AC Machines: Synchronous Machine

Alternators On Load

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Alternators On Load

- On no-load: $E_{ph} = 2.22 K_w \phi Z_{ph} f = 2.22 K_c K_d \phi Z_{ph} f$ Volts

$$K_c = \cos\frac{\alpha}{2} \qquad K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} \qquad m = \frac{\text{slots}}{\text{poles x phases}} \qquad \beta = \frac{180^\circ}{\text{slots/pole}}$$

- Whenever the load on the alternator is varied, the terminal voltage will also vary.
- This variation in terminal voltage is mainly due to three reasons:

✓ Voltage drop due to armature resistance (IR_a)

✓ Voltage drop due to armature leakage reactance (IX_L)

✓ Voltage drop due to armature reaction.

Alternators On Load

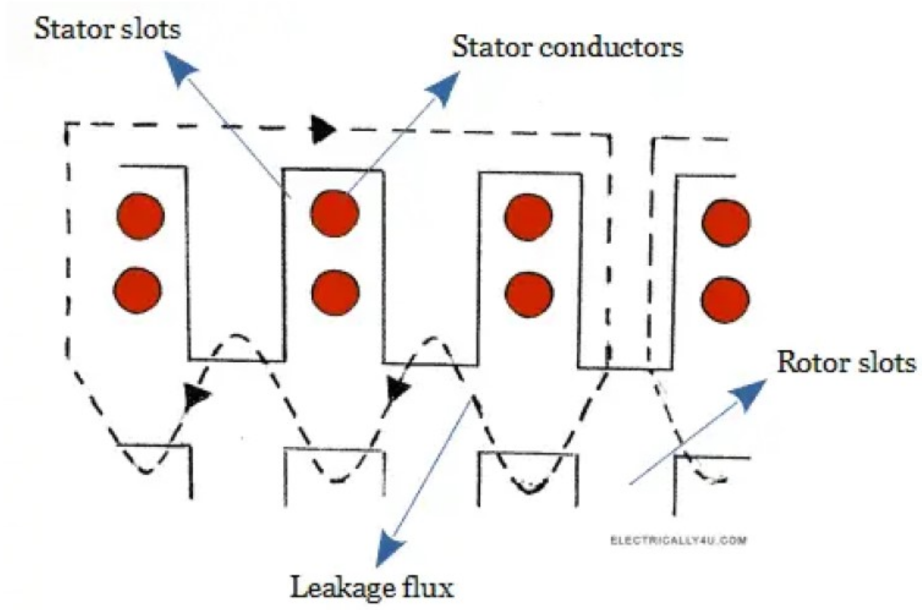
Voltage drop due to armature resistance (IR_a)

- The armature winding resistance per phase will cause a IRa voltage drop per phase.
- The voltage drop due to armature resistance is in phase with the armature current I

Voltage drop due to armature leakage reactance (IX_L)

- When current flows through armature conductors, the flux will start to flow through the armature core.
- Some flux will take different paths and do not cross the air gap which is called leakage flux.
- Leakage flux depends on the current flowing through the conductor.
- This leakage flux will set up an emf because of self-inductance.
- This emf leads the armature current I by 90^0.

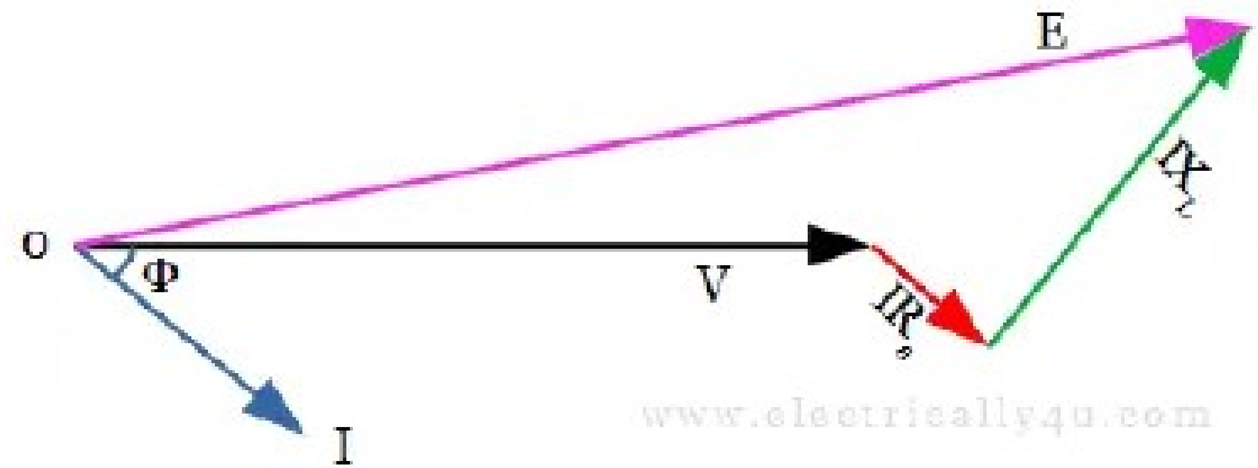
Alternators On Load: Leakage Flux



- The armature winding is said to possess a leakage reactance X_L.
- The voltage drop due to this reactance is IX_L.
- The generated emf has to overcome the voltage drop due to leakage reactance to give its output.
- $E = V + I\,(R_a + jX_L)$

