Module-3

Synchronous Generators: *Construction, working, Armature windings, winding factors, EMF equation. Harmonics–causes, reduction and elimination. Armature reaction, Synchronous reactance, Equivalent circuit.*
Synchronous Generators Analysis: *Open circuit and short circuit characteristics, Assessment of reactance-short circuit ratio, Alternator on load. Voltage regulation. Voltage regulation by EMF and MMF methods. Excitation control for constant terminal voltage. Numerical.*

Introduction: An alternator is defined as a machine which converts mechanical energy to electrical energy in the form of alternating current (at a specific voltage and frequency). Alternators are also known as synchronous generators.
Alternators produce the power for the electrical systems of modern vehicles. Previously, DC generators or dynamos were used instead. But after the development of the alternator, they replaced DC dynamos since alternators are more robust and lightweight.

Advantages of Rotating Magnetic Field:

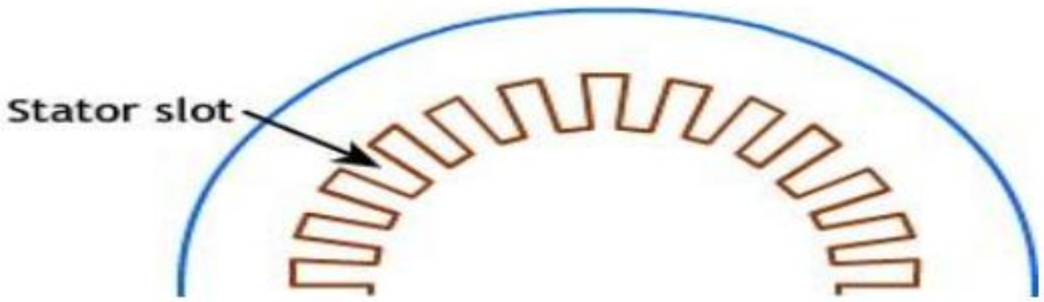
1. As the armature conductors are stationary, large space can be provided to accommodate a large number of conductors and insulation.
2. The armature is protected from mechanical and electrical stresses.
3. It is easier to collect large currents at very high voltages from stationary armature.
4. The problem of sparking at the slip rings is avoided.
5. The field is a low inertia circuit hence easy to rotate.
6. Construction is very simple due to stationary armature.
7. Only two slip rings are required for rotating field
8. Ventilation arrangements can be easily provided.

Construction of Synchronous Generator:

In Synchronous generators or alternators, the stationary winding is called the **'stator'** while the rotating winding is called the **'Rotor'**.

Stator:

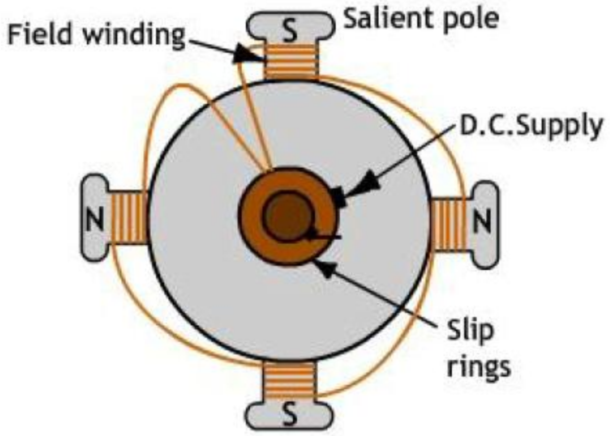
The stator in the synchronous generator is a stationary armature. This consists of a core and the slots to hold the armature winding. The stator core uses a laminated construction. It is built up of special steel stampings insulated from each other with varnish or paper. The laminated construction is basically to keep down eddy current losses.
Generally choice of material is steel to keep down hysteresis losses. The entire core is fabricated in a frame made of steel plates. The core has slots on its periphery for housing the armature conductors. The frame does not carry any flux and serves as the support to the core. Ventilation is maintained with the help of holes cast in the frame.



Rotor:
The rotor carries the field winding which is excited from an external DC source to produce a stationary rotor magnetic field. In order to reduce power loss due to eddy currents and hysteresis, the rotor core of the synchronous generator is made up of laminated sheet steel.

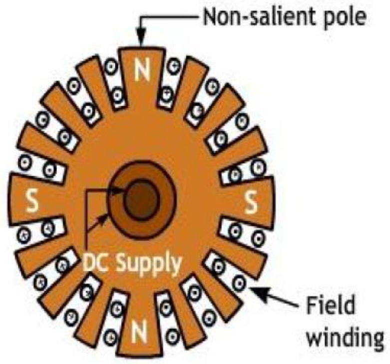
The rotor core is keyed to a rotor shaft which is connected to a prime mover like a turbine, engine, etc. This whole internal assembly is enclosed in a hollow cylindrical cover to provide mechanical strength to the machine and protect it from external impacts.
There are two types of rotor.
1) Salient Pole Type
2) Smooth Cylindrical Type

Salient Pole Type Alternator:



This is also called project pole type as all the poles are projected out from the surface of the rotor. The poles are built up of thick steel laminations. The poles are bolted to the rotor as shown in the figure above. The field winding is provided on the pole shoe. These rotors have large diameters and small axial lengths. The limiting factor for the size of the rotor is the centrifugal force acting on the rotating member of the machine. As the mechanical strength of salient pole type is less, this is preferred for low-speed alternators ranging from 125rpm to 500rpm. The prime movers used to drive such rotors are generally water turbines and IC engines.

Smooth Cylindrical Type Rotor. (Non-Salient or Non Projected Pole Type):



The rotor consists of a smooth solid steel cylinder having a number of slots to accommodate the field coils. These slots are covered at the top with the help of steel or manganese wedges. The unslotted portions of the cylinder itself act as the poles.
The poles are not projecting out and the surface of the rotor is smooth which maintains a uniform air gap

between the stator and rotor. These rotors have small diameters and large axial lengths. This is to keep peripheral speed within limits. The main advantage of this type is that these are mechanically very strong and thus preferred for high-speed alternators ranging from 1500 rpm to 3000 rpm. Such high-speed alternators are called 'turbo alternators'. The prime movers used to drive such types of rotors are steam turbines and electric motors.

Working Principle of Synchronous Generator:

The alternators work on the principle of electromagnetic induction. When there is a relative motion between the conductors and the flux, emf gets induced in the conductors.

In the synchronous generator, the rotor winding (field winding) is excited from a source of dc power to develop alternate N and S poles in the rotor. Now, this rotor is rotated in an anticlockwise direction with the help of a prime mover such as a turbine or engine. The speed of the rotation of the rotor is constant and is equal to synchronous speed.

The rotating magnetic field of the rotor cuts the armature conductors. Consequently, an emf is induced in the armature conductors due to electromagnetic induction. Since alternate N and S poles cut the armature conductors in each rotation, hence the induced emf is alternating in nature. The induced EMF in the armature is the result of the relative motion between the conductor and the field. The induced voltage is a sinusoidal wave.

The direction of the generated EMF can be determined by the Fleming's right rule and the frequency of it is given by,

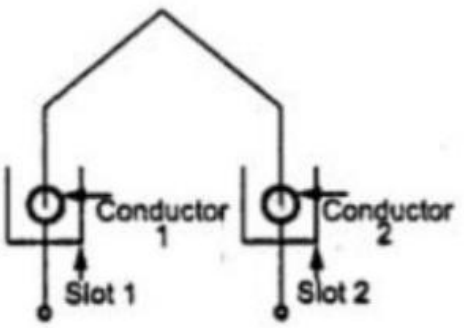
$$f = \frac{N_S P}{120} \text{ Hz}$$

Where P is the number of rotor poles, N_S is the synchronous speed in RPM (Revolution per Minute).

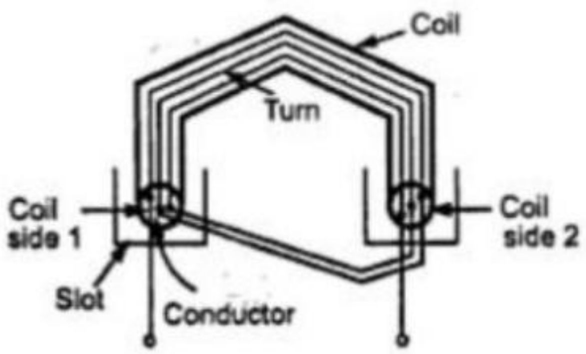
The magnitude of the generated voltage depends upon the speed of rotation of the rotor and the DC field excitation current. For the balanced condition, the generated voltage in each phase of the winding is the same but differ in phase by 120° electrical.

Winding Terminology:

1. **Conductor:** The part of the wire, which is under the influence of the magnetic field and responsible for the induced e.m.f. is called the active length of the conductor. The conductors are placed in the armature slots.
2. **Turn:** A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn.



(a)Turn



(b)Multiturn coil

3. **Coil:** As there are a number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called a multiturn coil. A coil may consist of a single-turn coil.

