EEP 225 : Electric Machines

Lecture 5
AC Machines I

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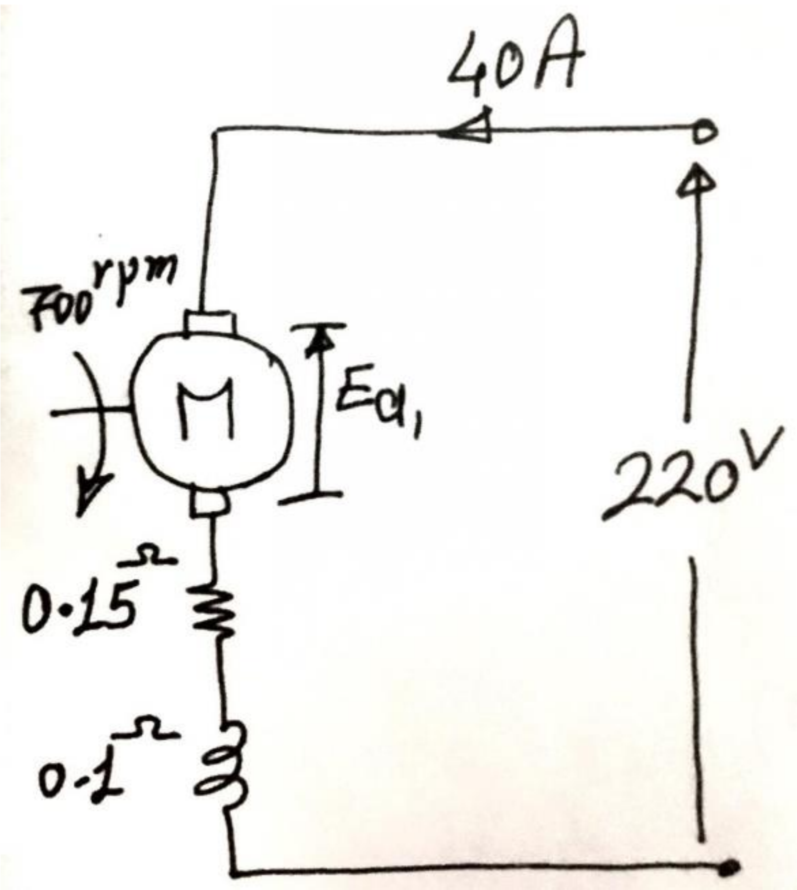
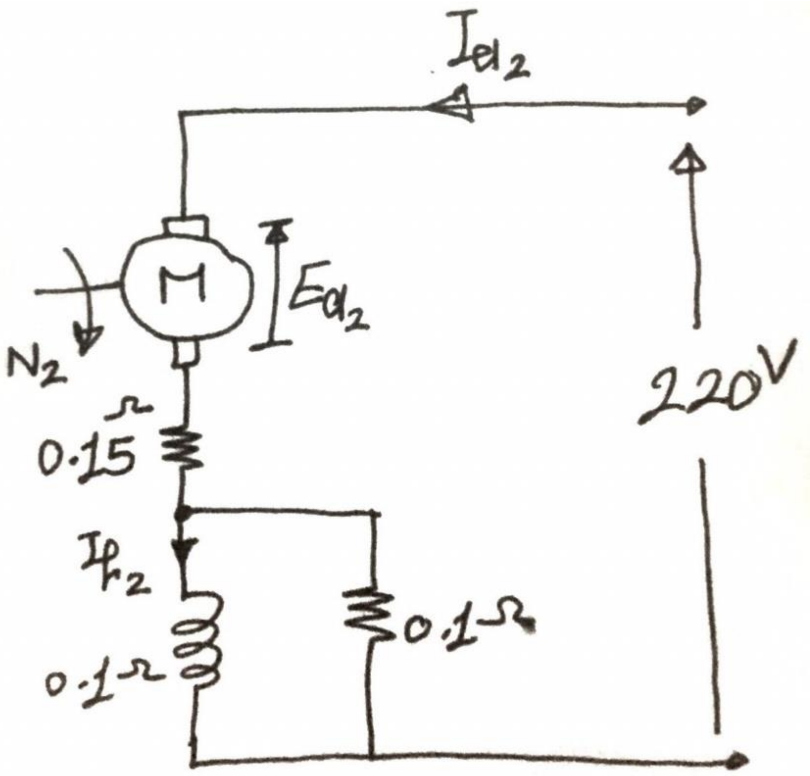
$\boxed{1.\ Q}$ — A 220 V DC series motor has an armature and series field resistances of 0.15Ω and 0.1Ω respectively. It takes a current of 40 A when running at 700 rpm. Calculate the current taken from the supply and the speed if the field is shunted by a resistance equal to the field resistance and the load torque is decreased by 25%. Neglect saturation.