Alternators On Load: Phasor Diagram

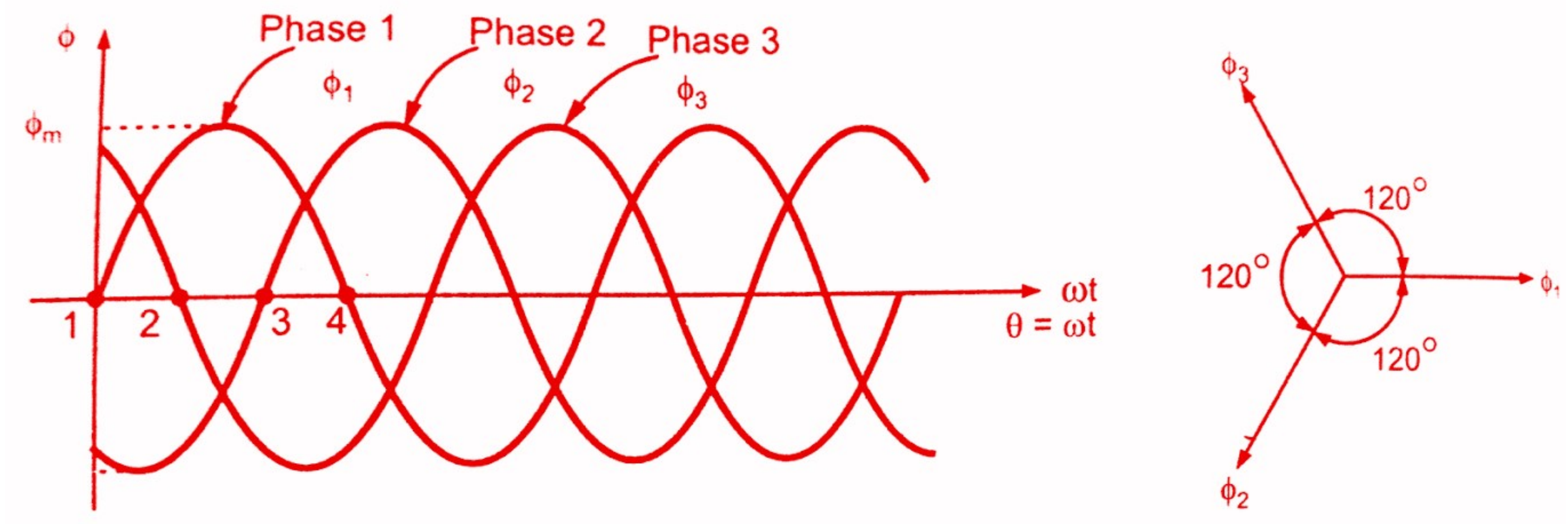
- The voltage phasor is taken as the reference phasor.
- The armature current lags behind the voltage by an angle Φ.
- Hence the current phasor is drawn at an angle Φ from the voltage phasor.
- The phasor for armature resistance drop is drawn parallel to the current phasor from the extremity of Voltage phasor V.
- Leakage reactance drop is drawn perpendicular to the current phasor from the extremity of IR_a phasor.
- Join 0 and the extremity of IX_L phasor to get E.



Production of Rotating Magnetic Field

- When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced.
- This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator.
- For this reason, it is called a rotating field.
- Consider a three phase windings displaced in space by 120°,supplied by a three phase a.c supply.
- The three phase currents are also displaced from each other by 120°.
- The flux produced by each phase current is also sinusoidal in nature and all three fluxes are separated from each other by 120°.
- If the phase sequence of the windings is 1-2-3, then the mathematical equation for the instantaneous values of the fluxes Φ1, Φ2 andΦ3

Production of Rotating Magnetic Field



As windings are identical and supply is balanced the amplitude of each flux is same i.e. Φm. The waveforms of three fluxes are shown in figure.

The mathematical equation for the instantaneous fluxes Φ_1, Φ_2 and Φ_3

$$\Phi_1 = \Phi_m \,\mathrm{Sin}\,(wt) = \Phi_m \sin\theta$$

$$\Phi_2 = \Phi_m \,\mathrm{Sin}\,(wt - 120^\circ) = \Phi_m \sin(\theta - 120^\circ)$$

$$\Phi_3 = \Phi_m \,\mathrm{Sin}\,(wt - 240^\circ) = \Phi_m \sin(\theta - 240^\circ)$$

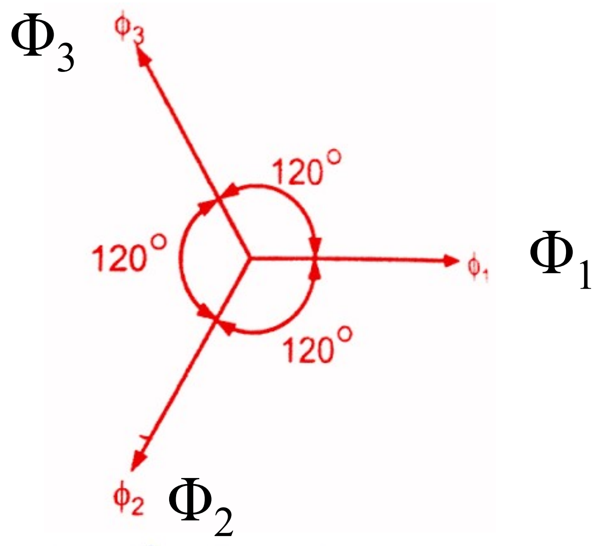
- The resultant flux Φ_T at any instant is given by phasor combination of Φ_1, Φ_2 and Φ_3 at that instant.
- Let us find out Φ_T at four different instants 1, 2, 3 and 4