4. **Coil side:** Coil consists of many turns. Part of the coil in each slot is called the coil side of a coil.
5. **Pole Pitch:** It is center to centre distance between the two adjacent poles. We have seen that for one rotation of the conductors, 2 poles are responsible for 360^0 electrical of e.m.f., 4 poles are responsible for 720^0 electrical of e.m.f. and so on. So 1 pole is responsible for 180^0 electrical of induced e.m.f.
   Note: So 180^0 electrical is also called one pole pitch. Practically how many slots are under one pole which are responsible for 180oelectrical, are measured to specify the pole pitch.
   e.g. Consider 2 pole, and 18 slots armature of an alternator. Then under 1 pole there are 18/2 i.e. 9 slots. So pole pitch is 9 slots or 180^0 electrical. This means 9 slots are responsible to produced a phase difference of 180^0 between the e.m.f.s induced in different conductors. This number of slots/poles is denoted as 'n'.

$$\text{Pole pitch} = 180^\circ \text{ electrical}$$
$$= \text{slots per pole (no. of slots/P)} = n$$

6. **Slot angle (β):** The phase difference contributed by one slot in degrees electrical is called slot angle β. As slots per pole contribute 180° electrical which is denoted as 'n', we can write,

$$1 \text{ slot angle} = 180^0/n$$

$$\beta = \frac{180^\circ}{n}$$

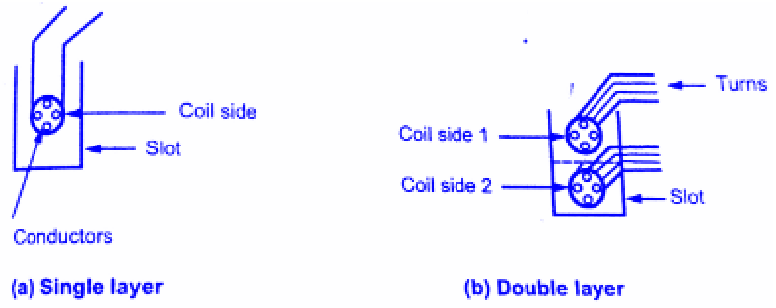
In the above example, $n = 18/2 = 9$, while $\beta = 180^0/n = 20^0$

Types of Armature Windings in Alternator:

The different types of armature windings in alternators are,

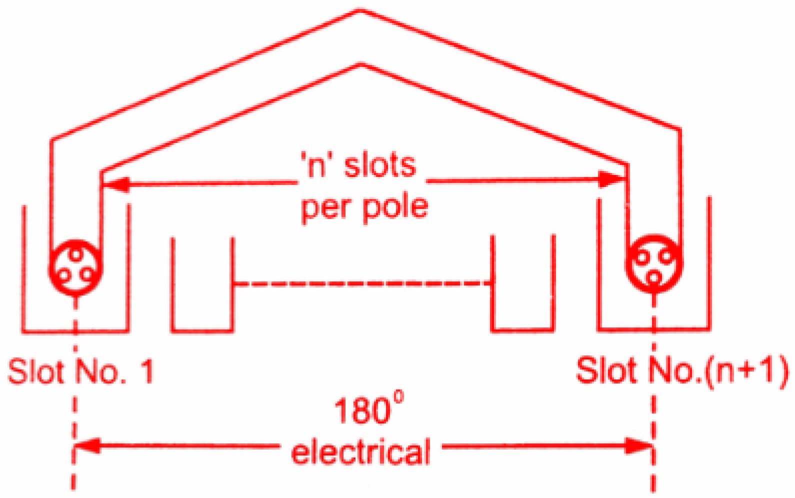
1. Single-layer and double-layer winding.
2. Full-pitch and short-pitch winding.
3. Concentrated and distributed winding.

1) Single Layer and Double Layer Winding : If a slot consists of only one coil side, winding is said to be a single layer. This is shown in figure(a). While there are two coil sides per slot, one, at the bottom and one at the top the winding is called double layer as shown in figure(b). A lot of space gets wasted in single layer hence in practice generally double layer winding is preferred.



2) Full Pitch and Short Pitch Winding: The one pole pitch is 180° electrical. The value of 'n', slots per pole indicates how many slots are contributing 180° electrical phase difference. So if the coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from the first slot, the winding is said to be full pitch winding and coil is called full pitch coil. For example, in 2 poles, 18 slots alternator, the pole pitch is n = 18/2 = 9 slots. So if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one pole pitch or n slots or 180° electrical apart, the coil is called full pitch coil. Here we can define one more term related to a coil called coil span.

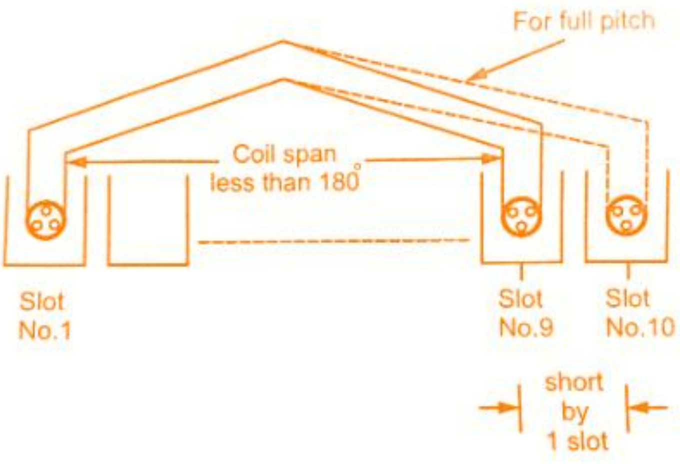
Coil Span:



Full Pitch Coil

It is the distance on the periphery of the armature, between two coil sides of a coil. It is usually expressed in terms of a number of slots or degrees electrical. So if the coil span is 'n' slots or 180° electrical the coil is called a 180° full pitch coil. This is shown in the figure to the left. As against this if coils are used in such a way that coil span is slightly less than a pole pitch i.e. less than 180° electrical, the coils are called, short-pitched coils or fractional-pitched coils. Generally, coils are shorted by one or two slots.

So in 18 slots, 2 pole alternators instead of connecting a coil side in slot No 1 to slot No.10, it is connected to a coil side in slot No.9 or slot No. 8, the coil is said to be short pitched coil, and winding are called short pitch winding.



Short Pitch Coil

Advantages of Short Pitch Coils:

1) The length required for the end connections of coils is less i.e. the inactive length of winding is less. So less copper is required. Hence economical.

2) Short pitching eliminates high-frequency harmonics which distort the sinusoidal nature of e.m.f. Hence waveform of an induced e.m.f. is more sinusoidal due to short pitching.

3) As high-frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimized. This increases efficiency.

Concentrated and distributed winding: Depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. This is denoted as 'm'.

m = Slots per pole per phase = n/number of phases

= n/3 (generally no. of phases is 3)

For example in 18 slots, 2 pole alternator we have, 8

n = 18/2 = 9

and m = 9/3

So we have 3 slots per pole per phase available. Now let 'x' number of conductors per phase are to be placed under one pole. And we have 3 slots per pole per phase available. But if all 'x' conductors per phase are placed in one slot keeping the remaining 2 slots per pole per phase empty then the winding is called concentrated winding.

EMF Equation of Synchronous Generator or Alternator:

Let Φ = Flux per pole, in Wb

P = Number of poles

N = Synchronous speed in r.p.m

f = Frequency of induced emf in Hz

Z = Total number of conductors

Zph = Conductors per phase connected in series

Zph = Z/3 as number of phases = 3

Consider a single conductor placed in a slot.

The average value of emf induced in a conductor = dΦ/dt

For one revolution of a conductor,

E_{avg} per conductor = (Flux cut in one revolution / Time taken for one revolution)

The total flux cut in one revolution is Φ x P.
The time taken for one revolution is 60/Ns seconds.

$$\therefore \quad e_{avg} \text{ per conductor } = \frac{\phi P}{\left(\frac{60}{N_s}\right)} = \phi \frac{PN_s}{60}$$

$$\text{But} \qquad f = \frac{PN_s}{120}$$

$$\therefore \qquad \frac{PN_s}{60} = 2f$$

Substituting in above equation

E_{avg} per conductor = 2 f Φ volts
Z conductors are connected in series per phase,
$E(avg)/phase = 2fZ\Phi\ volts.$
But Z=2T

$$E(avg)/phase = 2f\Phi 2T$$
$$= 4fT\Phi\ volts.$$

Wkt,

$$Form\ factor = rms\ value/average\ value = 1.11\ for\ sine\ wave.$$

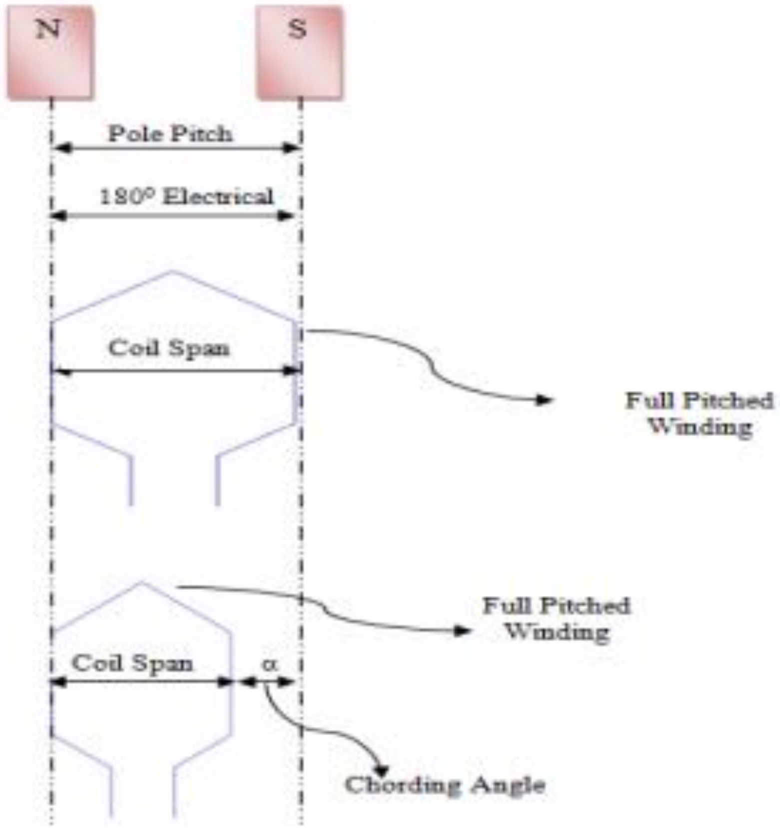
Therefore $E(rms/phase) = 4.44\ fT\Phi\ volts$

The above emf is derived assuming that the stator winding is full pitched and the emf's induced in the various conductors are equal in magnitude and does not have any phase difference. It is also assumed that all the conductors per pole per phase are connected in a single slot. But, in practice, the coils are short pitched. The conductors are uniformly distributed in all the slots of the stator. Due to these two facts, the emf induced in the alternator gets reduced by a small quantity. The equation for induced emf is modified as,
$Eph = 4.44KpKd\ fZ\Phi\ volts$
Where K_P=pitch factor
K_d= distribution factor

Pitch factor or coil span factor(Kp):
It is also known as coil span factor or chording factor. Pole pitch is the distance between two similar

points on adjacent poles and it is defined to be 180° electrical. Coil pitch or coil span is the distance between two adjacent sides of a coil.