A —



$$I_{a1} = I_{f1} = 40A$$
$$E_{a1} = 220 - 40 \times (0.15 + 0.1) = 210V$$



$$
\begin{aligned}
I_{f_2} &= 0.5 I_{a_2} \\
\frac{T_2}{T_1} &= \frac{I_{f_2}}{I_{f_1}} \times \frac{I_{a2}}{I_{a1}} \\
&= \frac{0.5 I_{a2}}{40} \times \frac{I_{a2}}{40} = 0.75 \\
&\therefore I_{a2} = 48.9897A \quad I_{f_2} = 24.49485A
\end{aligned}
$$

$$
\begin{aligned}
&E_{a2} = 220 - 48.9897 \times (0.15 + 0.05) = 210.2V \\
&\frac{E_{a2}}{E_{a1}} = \frac{N_2}{N_1} \times \frac{I_{f_2}}{I_{f_1}} \\
&\frac{210.2}{210} = \frac{N_2}{700} \times \frac{24.49}{40} \\
&\therefore N_2 = 1144.4 \text{ rpm}
\end{aligned}
$$

$\boxed{\text{2. Q}}$ — If we connect DC motors to a AC supply, which type of DC motors will work

A — Series motor will work. Small changes are usually made to it to operate efficiently.

1 AC Machines

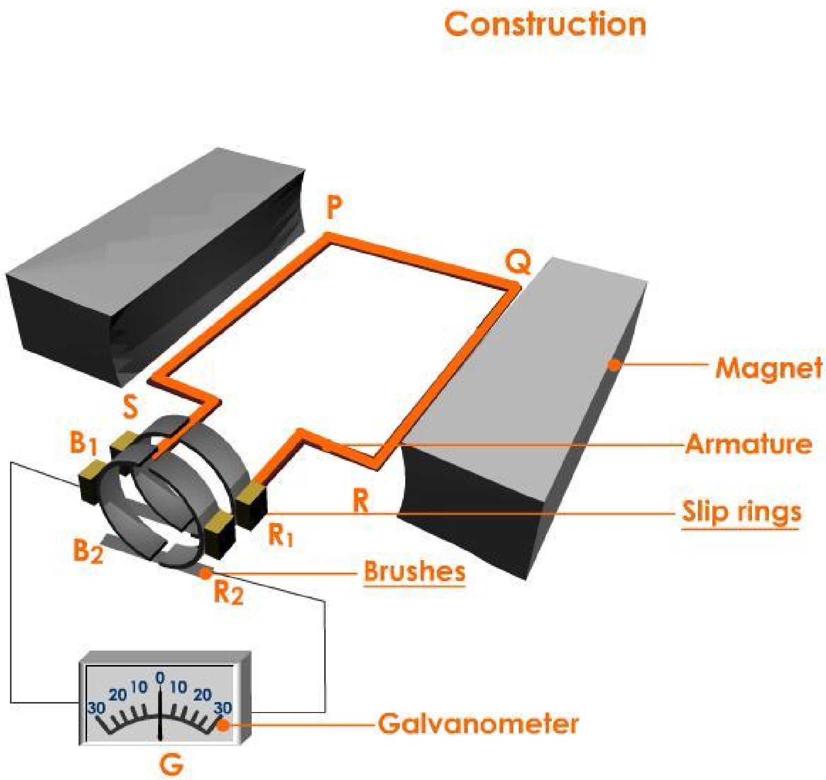


Figure 1: AC machines

There are two major classes of AC machines:

- **Synchronous machines**: field current is supplied by a separate DC source. Mainly used as generators. It is considered as the heart of the electrical power systems.
  The rating of the synchronous machines varies from several kilowatts to several hundreds of megawatts depending on its size and speed.
  The of voltage produced by the generator in power stations is around $20 \backsim 25$ KV [1]

- **Induction machines**: field current is supplied by magnetic induction (transformer action) into their field winding.
  Mainly used as motors.

[1]The biggest generator made ever is 27 KV

2 Basic Principle of Synchronous Machines

Note that AC generators are also known as alternators.

AC machines operate on the same fundamental principles of electromagnetic induction as DC generators. We can consider AC machine as a DC machines without commutator, since the commutator was used as a mechanical rectifier (convert the AC in armature coils into DC at the brushes).