Production of Rotating Magnetic Field

Case (i) $\theta = 0°$

- ✓ $\Phi_1 = \Phi_m \text{ Sin } 0° = 0$
- ✓ $\Phi_2 = \Phi_m \sin(-120°) = -0.866\,\Phi_m$
- ✓ $\Phi_3 = \Phi_m \text{ Sin }(-240°) = +0.866\,\Phi_m$
- ✓ And $\Phi_T = \Phi_1 + \Phi_2 + \Phi_3$

✓BD is perpendicular drawn from B on 'Φ_T'



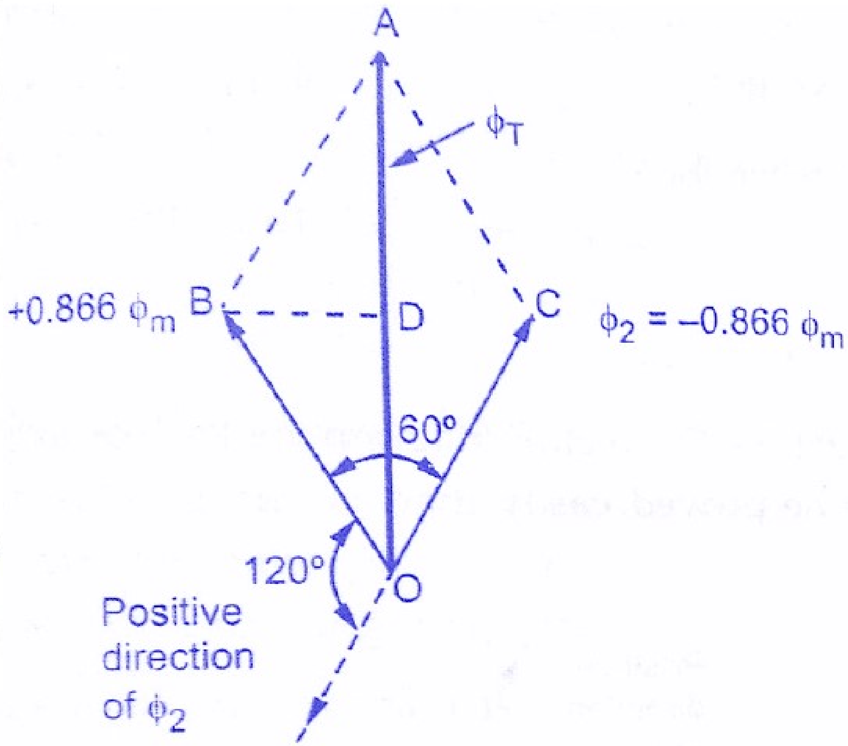
$$OD = DA = \frac{\phi_T}{2}$$

In Δ OBD, $\angle$ BOD = 30°

$$\cos 30° = \frac{OD}{OB} = \frac{\left(\frac{\phi_T}{2}\right)}{0.866\,\phi_m}$$