If the armature winding is so wound that the coil pitch equals the pole pitch then it is called a full-pitched winding. But for practical reasons, we make the coil span less than the pole pitch by angle α where α is called the chording angle(then the winding is said to be short pitched).
Due to this, the induced emf reduces by a pitch factor Kp, the pitch factor and $Kp = cos(\alpha/2)$



Distribution factor K_d : This is also known as the breadth factor or winding factor. Under the influence of each pole, Z/P conductors belong to one phase. All these conductors can be accommodated in one armature slot and we have to distribute them over two or more slots. This again reduces the induced emf by a factor K_d.

$$K_d = \frac{\sin\left({}^{m\beta}/_{2}\right)}{m \sin\left({}^{\beta}/_{2}\right)}$$

$$Where\ m = number\ of\ slots/pole/phase.$$

$$= total\ no.\ of\ armature\ slots/\ (no.\ of\ poles\ x\ no.\ of\ phases)$$

$$And\ \beta = \frac{180°}{(no. of\ slots \times\ pole)}$$

Taking these two factors into account,

$$E_{rms/ph} = 4.44\ K_p K_d\ fT\Phi\ volts$$

$$Or\ E_{rms/ph} = 4.44 K_w fT\ \Phi\ volts\ \dots\dots\dots\dots\dots..K_w = K_p K_d$$

Voltage Regulation of an Alternator: The total change in terminal voltage of the alternator from no load to full load, at constant speed and field excitation, is termed as voltage regulation.

[OR]

The voltage regulation of an alternator is the change in its terminal voltage when full load is removed keeping the field excitation and speed constant, divided by the rated terminal voltage.

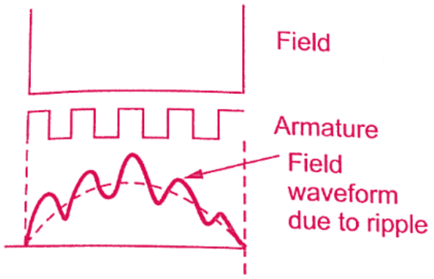
$$Regulation = \frac{E_0 - V}{V}$$

Where E_0= no-load terminal voltage.
V= full load terminal voltage.
The regulation is usually expressed as a % of the voltage drop from no load to full load w.r.t full load terminal voltage.

$$\%Regulation = \frac{E_0 - V}{V} \times 100$$

Harmonics: When the uniformly sinusoidally distributed air gap flux is cut by either the stationary or rotating armature sinusoidal emf is induced in the alternator. Hence the nature of the waveform of induced emf and current is sinusoidal. But when the alternator is loaded waveform will not continue to be sinusoidal or becomes non sinusoidal. Such non sinusoidal waveform is called a complex waveform. By using Fourier series representation, it is possible to represent complex nonsinusoidal waveforms in terms of a series of sinusoidal components called harmonics, whose frequencies are integral multiples of the fundamental wave. The fundamental waveform is having the frequency same as that of the complex wave.
The waveform, which is of the frequency twice that of the fundamental is called second harmonic. The one which is having the frequency three times that of the fundamental is called a third harmonic and so on. These harmonic components can be represented as follows.
Fundamental: $e_1 = Em_1 \text{ Sin } (\omega t \pm \theta_1)$
2nd Harmonic $e_2 = Em_2 \text{ Sin } (2\omega t \pm \theta_2)$
3rd Harmonic $e_3 = Em_3 \text{ Sin } (3\omega t \pm \theta_3)$
5th Harmonic $e_5 = Em_5 \text{ Sin } (5\omega t \pm \theta_5)$ etc.
In case of alternators as the field system and the stator coils are symmetrical the induced emf will also be symmetrical and hence the generated emf in an alternator will not contain any even harmonics.

Slot Harmonics:



As the armature or stator of an alternator is slotted, some harmonics are induced into the emf which is called slot harmonics. The presence of slot in the stator makes the air gap reluctance at the surface of the stator non uniform. Since in case of alternators the poles are moving or there is a relative motion between the stator and rotor, the slots and the teeth alternately occupy any point in the air gap. Due to this the reluctance or the air gap will be continuously varying. Due to this variation of reluctance ripples will be formed in the air gap between the rotor and stator slots and teeth. This ripple formed in the air gap will induce ripple emf called slot harmonics.

Harmonics Minimization:

1. **Distribution of armature windings :** Instead of having concentrated type of windings, they should be distributed in different slots. The distribution factor for harmonics is comparatively less than that of the fundamental and hence magnitude of harmonic e.m.f. is small.
2. **Chording:** The e.m.f. generated in the winding is proportional to cos $(x \propto /2)$ where $\propto$ is the angle of chording and x is the order of harmonic. If the proper value of the angle of chording is selected then harmonic e.m.f.s can be reduced significantly.
3. **Fractional slot windings:** The output voltage waveform will be free of harmonics by facilitating the use of fractional slot windings as the distribution factor will be smaller compared to that with the fundamental.
4. **Skewing:** Skewing the pole face will help eliminate the slot harmonics.
5. **Large length of air gap:** The reluctance will be increased by increasing the air gap and slot harmonics can be reduced.

Effect of Harmonics on induced emf:

The harmonics will affect both the pitch factor and distribution factor and hence the induced emf. In a well-designed alternator, the air gap flux density distribution will be symmetrical and hence can be represented in the Fourier series as follows.

$\mathbf{B = B_{m1}\sin \omega t + B_{m3} \sin 3\omega t + B_{m5}\sin 5\omega t + ...}$

The emf induced by the above flux density distribution is given by

$\mathbf{e = E_{m1}\sin \omega t + E_{m3} \sin 3\omega t + E_{m5}\sin 5\omega t + ...}$

The RMS value of the resultant voltage induced can be given as

$E_{ph} = \sqrt{[(E_1)^2 + (E_3)^2 + (E_5)^2 + \dots\dots\dots\dots\dots (E_n)^2]}$

And line voltage $E_{Line} = \sqrt{3} \times Eph$

Effect of Harmonics of pitch and distribution Factor:

The pitch factor is given by $\mathbf{K_p = \cos \alpha/2}$, where α is the chording angle.

For any harmonic say n^{th} harmonic, the pitch factor is given by $K_{pn} = \cos n\alpha/2$

The distribution factor is given by $\mathbf{K_d = (\sin m\beta/2) / (m \sin \beta/2)}$

For any harmonic say n^{th} harmonic, the distribution factor is given by

$\mathbf{K_{dn} = \sin m\, n\beta/2) / (m \sin n\beta/2)}$

Operation of Alternators:

The rotor winding is energized from the DC exciter and alternate N and S poles are developed on the rotor. When the rotor is rotated in the anti-clockwise direction by a prime mover, the stator or armature conductors are cut by the magnetic flux of rotor poles. Consequently, EMF is induced in the armature conductors due to electromagnetic induction.

The induced e.m.f. is alternating since N and S poles of rotor alternately pass the armature conductors. The direction of induced e.m.f. can be found by Fleming right-hand rule and frequency is given by;

$$\mathbf{f = PN / 120}$$

where N = speed of the rotor in r.p.m.
P = number of rotor poles

The magnitude of the voltage induced in each phase depends upon the rotor flux, the number and position of the conductors in the phase, and the speed of the rotor.

When the rotor is rotated, a 3-phase voltage is induced in the armature winding. The magnitude of induced e.m.f. depends upon the speed of rotation and the DC exciting current. The magnitude of e.m.f. in each phase of the armature winding is the same. However, they differ in phase by 120° electrical.

Similar to the case of DC generator, the behavior of a Synchronous generator connected to an external load is different than that at no load. To understand the performance of the Synchronous generator when it is loaded, consider the flux distributions in the machine when the armature also carries a current. Unlike in the DC machine in alternators the emf peak and the current peak will not occur in the same coil due to the effect of the power factor of the load. The current and the induced emf will be at their peaks in the same coil only for upf loads. For zero power factor lagging loads, the current reaches its peak in a coil that falls behind that coil wherein the induced emf is at its peak by 90 electrical degrees or half a pole-pitch. Likewise for zero power factor leading loads, the current reaches its peak in a coil that is ahead of that coil wherein the induced emf is at its peak by 90 electrical degrees or half a pole-pitch. For simplicity, assume the resistance and leakage reactance of the stator windings to be negligible. Also, assume the magnetic circuit to be linear i.e. the flux in the magnetic circuit is deemed to be proportional to the resultant ampere-turns - in other words the machine is operating in the linear portion of the magnetization characteristics. Thus the emf induced is the same as the terminal voltage, and the phase-angle between current and emf is determined only by the power factor (pf) of the external load connected to the synchronous generator.

Armature Reaction:

Magnetic fluxes in alternators
There are three main fluxes associated with an alternator:
(i) Main useful flux linked with both field & armature winding.
(ii) Leakage flux linked only with armature winding.
(iii) Leakage flux linked only with field winding.

Armature reaction in alternator is defined as the effect of armature flux on the main flux produced by the field poles.

An electric machine normally consists of field winding and armature winding. DC supply is given to the field winding to produce magnetic flux. The armature conductor is rotated at a synchronous speed with the aid of a prime mover.

When there exists a relative motion between the magnetic flux and armature winding, the armature conductor cuts the field flux. Hence there will be a change in flux linkage in the conductor.

According to Faraday’s law of Electromagnetic induction, an emf is induced in the armature conductors. When the load is applied to the armature terminals, the current starts flowing through the armature winding. Since the current is alternating in nature, it induces a flux in the conductor, called armature flux.