Note that AC machines operates at $\simeq$ 20 KV and hundreds of mega watts, so the current in this case is extremely high, no coil, brushes or skip rings can stand with this current density.

The solution is pretty simple, since what generates the voltage is the relative motion between the magnetic field and the conductor[2], it is no actually necessary that the coil is what ia rotating, we keep the coil (armature) fixed and rotate the field. Armature now is the stator.

Field is supplied from DC source, we feed it with brushes and skip rings as it rotates, since the rating of field current is way smaller than the rating of armature current, it is safer.

We inverted the machine, reversed the stator and the rotor.

In practical synchronous machines, they are usually built inverted. This means that the armature is stationary while the field system is set to rotate. This system ensures generation of high voltages in armature with considerable amount of safety.

2.1 Advantages of Having Stationary Armature

1. The output current (which is high) can be led directly from fixed terminals on the stator to the load without having to pass it through brush contacts.
2. It is easier to insulate stationary armature winding for high AC voltages of about 21 KV or more.
3. The slip rings and brushes are transferred to the low-voltage, low-power DC field circuit, which can be easily insulated.

[2] This is Faraday's law.

3 Construction of Synchronous Machines

3.1 Stator (Armature)

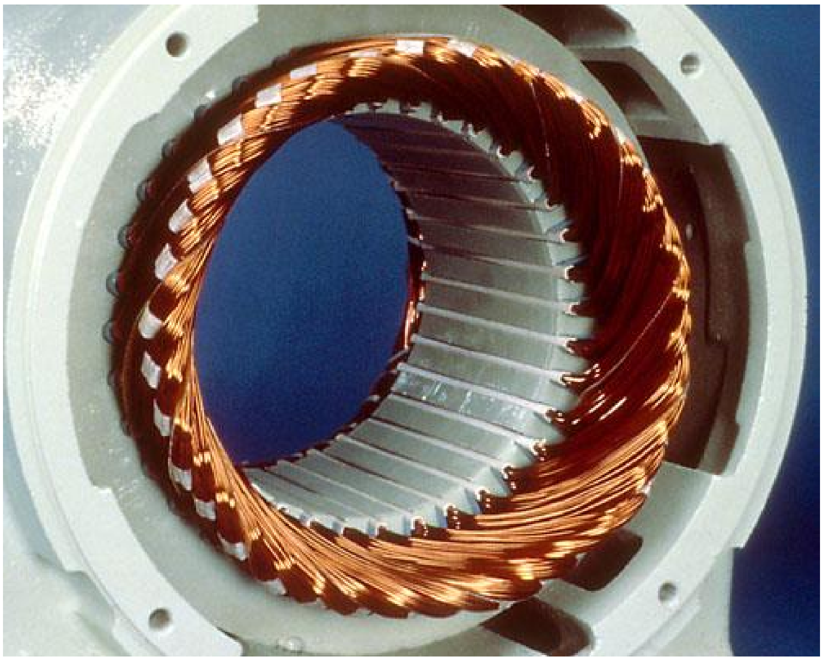


Figure 2: Stator (Armature)

- It is made of thin laminations of highly permeable steel in order to reduce the core losses (eddy currents).
- The inside of the stator has a number of slots to accommodate armature conductors.
- Armature conductors are symmetrically arranged to form a balanced polyphase (3 phase) winding.

  In big machines, there are 4 output terminals connected in star (Y) , in small machines, there are 6 output terminals, can be connected in star (Y) or delta (Δ)

3.2 Rotor (Field)

The field system is excited by low voltage DC supply (about 220V) through brushes pressed into two slip rings. The rotor has two types:

1. **Round Pole Rotor (Cylindrical Rotor)**: used in 2 or 4 pole, high-speed turbo-generator because it is mechanically stable.

2 pole generators are used in steam or gas power stations.

It is made of solid forged steel cylinder with a number of slots on its outer periphery. These slots are designed to accommodate the field coils.

2. **Salient Pole Rotor**: It is used in low-speed applications (e.g. hydro-power stations) as they can't withstand high centrifugal force, since it is less mechanically stable because irregular air gap.

   Usually has many poles.