$$\phi_T = 2 \times 0.866\,\phi_m \times \cos 30°$$

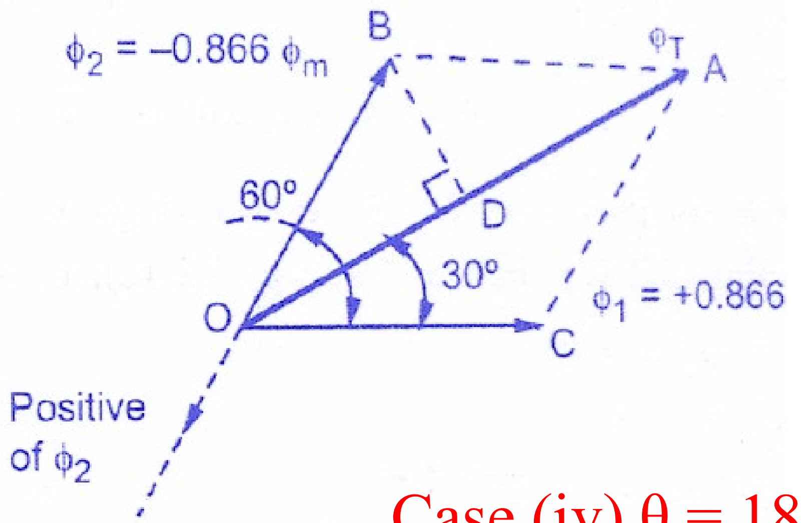
$$\phi_T = 1.5\,\phi_m$$



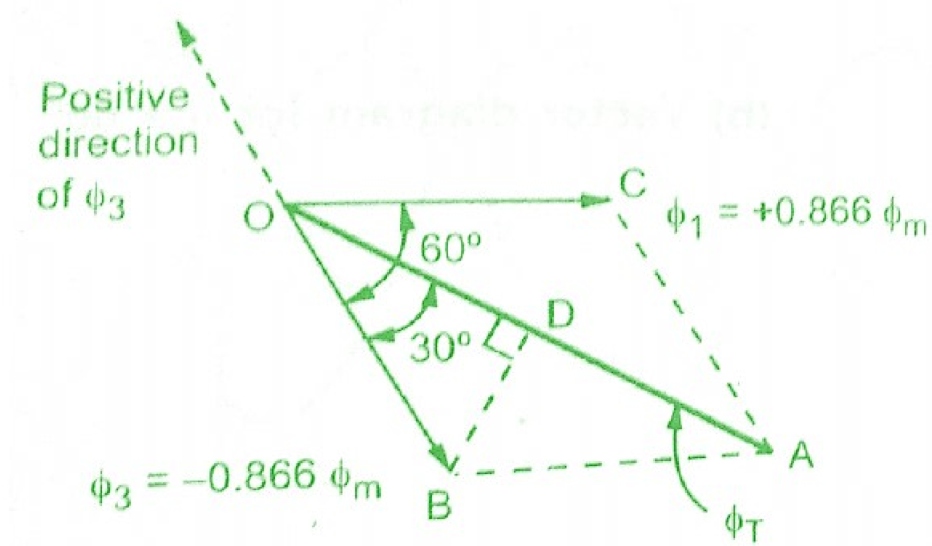
Production of Rotating Magnetic Field

Case (ii) $\theta = 60°$

- ✓ $\Phi_1 = \Phi_m \text{ Sin } 60° = +0.866\ \Phi_m$
- ✓ $\Phi_2 = \Phi_m \sin(-60°) = -0.866\ \Phi_m$
- ✓ $\Phi_3 = \Phi_m \text{ Sin } (-180°) = 0$
- ✓ And $\Phi_T = \Phi_1 + \Phi_2 + \Phi_3$

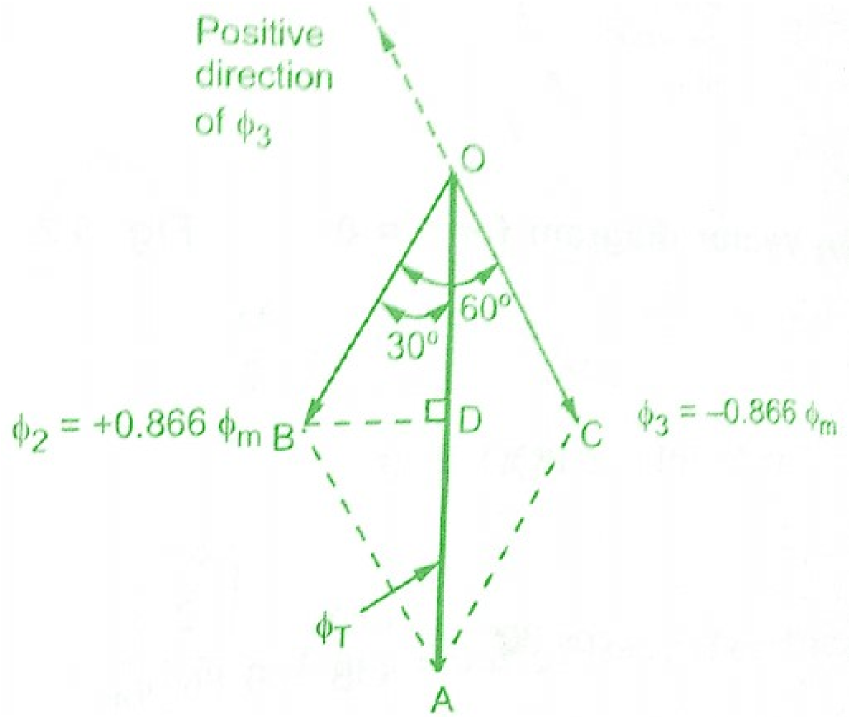


The magnitude of the resultant is same as before but it is rotated in space by 60° in clockwise direction, from its previous position



Case (iii) $\theta = 120°$

Case (iv) $\theta = 180°$



Production of Rotating Magnetic Field

- The resultant of the three alternating fluxes, separated from each other by 120°, has a constant amplitude of 1.5 Φm, where Φm is the maximum amplitude of an individual flux due to any phase.
- The resultant always keeps on rotating with a certain speed in space
- Hence we can include that the three phase stationary winding when connected to a three phase a.c. apply produces a rotating magnetic field.
- The speed of the resultant is 180° in space, for 180° electrical of the fluxes for a 2 pole.
- If the winding is wound for P poles, then resultant will complete 2/p revolutions for 360° electrical of the fluxes.
- So resultant flux bears a fixed relation between the speed of rotation (Ns), supply frequency (f) and the number of poles (P) for which winding is wound.
- So for a rotating magnetic field: Ns = 120.f/P r.p.m.

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- So for a rotating magnetic field: $Ns = 120.f/P$ r.p.m.

Armature Reaction in Alternators

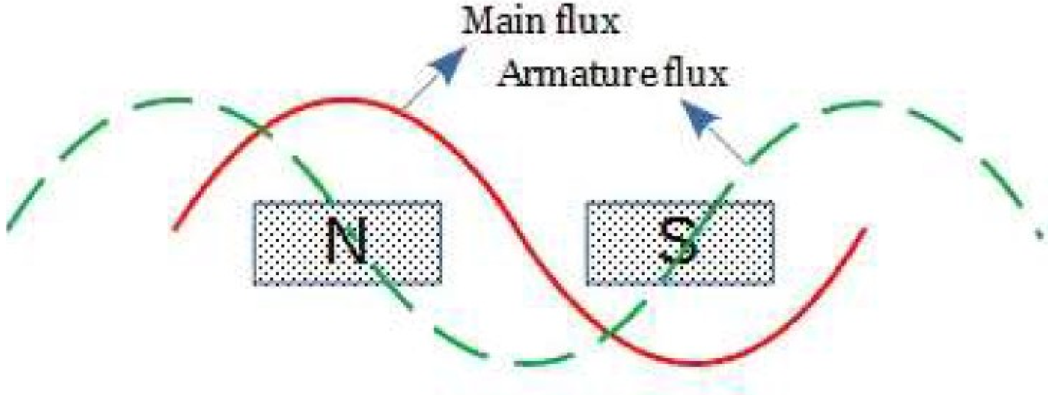
- Armature reaction in alternator is defined as the effect of armature flux on the main flux produced by the field poles.
- Armature reaction depend on the type of load applied to the alternator (UPF, ZPF lag/lead, Lag/lead)