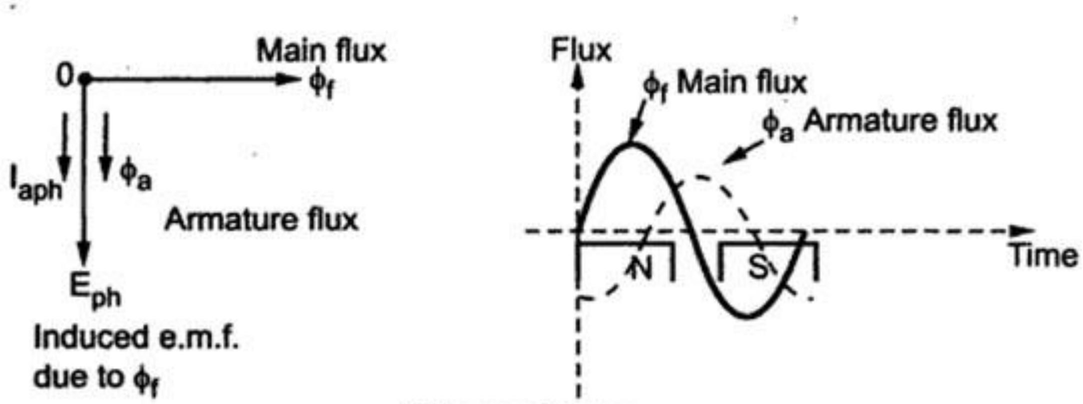
The armature flux thus produced will react with the main field flux and distort the effect of the main flux, called armature reaction in alternator or synchronous generator. Due to this distortion, the resultant flux will either strengthen or weaken.

The distortion may depend on the type of load applied to the alternator. A DC Generator also has more or less similar armature reaction effects. In this section, let us discuss the different armature reaction effects, that can be seen at different loads in detail.

Armature reaction at unity power factor 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 900 with respect to the main flux. The below shows the phasor diagram at unity power factor load.



Unity power Factor

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. As you can see from the waveform that, 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.

You can also notice, the armature flux also assists the main flux at another point. In this case, the armature reaction strengthens the main field flux. Due to these effects, the main field flux will get distorted, without causing much change to the generated voltage.

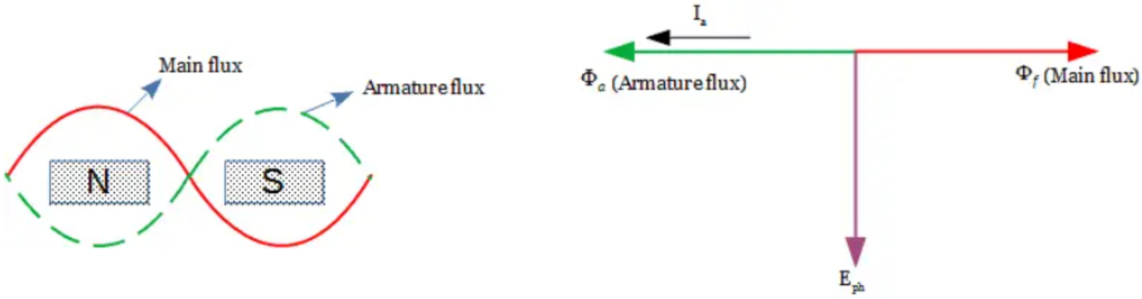
In other words, flux density at the trailing tip of the pole is increased while flux at the leading tip of the pole decreases. Due to this, the armature reaction at resistive load is said to have a distorting effect maintaining the constant average field strength.

Armature reaction at zero power factor lagging load

When a pure inductive load with zero lagging power factor is connected to the alternator, the load current starts to flow through the armature conductors.

The armature current will be delayed by 900 and so the armature flux produced will also be shifted by 900 with respect to the poles.

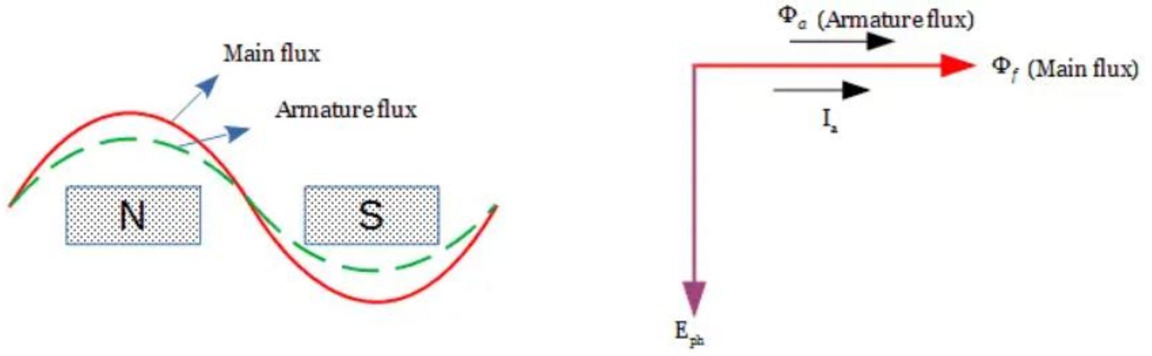
There will be a phase difference of 900 between the armature flux and main field flux. It can be seen that the armature flux will be in direct opposition to the main flux. The below shows the phasor diagram at lagging power factor load.



Waveform and phasor diagram for demagnetizing effect

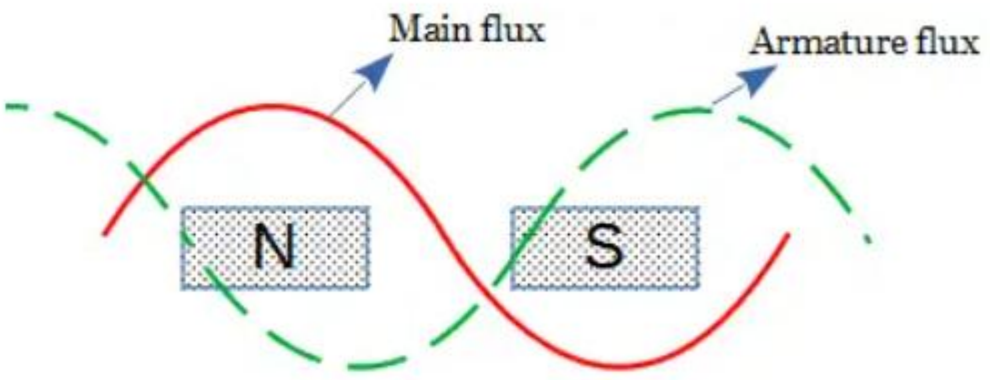
Thus the main flux gets decreased in this loading condition. This effect of armature reaction on this load is said to be a demagnetizing effect.
Due to this, the main field flux gets weaken and so the emf induced will be reduced. To maintain the same value of generated emf, filed excitation will have to be increased to overcome the demagnetizing effect.

Armature reaction at zero power factor leading load:
When a pure capacitive load with zero leading power factor is connected, the load current starts to flow through the armature conductors.
In this load condition, the load current will be advanced by 900 and so the armature flux produced will also be advanced by 900 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. The below shows the phasor diagram at leading power factor load.



Waveform and phasor diagram for magnetizing effect

The armature reaction in this load is said to be a magnetizing effect. Due to this effect, the main field flux gets weaken and so the emf induced will be reduced. To maintain the same value of generated emf, filed excitation will have to be reduced to overcome the magnetizing effect.
For any intermediate power factor, the effect of armature reaction in alternator will be partly distorting and partly demagnetizing.



From the explanations, we can summarize that

1. When an alternator supplies a load at the unity power factor, the effect of armature reaction is partly cross magnetizing and partly distorting.
2. The effect of armature reaction is demagnetizing when an alternator supplies a load at a lagging power factor.
3. When an alternator supplies a load at the leading power factor, the effect of armature reaction is magnetizing.

4. When an alternator supplies a load at the intermediate power factor, the effect of armature reaction is partly distorting and partly demagnetizing.
5. The effects of armature reaction may cause the generated emf to vary. In order to overcome that, the main flux is varied to generate the rated voltage.

Synchronous Reactance and Impedance:

When an alternator is loaded, there will be a circulation of load current in the armature winding. Once the load on the alternator is increased, the terminal voltage changes (for constant excitation) due to the following reasons,

Voltage drop due to armature resistance, IRa.

Voltage drop due to synchronous reactance.

Armature Resistance :

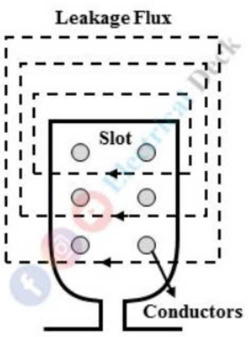
The armature resistance per phase Ra causes a voltage drop per phase of IRa which is in phase with the armature current. The armature resistance per phase can be measured directly by voltmeter and ammeter (ohm's law) method or by using a wheat stone bridge.

Synchronous Reactance :

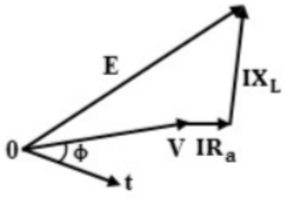
The synchronous reactance of an alternator or synchronous generator is a combination of armature leakage reactance and armature reaction reactance.

Armature Leakage Reactance (X_L) :

When the current flows through the armature conductors the flux set up by the conductors do not cross the air-gap, but complete its path in the armature through the air around the conductor itself. Such a flux is known as leakage flux as shown below figure.



The leakage flux sets an emf leading the load current I by 90° and proportional to the load current I. Hence, armature winding is assumed to possess leakage reactance XL (in addition to Ra) such that the voltage drop due to this is IXL as shown in the below vector diagram.



Generated emf, E will be,

$$E = V + IR_a + j\,IX_L$$
$$= V + I\,(R_a + jX_L)$$

Where, X_L = Armature leakage reactance = $2\pi f L$ Ω/ph.

Armature Reaction Reactance (Xa) :

In an alternator or synchronous generator in addition to the armature winding resistance drop and leakage reactance drop, there is a drop in terminal voltage due to armature reaction. Generally, the load connected to the alternator is of inductive type. We know that the armature reaction is of demagnetizing effect for inductive loads i.e., the armature flux due to armature current tries to demagnetize the main flux.

In order to balance the terminal voltage by quantifying the voltage drop due to the armature reaction. The effect of armature reaction is accounted for by assuming the presence of a fictitious reactance Xa in the armature winding known as armature reaction reactance.