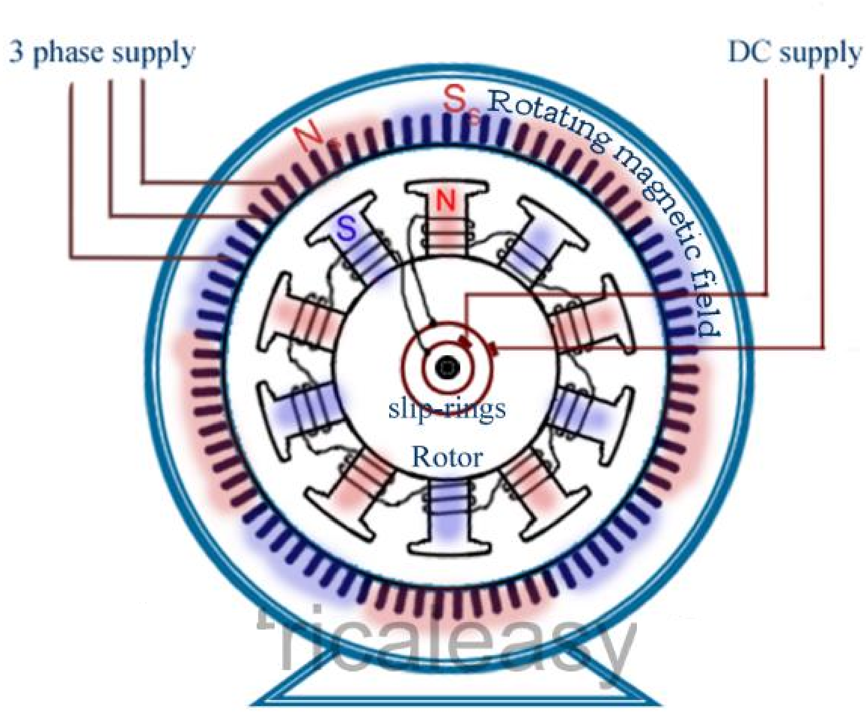


Figure 3: Salient Pole Rotor

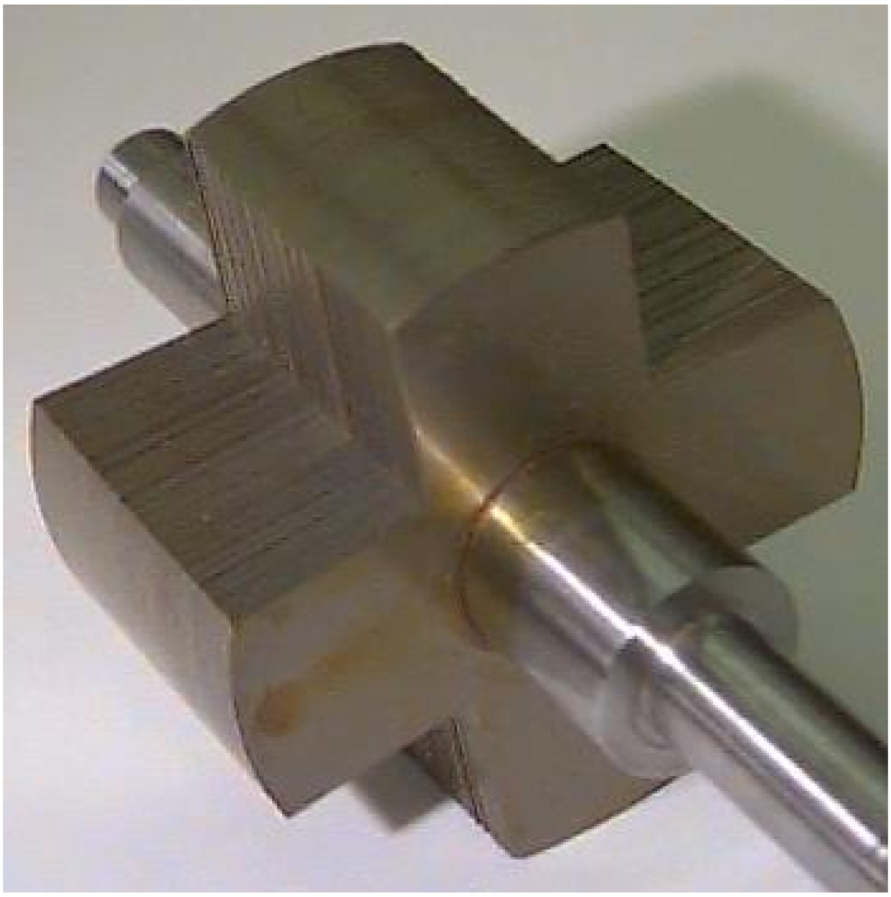


Figure 4: Salient Pole Rotor

4 Brushless Exciter

Because of existence of skip rings ans brushes, regular maintenance are required. Maintenance is expensive, since it the generator is shut down during maintenance, that is why we design brushless machines to supply the DC field current.

