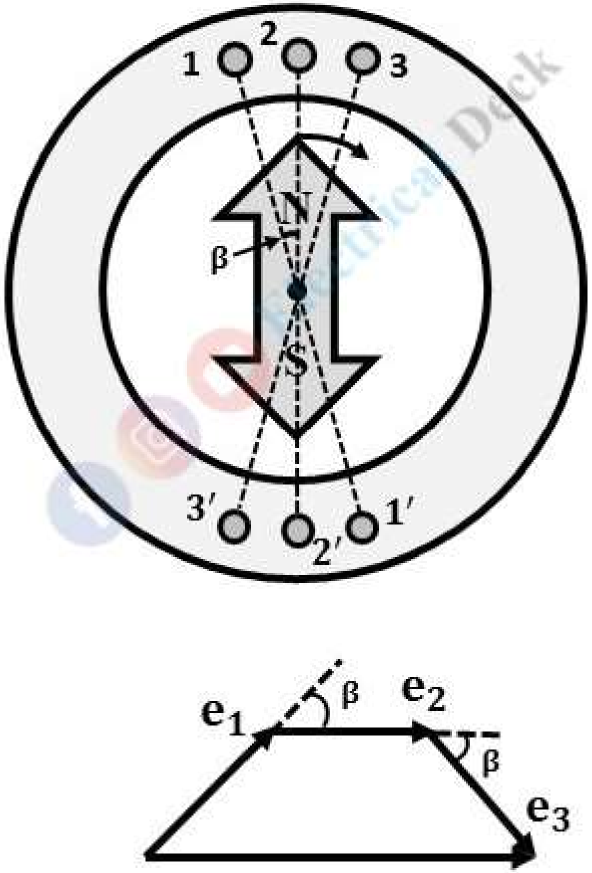
Distribution Factor Breadth Factor Spread factor

Concentrated winding



$$e = e_1 + e_2 + e_2$$

Distributed winding



$$e = e_1 + e_2 + e_2$$

Distribution Factor Breadth Factor Spread factor

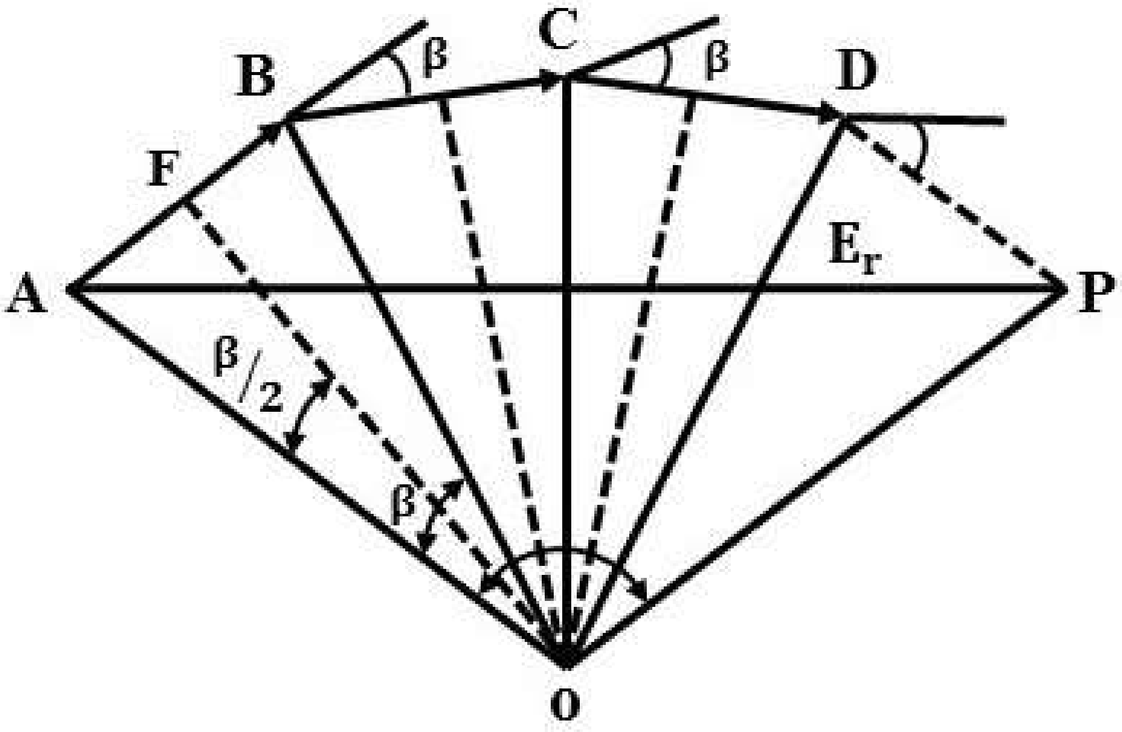
- Let
- n = Number of slots per pole
- m = Number of slots per pole per phase
- Es = EMF induced in each coil side
- β = Angular displacement between slots
- m β = Phase spread angle
- Er = Vector sum of the EMFs induced per phase in one polar group