Therefore, the sum of the fictitious armature reaction reactance Xa due to the effect of the armature reaction and the leakage reactance X_L of the armature is known as synchronous reactance Xs.

$$i.e., X_s = X_L + X_{ar}$$

Synchronous Impedance :

The synchronous impedance may be defined as the vector sum of the armature resistance and synchronous reactance. It is denoted as Zs.

$$Z_s = \sqrt{R_a^2 + X_s^2}$$

Where,

- R_a = Armature resistance
- X_s = Synchronous reactance (X_L + X_a)

Therefore, the relationship between induced emf E and the terminal voltage V can be represented as,

$$E = V + IR_a + jI(X_a + X_L)$$

$$E = V + IR_a + j\,IX_s$$

$$E = V + I(R_a + X_s)$$

$$E = V + IZ_s$$

Where,

- E = EMF induced on load.
- V = Terminal voltage. It is vectorially less than E_o (no-load emf) by IZ_s.
- I = Armature current per-phase.
- IZ_s = Voltage drop in an alternator.

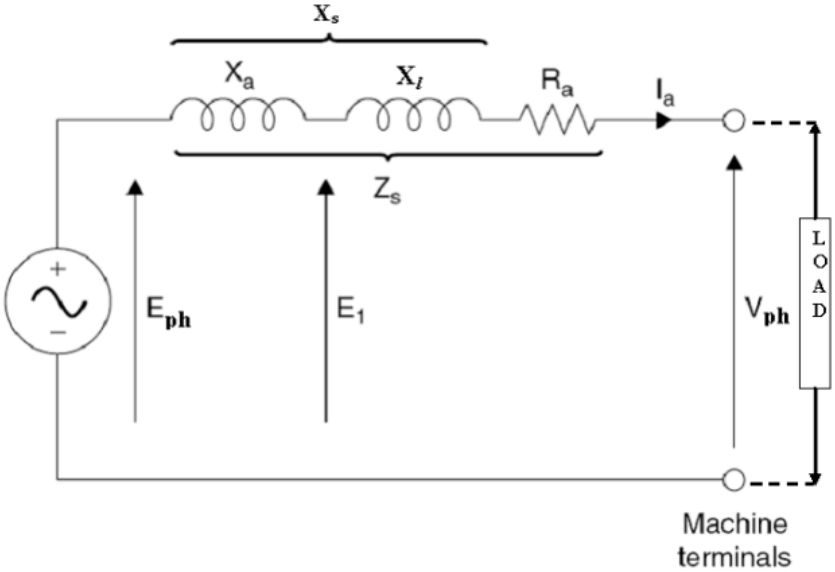
Generally, the alternator rotates at synchronous speed. Hence, when the alternator has loaded the word 'Synchronous' is used to specify the reactance and impedance of the alternator. Since synchronous reactance varies with variation in load condition and its power factor. This in turn also changes the synchronous impedance.

Effect of Synchronous Impedance :

1. The following are the various effects of synchronous impedance,
2. Voltage drop increases.
3. Supply voltage decreases.
4. Power loss takes place (since impedance includes resistance).
5. Heat is produced.
6. Voltage regulation increases.

7. Efficiency decreases.
8. For large alternators cooling system is required

Equivalent Circuit of Synchronous Generator:

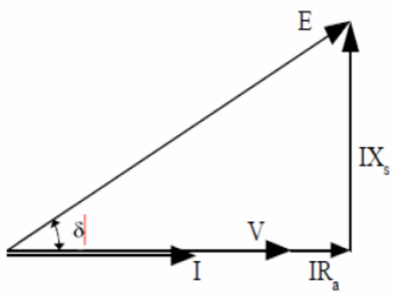


The three important parameters of armature winding namely armature resistance Ra, leakage reactance X_L and armature reaction reactance Xar. If E_{ph} is induced emf per phase on no load condition, then on load it changes to E' due to armature reaction. As current Ia flows through the armature, there are two voltage drops across R_a and XL as Ia Ra and Ia X_L respectively. Hence terminal voltage V is less than E' by the amount equal to the drops across R_a and X_L.
The leakage reactance X_L and the armature reaction reactance Xar are combined to get synchronous reactance Xs.
Eph = Induced emf per phase on no load
Vph = Terminal voltage per phase on load
Iaph = Armature resistance per phase
Zs = Synchronous impedance per phase

Phasor diagram

In the phasor diagrams E is the induced emf /phase = Eph and V is the terminal voltage /phase = Vph. From each of the phasor diagrams the expression for the induced emf Eph can be expressed in terms of Vph, armature current, resistance, reactances and impedance of the machine as follows.

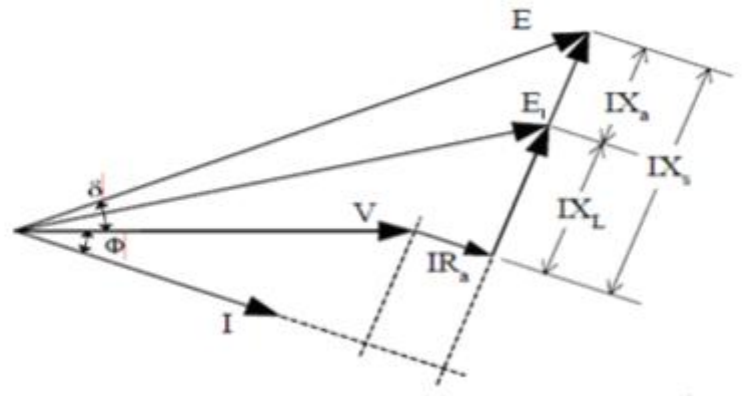
Unity power factor load



Under unity power factor load: $E_{ph} = (V + IR_a) + j\,(IX_S)$

$$E_{ph} = \sqrt{[\,(V + IR_a)^2 + (IX_S)^2]}$$

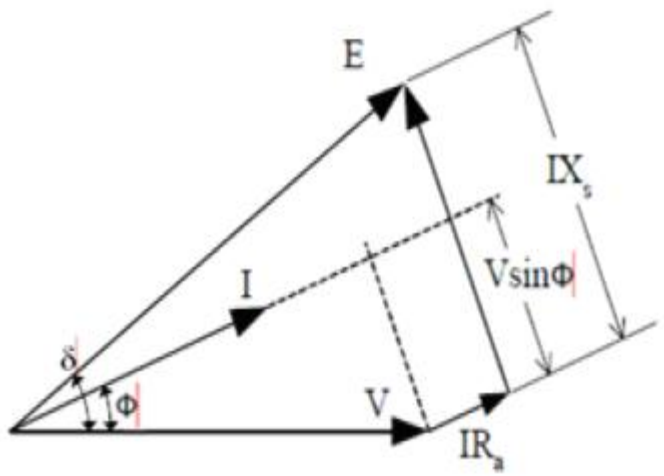
Zero power factor lagging



Under zero power factor lagging: $E_{ph} = V + (IR_a + j\,IX_S) = V + I(R_a + j\,X_S)$

The above expression can also be written as $E_{ph} = \sqrt{[\,(V\cos\Phi + IR_a)^2 + (V\sin\Phi + IX_S)^2]}$

Zero power factor leading

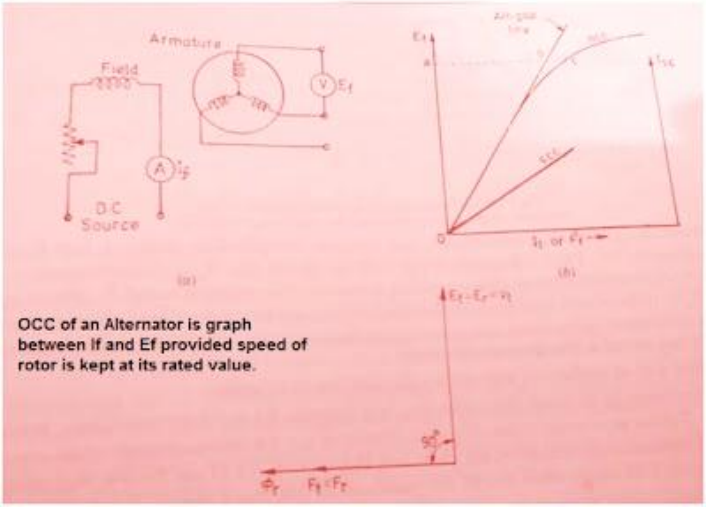


Synchronous Generator Analysis

Open Circuit and Short Circuit Characteristics of Synchronous Generator:

Open Circuit Test and Short Circuit Test are performed on a Synchronous Machine to find out the parameters of Synchronous Machine and hence to have an idea of their performance. Open Circuit Test of Synchronous Machine is also called No Load, Saturation or Magnetizing Characteristics for the reason which will be clear after going through the post.

For getting the Open Circuit Characteristics of Synchronous Machine, the alternator is first driven at its rated speed and the open terminal voltage i.e. voltage across the armature terminal is noted by varying the field current. Thus Open Circuit Characteristic or OCC is basically the plot between the armature terminal voltage Ef versus field current If while keeping the speed of rotor at rated value. It shall be noted that for OCC, the final value of Ef shall be 125% of the rated voltage.



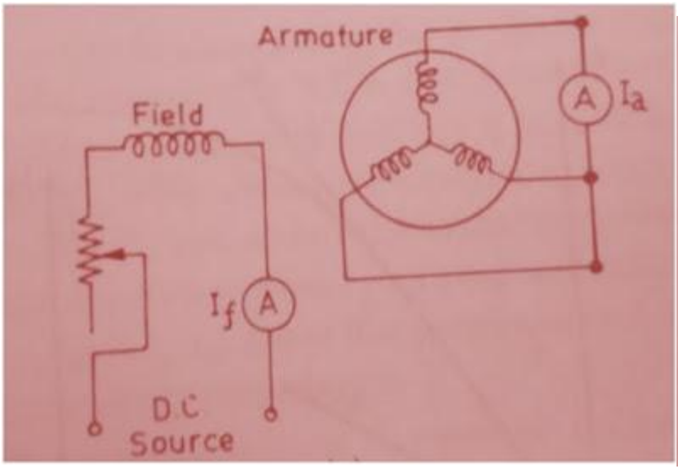
As clear from the figure above, an Ammeter is connected in series with the field circuit to measure the field current and a Voltmeter is connected across the armature terminals to note down the voltage generated. Figure (b) shows the plot between If and Ef. It can be seen from the graph that the relationship between the field current Ifand no load generated voltage Ef is linear up to certain value of field current but as the the field current increases the relationship no longer remains linear. The linear part of the relationship is because, at small value of filed current the whole mmf is required by the air gap to create magnetic flux but as the value of mmf exceeds some certain value, the iron parts get saturated and hence the relationship between the flux (No load generated emf is proportional to flux) and field current no longer remain linear.