A brushless exciter is a small AC generator with its field circuit mounted on the stator and its armature circuit mounted on the rotor shaft. The three-phase output of the exciter generator is rectified to DC by a three-phase electronically by a full bridge diode rectifier circuit also mounted on the shaft of the generator, and is then fed into the main dc field circuit.

By controlling the small DC field current of the exciter generator (located on the stator), it is possible to adjust the field current on the main machine without slip rings (there was two) and brushes. This requires less maintenance.

5 Principles of Operation

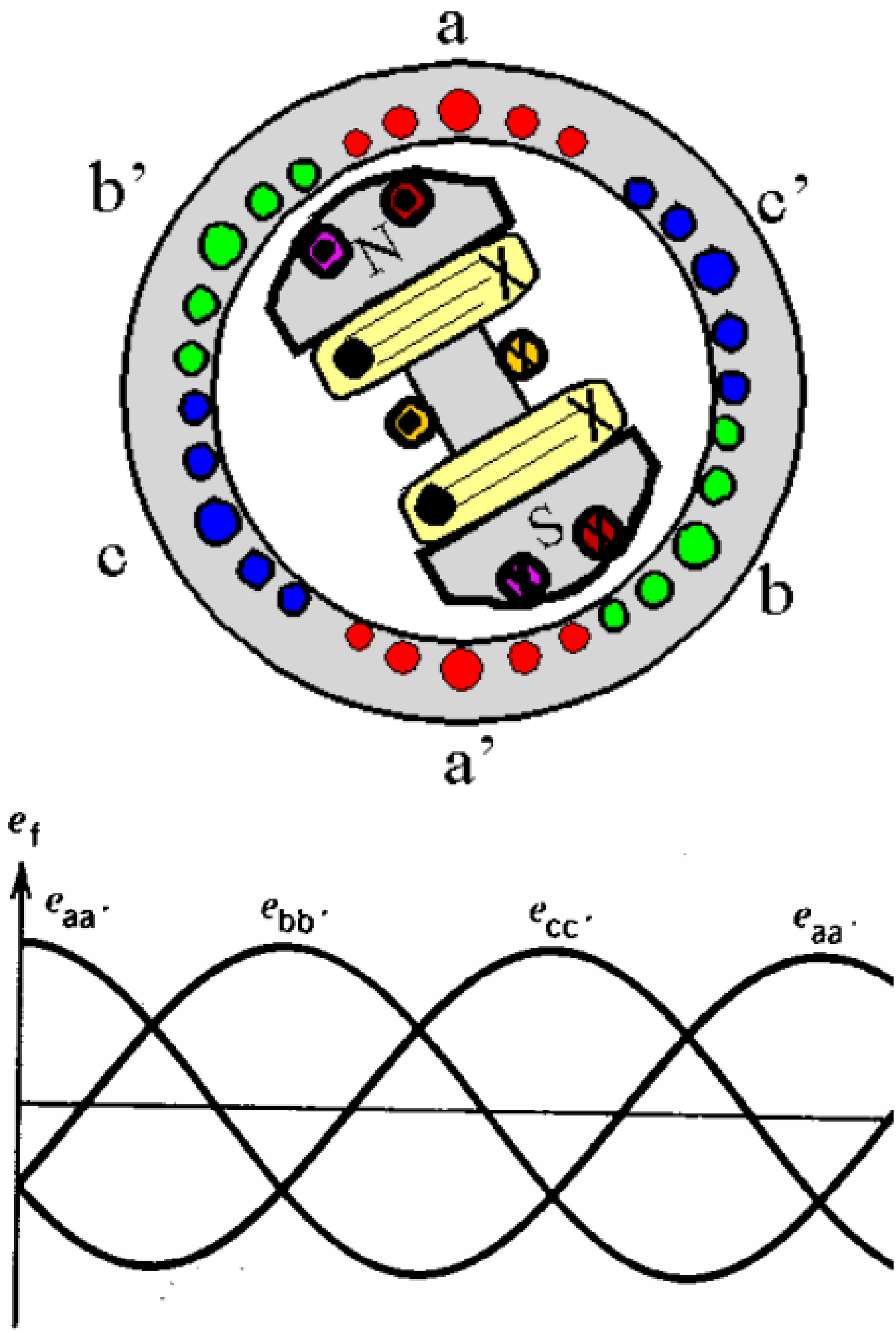


Figure 5: A three phase AC generator having three identical winding displaced apart from each other by 120 degrees electrical produces three equal voltages of the same frequency having a phase difference of 120°

1. When a DC field current flows through the rotor field winding, it establishes a flux in the air-gap. If the rotor is now rotated by a prime-mover, a revolving field is produced in the air-gap
2. The rotating flux will link the armature windings aa', bb',and cc' and will induce voltages in these stator windings.
3. These induced voltages have the same magnitudes but are phase-shifted by 120°.
4. The rotor speed and the frequency of the induced voltages are related to each other.