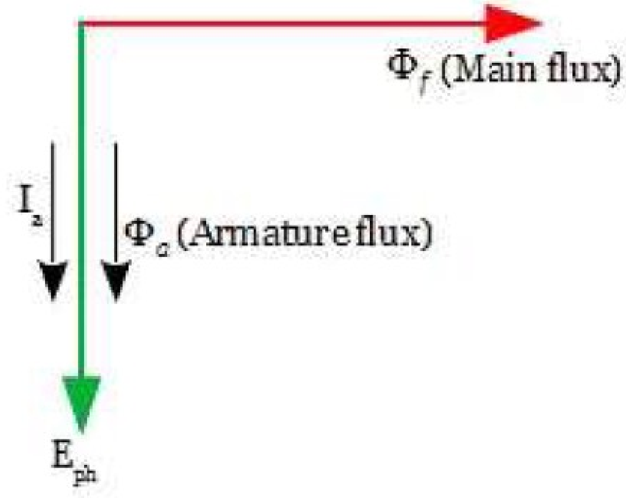
Unity Power Factor (UPF): Purely Resistive Load

- When a resistive load with a unity power factor is connected to the alternator, the load current will start to flow through the armature winding.
- As it is a pure resistive load, the armature current will be in phase with the induced voltage.
- The armature current will produce its own flux in the conductor, which will also be in phase with the induced voltage.
- Since the induced emf lags behind the main field flux by 90^0, the armature flux produced will also be delayed by 90^0 with respect to the main flux.

Armature Reaction in Alternators

Unity Power Factor (UPF):

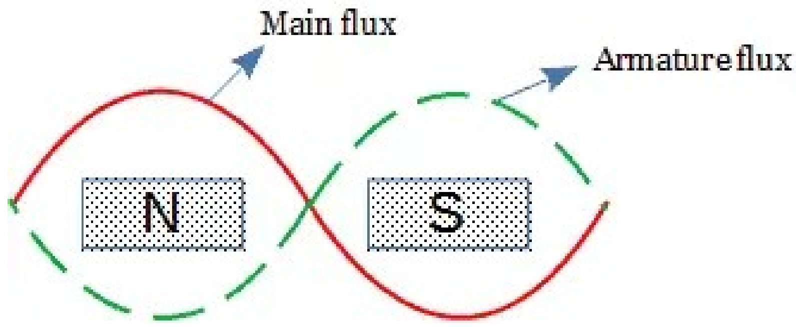


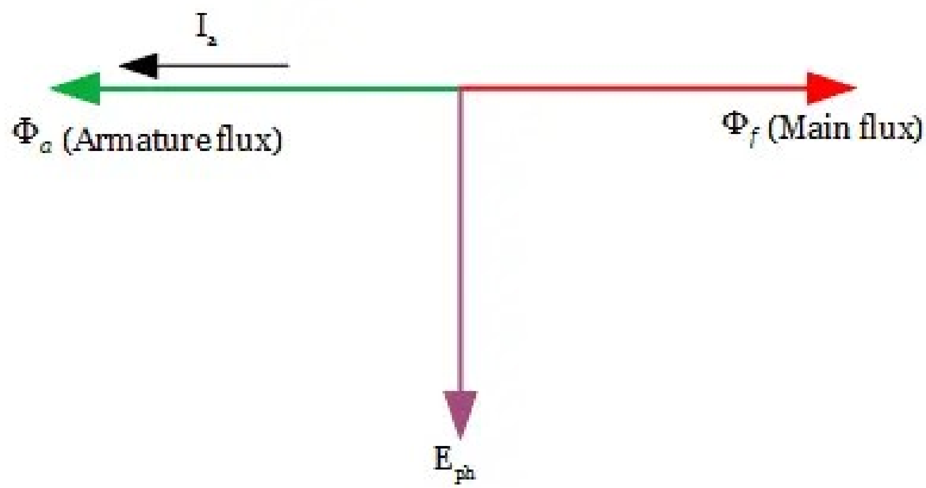


- ❖ As the armature flux act on the main field flux perpendicularly, the distribution of main field flux under a pole face does not remain uniformly distributed.
- ❖ Flux density at the trailing tip of the pole is increased while flux at the leading tip of the pole decreases.
- ❖ The armature flux will cross and distorts the main field flux at one point, thereby weakening the main flux.
- ❖ This is said to be a cross magnetizing effect.

Armature Reaction in Alternators

Zero Power Factor Lag (ZPF Lag):