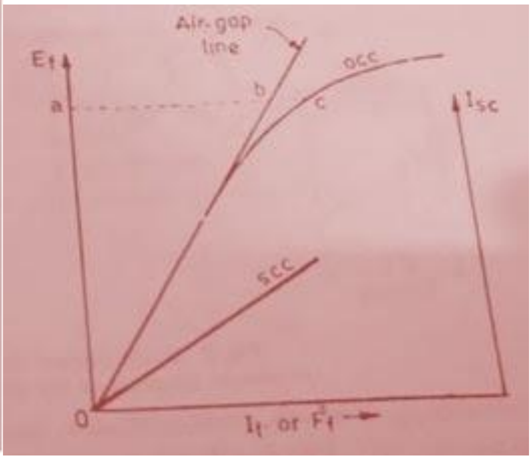
Next assume that if there were no saturation (assuming no iron part is present rather only air gap is present), the relationship between the field current and no load voltage would have been a straight line and that is why the straight line ob in the figure is called Air Gap Line.

Thus we observe that because of saturation in iron parts of machine, the no load generated voltage Efdoes not increase in the same proportion as the increase in field current.

Short Circuit Test of Synchronous Machine:

For performing Short Circuit Test on an Alternator, the machine is driven at rated synchronous speed and the armature terminals are short circuited through an Ammeter as shown in figure below.





Now the field current If is gradually increased from zero until the armature short circuit current reaches its maximum safe value i.e. 125 to 150% of its rated current value. Readings of field current If and short circuit current are noted and plotted.
If you see the above plot of Short Circuit Test, you notice that the short circuit characteristics of a synchronous machine is a straight line.

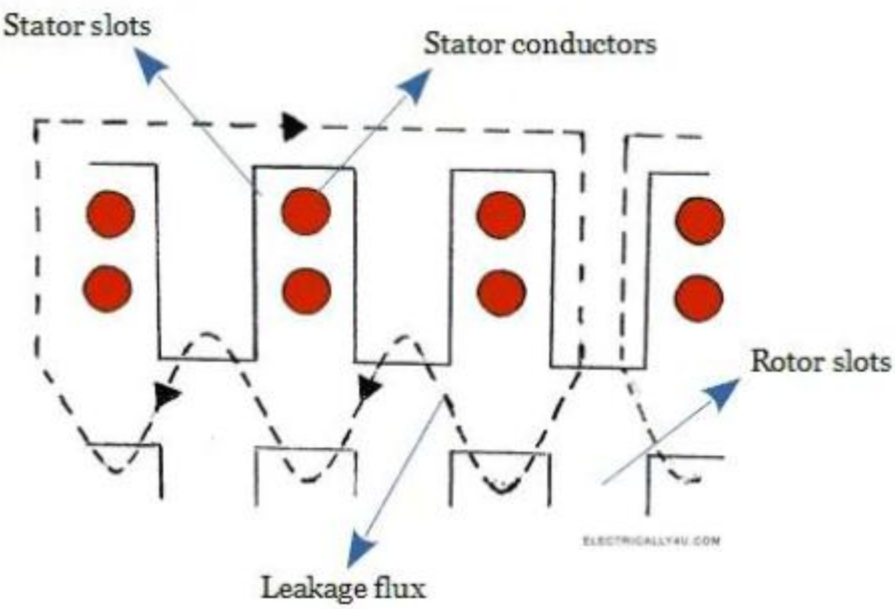
Alternator on load:

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 IRa, Voltage drop due to armature leakage reactance IX_L and Voltage drop due to armature reaction.

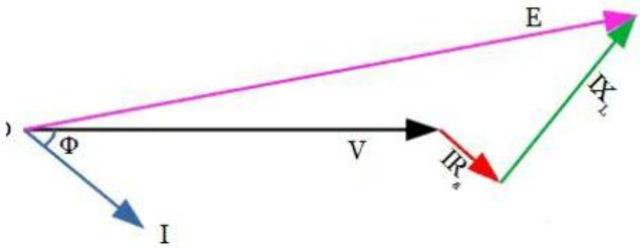
Effect of Load on Alternator:

Voltage drop due to armature resistance: 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. Practically, this voltage drop is negligible.

Voltage drop due to armature leakage reactance: 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 and are called leakage flux.



Here, the leakage flux depends on the current flowing through the conductor and its phase relationship with the terminal voltage. This leakage flux will set up an emf because of self-inductance. This emf is known as reactance emf, which leads the armature current I by 90^0. Thus, 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.



The above phasor diagram is constructed as below,

- 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 IRa phasor.
- Join 0 and the extremity of IX_L phasor to get Eb.

Voltage drop due to armature reaction

Armature reaction is the effect of armature flux on the main field flux. The effect of Armature reaction can be seen in the DC generator as well.

But compared to the DC generator, the power factor of the load in an alternator has a considerable effect on armature reaction. While we talk about the power factor on loading conditions, we consider three cases.

- Unity power factor load.
- Zero power factor lagging load
- Zero power factor leading load.

The armature reaction in the alternator produces different effects such as cross magnetizing effect, demagnetizing effect, and magnetizing effect. These effects cause distortion in main field flux, thereby affecting the generated emf.

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 armature reactance reaction is represented as IXa.

The leakage reactance X_L and armature reaction reactance Xa together called as 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 synchronous impedance of an alternator.

From the discussions above, it is clear that the variation in load causes the terminal voltage of the alternator to change. It is due to the synchronous impedance of the alternator.
Now let us look at the phasor diagrams of alternator for different load conditions.
Phasor diagrams of Alternator on Load
To draw the phasor diagrams, let us know the terms used in the below 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. It is vectorially less than E by IZ and also vectorially less than E_0 by IZ_S.
Φ is the cosine angle between terminal voltage and current.
The impedances are given by

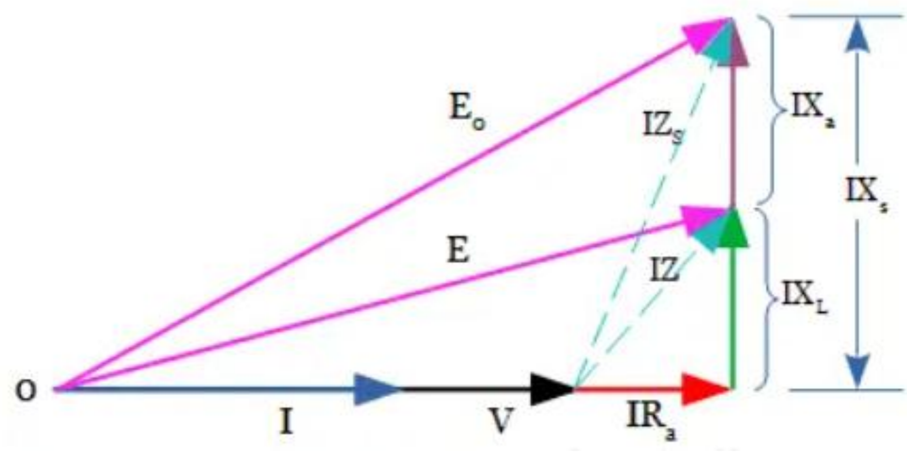
$$Z = R_a + jX_L = \sqrt{(R_a^2 + X_L^2)} \quad Z_S = R_a + jX_S = \sqrt{(R_a^2 + X_S^2)}$$

where X_L is the leakage reactance, Xa is the armature reaction reactance and X_S is the synchronous reactance and Z_S is the synchronous impedance.

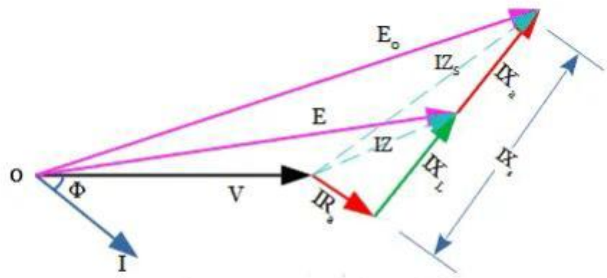
Unity power factor load

Voltage phasor V is taken as the reference phasor.

1. For unity power factor load, V and I phasor are in phase. So the Current phasor I is drawn on the
2. voltage phasor V.
3. The phasor of Armature resistance drop IRa is drawn parallel to the current phasor from the extremity of V phasor.
4. The armature leakage resistance drop IXL is drawn perpendicular to the current phasor, from the extremity of IRa phasor.
5. Join V phasor and IXL phasor to get IZ phasor(shown as a dotted line).
6. Join O and the extremity of IZ to get E(shown as a pink colour line)
7. Draw the armature reaction reactance drop phasor IXS perpendicular to the current phasor from the extremity of IXL phasor.
8. Join V phasor and IXS phasor to get IZS phasor(shown as a dotted line).
9. Join O and the extremity of IZS to get E0(shown as a pink colour line)

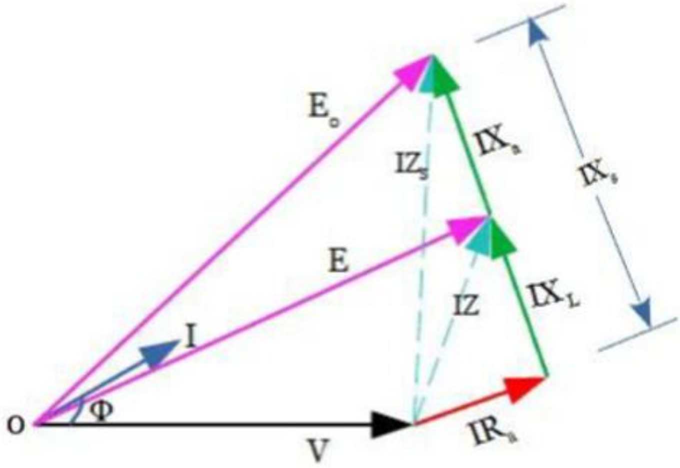


Lagging power factor load



The only change is that here current lags behind the voltage by an angle Φ. So draw the current phasor at an angle Φ with respect to voltage phasor V.