5.1 Relation between Speed and Frequency

Obviously, one cycle of emf is induced in a conductor when one pair of poles passes over it. let

P : Total number of field poles.
N_s : Speed of the rotor (synchronous speed) in rpm.
f_s : Frequency of generated emf in Hz.

Therefore:

No. of complete cycles of emf per revolution = no. of poles (P) / 2
No. of complete revolutions per second = $N_s/60$
No. of complete cycles per second = f_s

$$\frac{\text{cycle}}{\text{sec}} = \frac{\text{cycle}}{\text{rev}} \times \frac{\text{rev}}{\text{sec}}$$

$$f_s = \frac{P}{2} \times \frac{N_s}{60}$$

$$\boxed{\therefore N_s = 120\,\frac{f_s}{P}}$$

As shown, turbo generators used in gas and steam stations are 2 poles generators (the minimum number of poles possible to obtain the highest possible speed).

At what speed should the generator work to get a 50 Hz frequency? by substituting in the equation with various number of poles, we get the following table.

No. of poles (P)	2	4	6	8	10	12
Speed (N_s) in rpm	3000	1500	100	750	600	500

[3]

As shown, the rotational speed is **synchronized** with the line frequency. That's why we call it synchronous machines.

$\boxed{\text{3. Q}}$ — At which generator the number of poles is more. Hydro-stations generators or gas stations generators?

A — Since hydro-stations generators operate ate lower speeds, they have more poles. Remember that $N_s \propto \frac{1}{P}$

6 Induced EMF in Transformer

- Remember: Faraday's law:

$$\text{emf} = -N\frac{d\phi}{dt}$$

emf : inducted voltage
N : number of turns
$\Delta\phi$: change in magnetic flux
Δt : change in time

Assume that the flux is sinusoidaly distributed

$$\phi(t) = \phi_m \sin(\omega t)$$

[3]If the frequency is 60 Hz, this table must be re-calculated

$$
\begin{aligned}
\phi(t) &= \phi_m \sin(\omega t) \\
e(t) &= N \frac{d}{dt}(\phi_m \sin(\omega t)) \\
e(t) &= N_{\text{ph}}\, \phi_m\, \omega \cos(\omega t) \\
&= 2\, \pi\, f\, N_{\text{ph}}\, \phi_m \cos(\omega t) \\
\therefore E_{\text{ph}} &= \frac{2\pi}{\sqrt{2}}\, f\, \phi\, N_{\text{ph}} = 4.44 f\, \phi\, N_{\text{ph}}
\end{aligned}
$$

The EMF equation of synchronous machines is similar to that of the transformer (remember that transformer is a static AC machine) *except* for the winding factor as transformer has *concentrated winding* while rotating machines have *distributed winding*. So the previous equation must be multiplied by a factor to be used in synchronous machines.

Figure 6: From left to right: concentrated winding in transformer, concentrated winding in machines, distributed winding in machines