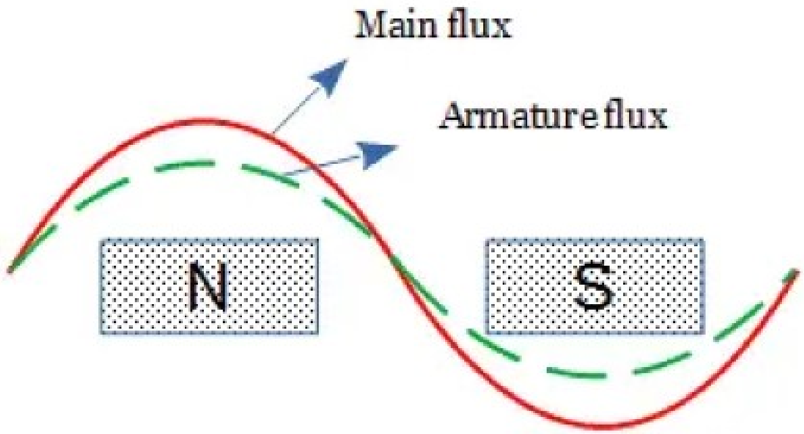


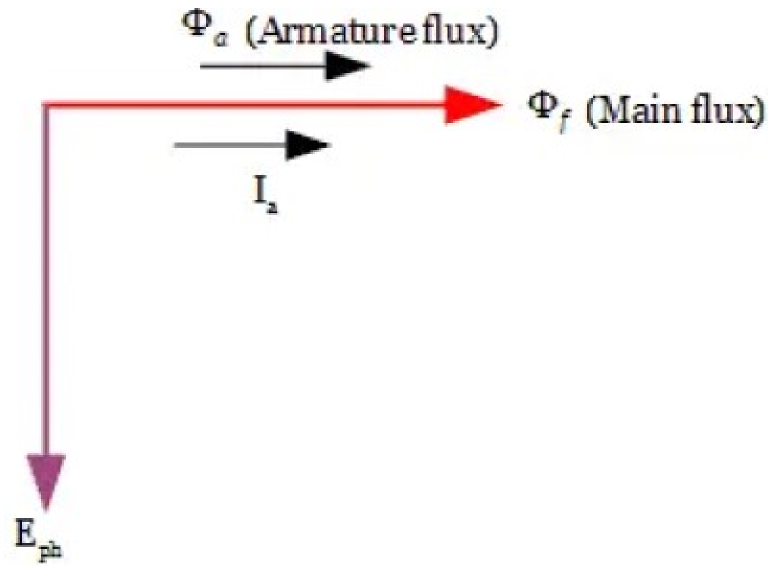


- When a pure inductive load with zero lagging power factor is connected to the alternator, the armature current will be delayed by 90^0 and so the armature flux produced will also be shifted by 90^0 with respect to the poles.
- The armature flux will be in direct opposition to the main flux.
- This effect of armature reaction on this load (ZPF Lag) is said to be a demagnetizing effect.

Armature Reaction in Alternators

Zero Power Factor Lead (ZPF Lead):





- When a pure capacitive load with zero leading power factor is connected, the load current will be advanced by 90^0 and so the armature flux produced will also be advanced by 90^0 with respect to emf induced.
- So the armature flux will be in phase with the main field flux, resulting in strengthening of the field flux.
- Thus the main flux gets increased in this loading condition.
- This effect of armature reaction on this load (ZPF Lead) is said to be a magnetizing effect.

Armature Reaction in Alternators

- When an alternator supplies a load at the unity power factor, the effect of armature reaction is partly cross magnetizing and partly distorting.
- The effect of armature reaction is demagnetizing when an alternator supplies a load at a lagging power factor.
- When an alternator supplies a load at the leading power factor, the effect of armature reaction is magnetizing.
- When an alternator supplies a load at the intermediate power factor, the effect of armature reaction is partly distorting and partly demagnetizing.
- The effects of armature reaction may cause the generated emf to vary.
- The voltage drop due to armature reaction may be assumed as there is a presence of fictitious reactance Xa called armature reactance reaction.
- The voltage drop due to the armature reaction is represented as IXa.

Armature Reaction in Alternators

- The leakage reactance X_L and armature reaction reactance Xa together called synchronous reactance X_S. ($X_S = X_L + X_a$)
- Thus the voltage drop in an alternator under loaded conditions is the total sum of voltage drop due to armature resistance, armature leakage reactance, and armature reaction reactance.
- $V = I R_a + j I X_L + j I X_a = I(R_a + j X_L + j X_a) = I(R_a + j(X_L + X_a))$
- $V = I(R_a + j X_S) = I Z_S$
- Where Z_S is known as the **synchronous impedance** of an alternator.
- **Phasor Diagrams:**

✓ E_0 is the no-load voltage. It is the maximum voltage induced in the armature without giving any load.

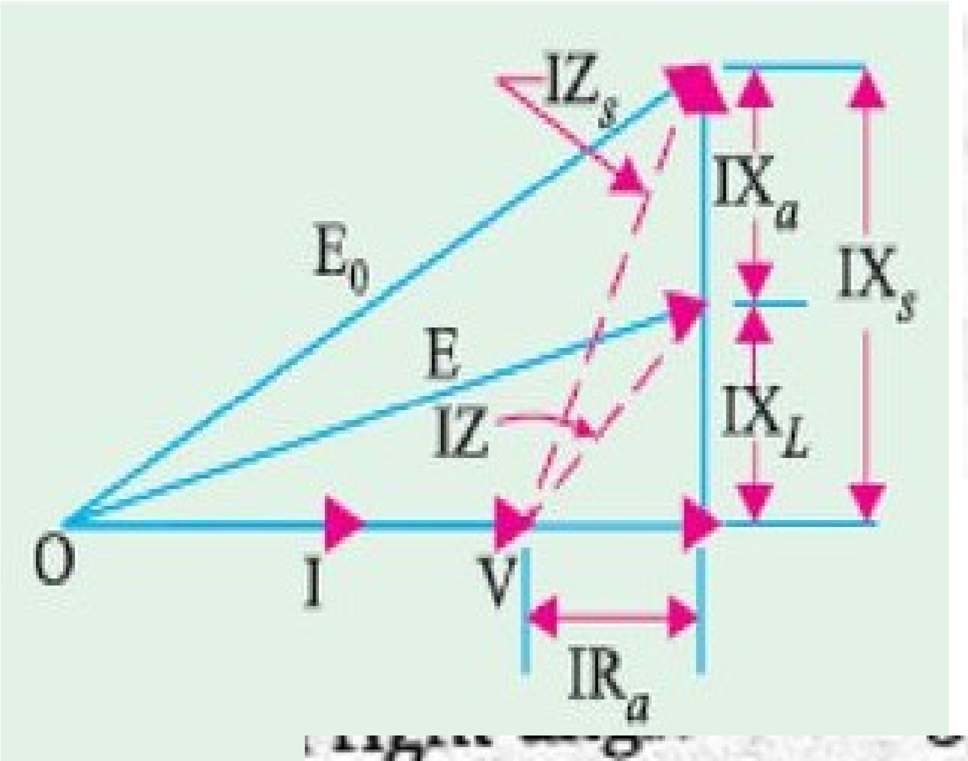
✓ E is the load voltage. It is the induced voltage after overcoming the armature reaction. E is vectorially less than the no-load voltage.