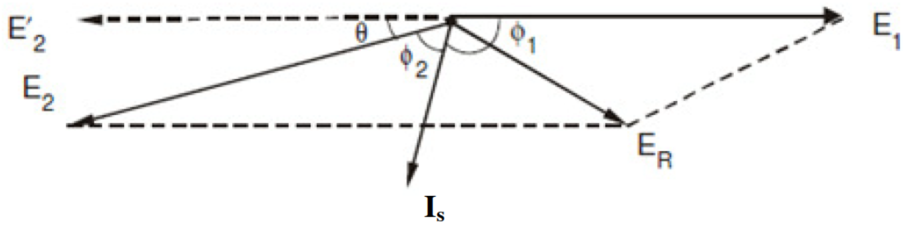
Leading power factor load

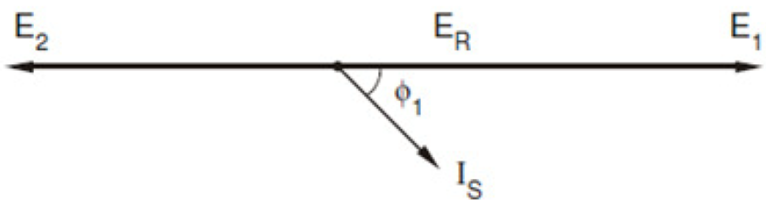


For the leading power factor load, the phasor diagram is also drawn similar to that of the unity power factor. But the only difference is that here current leads the voltage by an angle Φ. So the current phasor is drawn at an angle Φ with respect to voltage phasor V.

Excitation control for constant terminal voltage: (Students)

A change in the excitation of an alternator running in parallel with other affects only its KVA output; it does not affect the KW output. A change in the excitation, thus, affects only the power factor of its output.





Let two similar alternators of the same rating be operating in parallel, receivingequal power inputs from their prime movers. Neglecting losses, their kW outputs are therefore equal. If their excitations are the same, they induce the same emf, and since they are in parallel their terminal voltages are also the same. When delivering a total load of I amperes at a power-factor of cos f, each alternator delivers half the total current.

I1 = I2 =0.5 I

Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current, Is, is zero. Since the armature resistance is neglected, the vector difference between E1 = E2 and V is equal to

$$I_1 X_{S_1} = I_2 X_{S_2}$$

this vector leading the current I by 90°,
where X_{S1} and X_{S2} are the synchronous reactances of the two alternators respectively. Now examine the effect of reducing the excitation of the second alternator. E2 is therefore reduced as shown in Figure.This reduces the terminal voltage slightly, so let the excitation of the first alternator be increased to bring the terminal voltage back to its original value. Since the two alternator inputs are unchanged and losses are neglected, the two kW outputs are the same as before. The current I2 is changed due to the change in E2, but the active components of both I1 and I2 remain unaltered. It will be observed that there is a small change in the load angles of the two alternators, this angle being slightly increased in the case of the weakly excited alternator and slightly decreased in the case of the strongly excited alternator. It will also be observed that I1 + I2 = I, the total load current.

Voltage Regulation:

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.
Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed with out change in speed and excitation. Or The numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.
Hence regulation can be expressed as

$$\% \text{ Regulation} = (E_{ph} - V_{ph} / V_{ph}) \times 100$$

where E_{ph} = induced emf /phase, V_{ph} = rated terminal voltage/phase

Methods of finding Voltage Regulation:

The voltage regulation of an alternator can be determined by
different methods. In case of small generators it can be determined by direct loading whereas in case of large generators it can not determined by direct loading but will be usually predetermined by different methods. Following are the different methods used for predetermination of regulation of alternators.

1. Direct loading method
2. EMF method or Synchronous impedance method
3. MMF(Magneto Motive Force) method or Ampere turns method
4. ASA(American Standards Association) modified MMF method
5. ZPF(Zero Power Factor) method or Potier triangle method

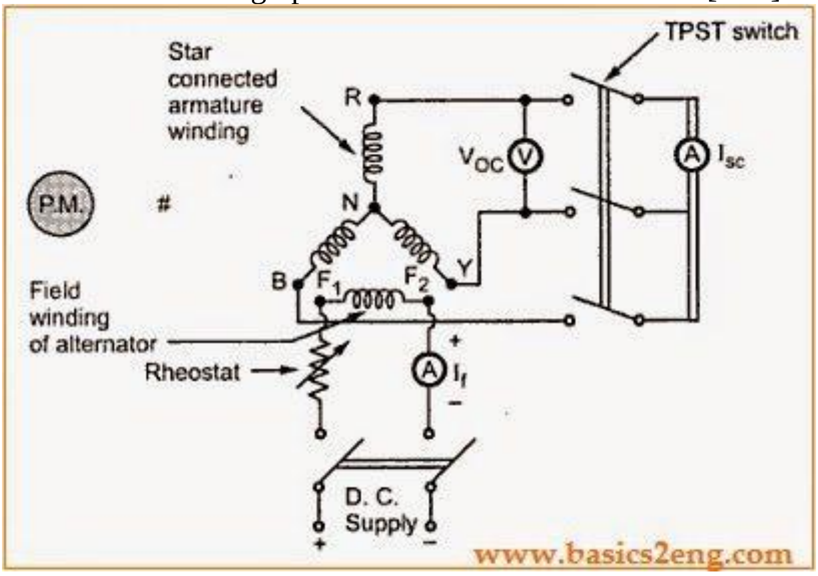
Voltage Regulation by EMF method:

Generally, we use this Synchronous Impedance Method for high-speed Alternators or synchronous generator. This method is also known as EMF method. Before calculating the voltage regulation we need to calculate the following data.

1.Armature Resistance per phase [Ra]

2.Open Circuit characteristics which is a graph between open circuit voltage [Vo.c.] and field current.

3.Short circuit characteristics which is a graph between short circuit current [Is.c.] and field current.



The alternator or synchronous generator is coupled with the prime mover to drive the alternator at synchronous speed. The armature of the alternator or synchronous generator is connected to the TPST switch. The three terminals of the switch are short-circuited by an ammeter.

The voltmeter is connected between two line terminals to measure the o.c voltage of the alternator. For excitation, a DC supply is connected to field winding. A rheostat is also connected in series with the DC supply which is used to vary the field current i.e. field excitation.

1. O.C test

Procedure:

1. By using the prime mover start the alternator or synchronous generator and adjust its speed to the Synchronous speed.
2. Note that the rheostat should be in maximum position and switch on the D.C supply.
3. The T.P.S.T. switch should be kept open in the armature circuit.
4. Field current is varied from its min. value to the rated value using the rheostat. So now flux increases, which leads to an increase in the induced e.m.f. The voltmeter now the actual line value of open circuit voltage. For various values of field currents, voltmeter readings are noted in a table.

Sr. No.	I_f A	V_{oc} (line) V	V_{oc} (phase) = V_{oc} (line)/$\sqrt{3}$ V
1			
2			
:			
:			

Now plot a graph between o.c phase voltage and field current. The graph obtained is called o.c.c .

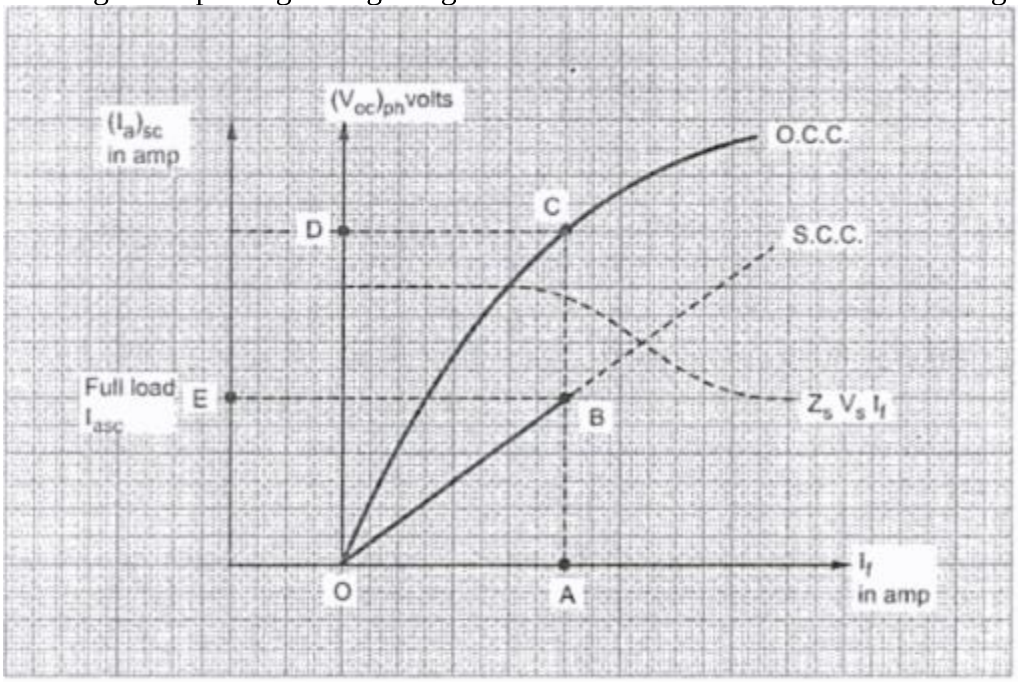
2. S.C test

Procedure:

1. After the o.c test, the field rheostat should be kept at max. Position, reducing field current to min. value.
2. Now the T.P.S.T switch is closed.
3. The armature gets short-circuited because ammeter has negligible resistance. Now increase the field excitation is increased gradually till full load current is obtained through armature windings.
4. 4)Now plot a graph between s.c armature current and field current.The graph obtained is called S.C.C.