$$
\boxed{E_{\text{ph}} = 4.44 f\, \phi\, N_{\text{ph}}\, k_w}
$$

$$
k_w = k_d \times k_p
$$

k_w : Winding factor
k_d : Distribution factor
k_p : Pitch factor

$$
N_{\text{ph}} = \frac{Z}{2 \times \text{number of phases}}
$$

N_{ph} : Number of armature turns per phase
Z : Number of armature conductors

$$\therefore E \propto f \times \phi$$

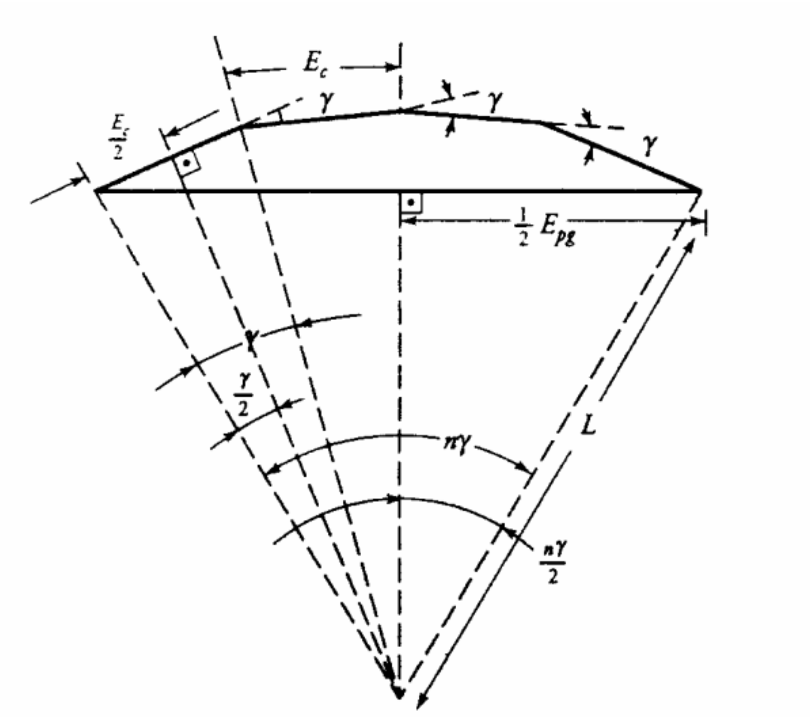
$$\because \phi \propto I_f$$

$$\therefore E \propto f \times I_f$$

$$\therefore \boxed{\frac{E_2}{E_1} = \frac{f_2}{f_1} \times \frac{I_{f2}}{I_{f1}}}$$

$\boxed{\text{4. Q}}$ — Two direct coupled alternators running at 300 rpm having total number of poles of 12 and 16 respectively. Find the frequency of the generated emf of each machine.

A —



Since the two machines are direct couples:

$$\therefore N_1 = N_2 = 300rpm$$

$$\because P_1 = 12 \quad P_2 = 16$$

$$\because f = \frac{P\,N}{120}$$

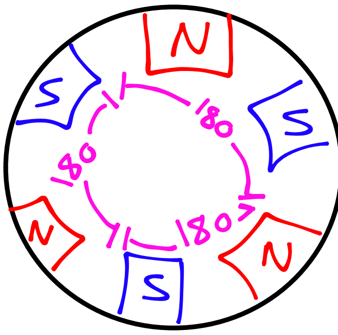
$$\therefore f_1 = \frac{12 \times 300}{120} = 30 \text{ Hz}$$

$$\therefore f_2 = \frac{16 \times 300}{120} = 40 \text{ Hz}$$

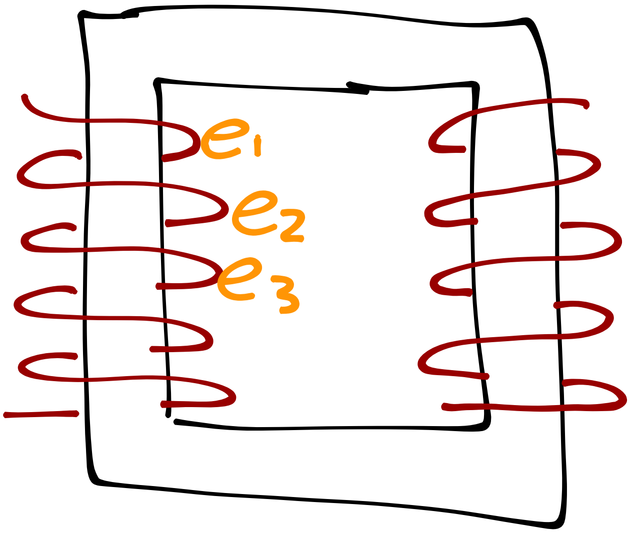
6.1 Distribution Factor

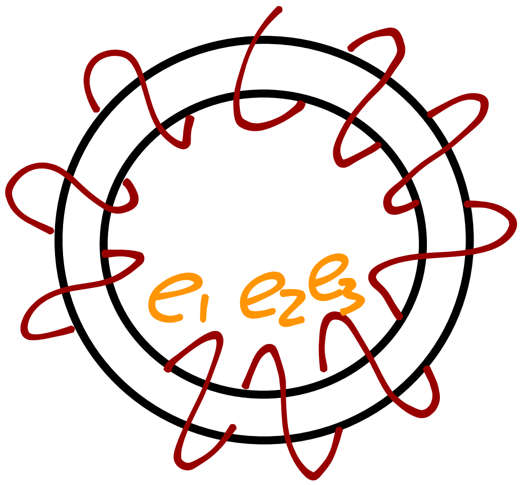
You know θ mechanical [same as θ in geometry