$$m = \frac{\text{slots}}{\text{poles x phases}} \qquad \beta = \frac{180^\circ}{\text{slots/pole}} = \frac{180^\circ \text{ x poles}}{\text{slots}}$$

Distribution Factor Breadth Factor Spread factor

- The below figure shows the magnitude and direction of induced EMFs in coils AB, BC, CD..... of one phase with a successive phase displacement of β°.
- The resultant emf Er is represented by the phasor AP.

- If bisectors are drawn on AB, BC, CD..... they would meet at common point O.
- The point O would be the circumcentre of the circle having AB, BC, CD..... as chords.
- From the figure AB = BC = CD = ... = Er.
- From △ OAB, if OF is the perpendicular drawn to AB.



Distribution Factor Breadth Factor Spread factor

$$\sin\frac{\beta}{2} = \frac{\frac{AB}{2}}{OA} = \frac{\frac{E_s}{2}}{OA} \qquad E_s = 2 \times OA \times \sin\frac{\beta}{2}$$

Arithmetic sum $= m \times 2 \times OA \times \sin\frac{\beta}{2}$

Vector sum $E_r = AP = 2 \times OA \times \sin\frac{AOP}{2} = 2 \times OA \times \sin\frac{m\beta}{2}$

Therefore Distribution factor $K_d = \frac{Vector\ sum}{Arithmetic\ sum}$

$$= \frac{2 \times OA \times \sin\frac{m\beta}{2}}{m \times 2 \times OA \times \sin\frac{\beta}{2}} = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$$

Winding Factor $K_w = K_c\, K_d$

$E_{ph} = 2.22 K_w \phi Z_{ph} f = 2.22 K_c K_d \phi Z_{ph} f$ Volts

EMF Equation: Problems

- P1: A 3-phase, 6-pole star connected alternator revolves at 1000 rpm. The stator has 90 slots and 8 conductors per slot. The flux per pole is 0.05 Wb. Calculate the generated voltage if the winding factor is 0.96.

($E_L = \sqrt{3}$ x$2.22 K_w \phi f Z_{ph}$=2214.7 V)

- P1: A 3-phase, 16-pole synchronous generator has a resultant air-gap flux of 0.06 Wb per pole. The stator has 2 slots per pole per phase and 4 concoctors per slot in 2 layers. The coil span is 150^0 electrical. Calculate the line voltage when the machine runs at 375 rpm.

($E_L = \sqrt{3}$ x2.22x0.9659x0.9659x0.06x50x128= 1377.5 V)

- P3: A 3-phase, 50 Hz, 2-pole star connected synchronous generator has 54 slots with 4 conductors per slot. The pitch of the coil is 2 slots less than the pole pitch. If the machine gives 3300 V line voltage, calculate the useful flux per pole.

(Φ=0 .2512 Wb)