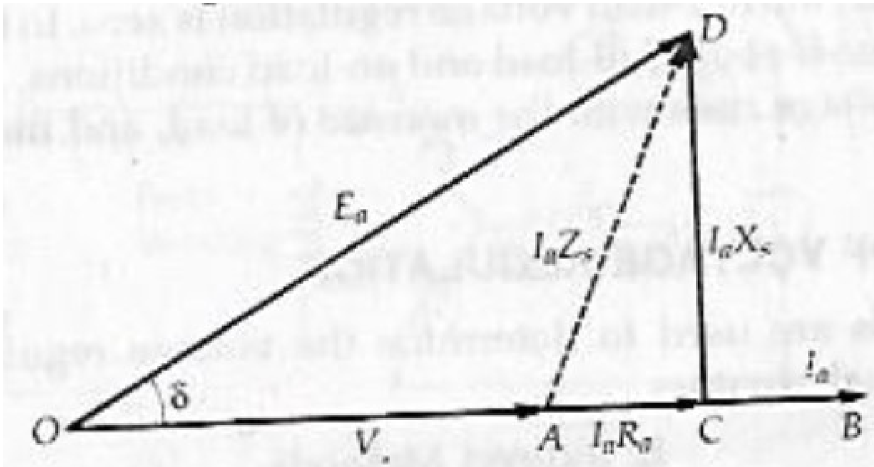
✓ I is the armature current per phase

✓ V is the terminal voltage. .

Armature Reaction in Alternators

Unity Power Factor (UPF):





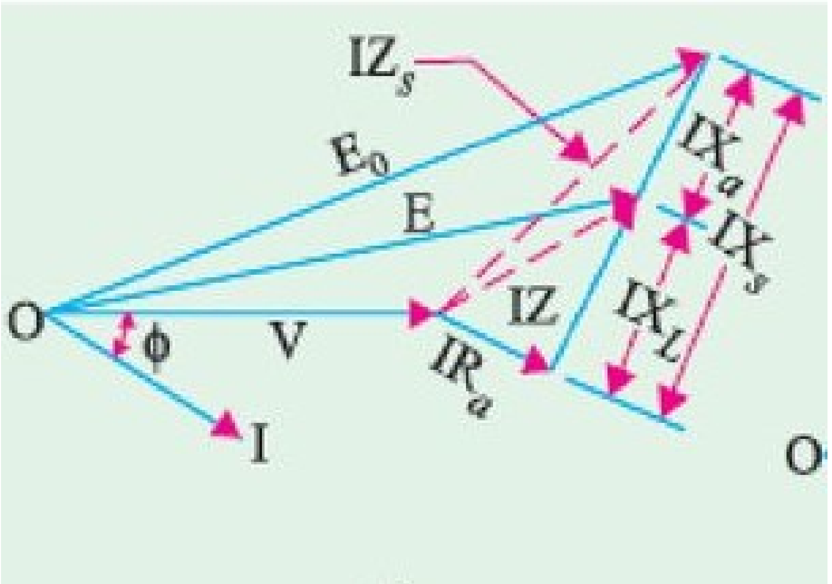
$$(OD)^2 = (OC)^2 + (CD)^2 = (OA + AC)^2 + (CD)^2$$