What is θ electrical → between N and S $\boxed{180°}$



So $\theta_{elec} = \frac{P}{2} \theta_{mech}$





$E_{Total} = e_1 + e_2 + e_3$ $\quad E_{Tot} \neq e_1 + e_2 + e_3$

Not in phase

$$kd = \frac{\text{vector sum}}{\text{arithmetic sum}}$$

we calculate as distributed then multiply by kd as correction factor

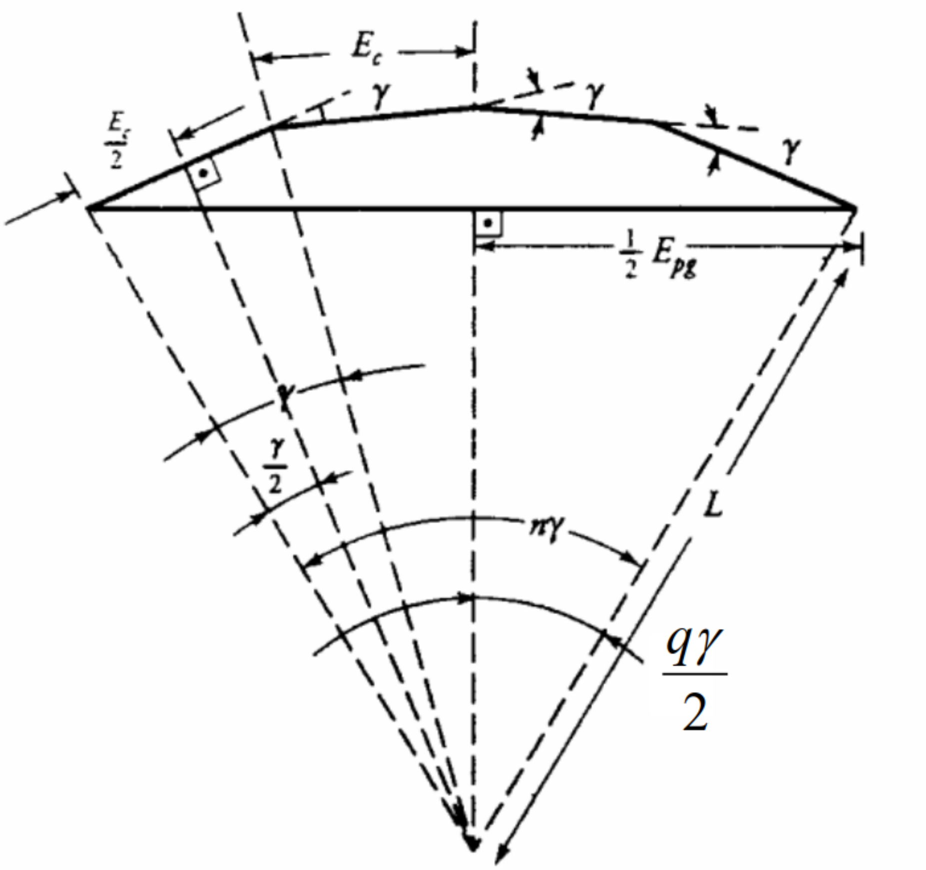
$$\theta_{\text{electrical}} = \frac{P}{2} \times \theta_{\text{mechanical}}$$

The coils of each phase are not concentrated in one slot, but are distributed in a number of slots to form polar groups under each pole. These coils are displaced from each other by a certain angle. Therefore the emfs induced in coil sides within a polar group are not in phase with each other, but differ by an angle equal to the angular displacement of the slots.

$$K_d = \frac{\text{emf of distributed winding}}{\text{emf of conc winding}} = \frac{\text{Vector sum of emf per phase}}{\text{Arithmetic sum of emf per phase}}$$

Let's define q : number of slots per pole per phase.

$$q = S \times \frac{1}{P} \times \frac{1}{n}$$



Note that q is normally an integer ranging from 2 to 7.[4]

[4] In most problems it will be 3 or 4

Let's define γ : Slot angle, the displacement between slots

$$\begin{aligned}\gamma &= \frac{\theta_{\text{electrical}}}{S} \\ &= \frac{\frac{P}{2} \times \theta_{\text{mechanical}}}{S} \\ &= \frac{180 \times P}{S}\end{aligned}$$

So, let's derive K_d:

$$K_d = \frac{E_{pg}}{q \times E_c} = \frac{2 \times L \sin\left(\frac{q\gamma}{2}\right)}{q \times 2L \sin\left(\frac{\gamma}{2}\right)}$$

$$\boxed{K_d = \frac{\sin\left(\frac{q\gamma}{2}\right)}{q \sin\left(\frac{\gamma}{2}\right)}}$$

Note that K_d is less than 1, and it equals 1 only if all conductors are placed in one slot, or as in transformer.