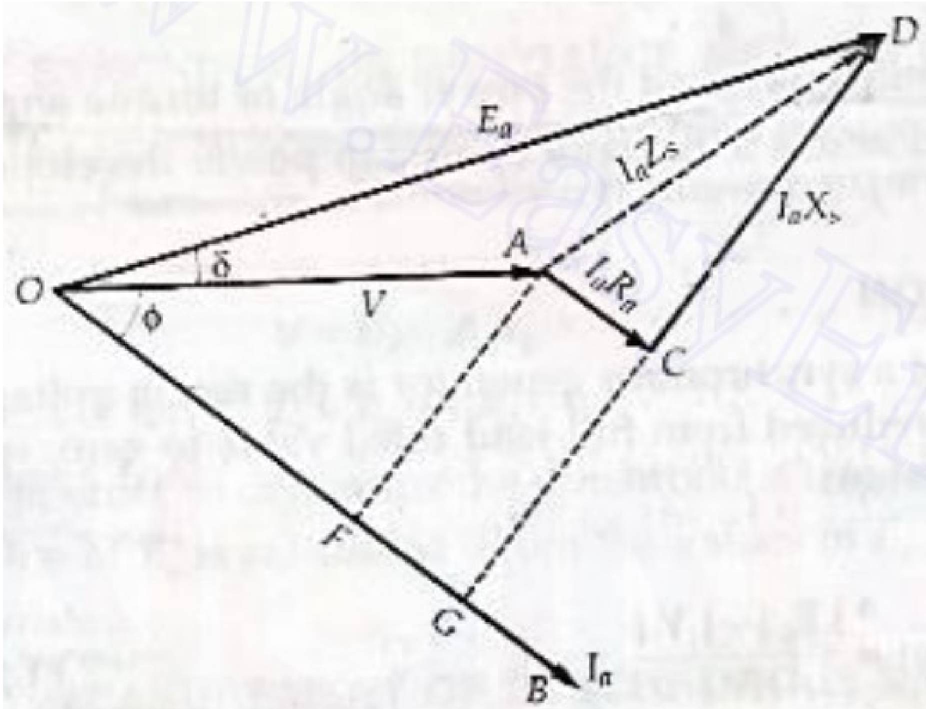
$$E_a^2 = (V + I_aR_a)^2 + (I_aX_s)^2$$

$$E_a = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$$

Armature Reaction in Alternators

Lagging Power Factor:





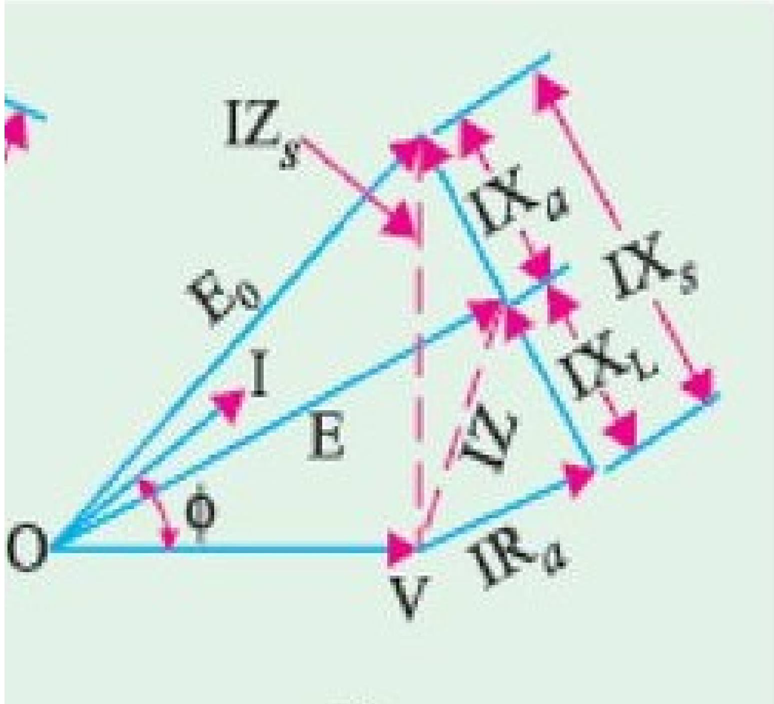
$$OD^2 = OG^2 + GD^2 = (OF + FG)^2 + (GC + CD)^2$$

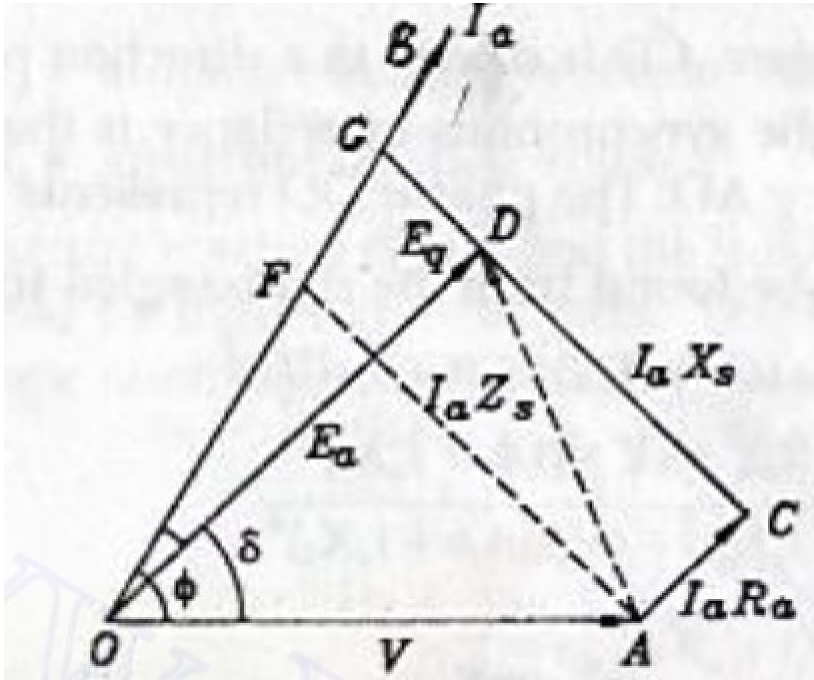
$$E_a^2 = (V \cos \phi + I_a R_a)^2 + (V \sin \phi + I_a X_s)^2$$

$$E_a = \sqrt{(V \cos \phi + I_a R_a)^2 + (V \sin \phi + I_a X_s)^2}$$

Armature Reaction in Alternators

Leading Power Factor:





$$OD^2 = OG^2 + GD^2 = (OF + FG)^2 + (GC - CD)^2$$

$$E_a^2 = (V \cos \phi + I_a R_a)^2 + (V \sin \phi - I_a X_s)^2$$

$$E_a = \sqrt{(V \cos \phi + I_a R_a)^2 + (V \sin \phi - I_a X_s)^2}$$