Sr. No.	I_f A	Short circuit armature current per phase (I_{asc}) A
1		
2		

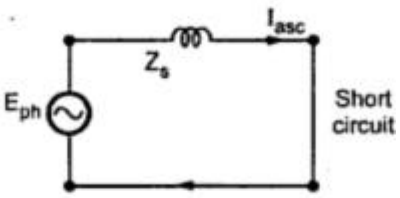
This is observed on the ammeter connected in the armature circuit. Tabulate the values of field current and armature current values obtained.
The S.C.C. is a straight line passing through origin but o.c.c resembles a B.H curve of a magnetic material.



1. Determination of Impedance from O.C.C. and S.C.C.

The synchronous impedance of the alternator changes as load condition changes. O.C.C. and S.C.C. can be used to determine Zs for any load and load p.f. conditions.

In short circuit test, external load impedance is zero. The short circuit armature current is circulated against the impedance of the armature winding which is Zs. The voltage responsible for driving this short circuit current is internally induced e.m.f. This can be shown in the equivalent circuit drawn in the Fig.



From the equivalent circuit we can write, Zs = Eph/ Iasc

This is what we are interested in obtaining to calculate value of Zs. So expression for Zs can be modified as

$$Z_s = \left.\frac{(V_{oc})_{ph}}{(I_{asc})_{ph}}\right|_{\text{for same } I_f}$$

Thus in general,

$$Z_s = \left.\frac{\text{Phase e.m.f. on open circuit}}{\text{Phase current on short circuit}}\right|_{\text{For same excitation current}}$$

Voltage Regulation of synchronous generator Calculations:

Zs can be determined from O.C.C and S.C.C for any load condition.The value of Ra should be known now.So it can be measured by applying d.c known voltage across the two terminals.

Now $$Z_s = \sqrt{(R_a)^2 + (X_s)^2}$$

$$\therefore \quad X_s = \sqrt{(Z_s)^2 - (R_a)^2}\ \Omega/\text{ph}$$

So now induced e.m.f per phase is calculated as follows:

$$E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi \pm I_a X_s)^2}$$

Voltage regulation of alternator or synchronous generator is calculated by using the below formula, Voltage Regulation Of Alternator Using Synchronous Impedance Method.

Voltage Regulation by MMF method:

This method of determining the regulation of an alternator is also called the Ampere-turn method or Rothert's M.M.F. method. The method is based on the results of open circuit test and short circuit test on an alternator.

For any synchronous generator i.e. alternator, it requires m.m.f. which is a product of field current and turns of field winding for two separate purposes.

1. It must have an m.m.f. necessary to induce the rated terminal voltage on open circuit.
2. It must have an m.m.f. equal and opposite to that of armature reaction m.m.f.

The field m.m.f. required to induce the rated terminal voltage on open circuit can be obtained from open circuit test results and open circuit characteristics. This is denoted as $\mathbf{f_1}$.

We know that the synchronous impedance has two components, armature resistance and synchronous reactance. Now synchronous reactance also has two components, armature leakage reactance and armature reaction reactance. In short circuit test, field m.m.f. is necessary to overcome drop across armature resistance and leakage reactance and also to overcome the effect of armature reaction. But drop across armature resistance and also to overcome the effect of armature reaction. But drop across armature resistance and leakage reactance is very small and can be neglected. Thus in a short circuit test, field m.m.f. circulates the full load current balancing the armature reaction effect. The value of ampere-turns required to circulate full load current can be obtained from short circuit characteristics. This is denoted as $\mathbf{f_2}$.

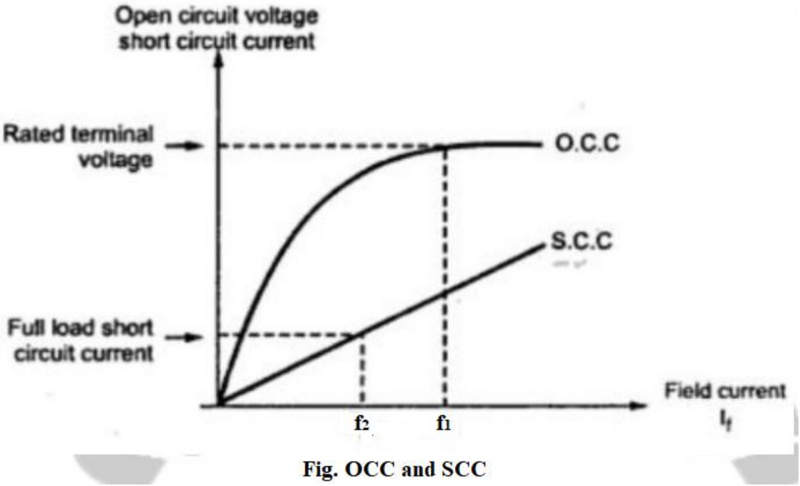
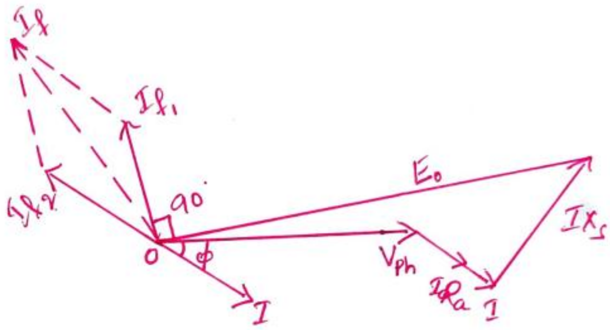


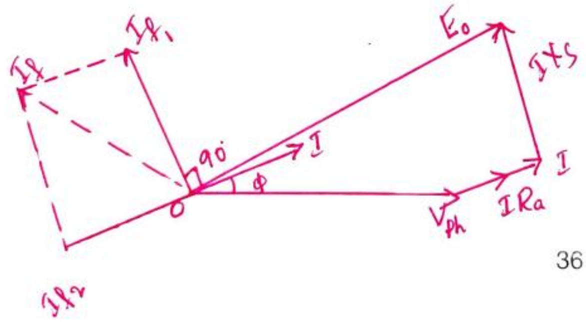
Fig. OCC and SCC

If the alternator is supplying full load, then total field m.m.f. is the vector sum of its two components $\mathbf{f_1}$ and $\mathbf{f_2}$. This depends on the power factor of the load which the alternator is supplying. The resultant field m.m.f. is denoted as **f.**

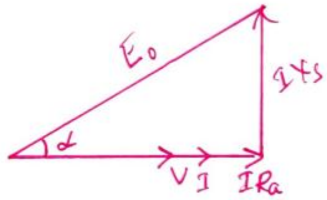
Zero lagging p.f. : As long as the power factor is zero lagging, the armature reaction is completely demagnetizing. Hence the resultant **f** is the algebraic sum of the two components $\mathbf{f_1}$ and $\mathbf{f_2}$. Field m.m.f. is not only required to produce rated terminal voltage but also required to overcome completely demagnetizing armature reaction effect.



Zero leading p.f. : When the power factor is zero leading then the armature reaction is totally magnetising and helps main flux to induce rated terminal voltage. Hence net field m.m.f. required is less than that required to induce rated voltage normally, as part of its function is done by magnetising armature reaction component. The net field m.m.f. is the algebraic difference between the two components $\mathbf{f_1}$ and $\mathbf{f_2}$.



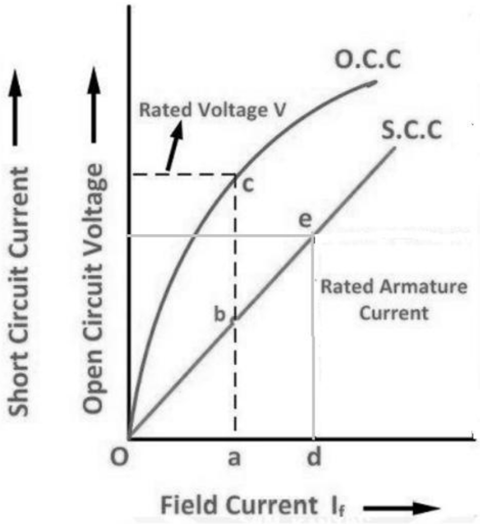
Unity p.f. : Under unity power factor condition, the armature reaction is cross-magnetising and its effect is to distort the main flux. Thus and F are at right angles to each other and hence resultant m.m.f. is the vector sum of $\mathbf{f_1}$ and $\mathbf{f_2}$.



The regulation of the alternator is found from the relation shown below:

$$\text{Regulation} = \frac{E_0 - V}{V} \times 100\%$$

Short Circuit Ratio: The short circuit ratio is the ratio of the excitation required to produce open circuit voltage equal to the rated voltage to the excitation required to produce rated full load current under short circuit.



The short circuit ratio can be calculated from the open-circuit characteristic (O.C.C) at rated speed and the short circuit characteristic (S.C.C) of a three-phase

synchronous machine as shown in the figure below:

$$\text{Mathematically, SCR (short circuit ratio)} = \frac{I_f \text{ for rated open circuit voltage}}{I_f \text{ for rated short circuit current}}$$

From open and short circuit test it is known that,

$$Z_s = \left.\frac{V_{oc\,(ph)}}{I_{asc(ph)}}\right|_{\text{For same } I_f} = X_s \text{ (Neglecting } R_a\text{)}$$

SCR = oa/od

Since the triangles Oab and Ode are similar. Therefore,

SCR = oa/od = ab/de

The direct axis synchronous reactance Xd is defined as the ratio of open-circuit voltage for a given field current to the armature short circuit current for the same field current. For the field current equal to Oa, the direct axis synchronous reactance in ohms is given by the equation shown below:

$$X_d = \frac{ac}{ab}$$

The per-unit value of Xd is given as:

$$X_d(p.u) = \frac{Xd}{Base\ Impedance}$$

But, the base impedance is:

$$\text{Base Impedance} = \frac{\text{Per phase rated voltage}}{\text{Per phase armature rated current}}$$

$$\text{Base Impedance} = \frac{ac}{de}$$

$$Xd(p.)u = \frac{de}{ab}$$

$$SCR = \frac{1}{Xd}$$

Significance of SCR:

1. For low value of SCR, the value of Xs is more hence the drop Ia Xs is more. Hence the machine requires large changes in the field current (excitation) for the small changes in the load, to keep terminal voltage constant.
2. A low value of SCR indicates smaller air gap and poor regulation due to large Ia Xs drop.
3. The synchronous power is inversely proportional to Xs. This is the power which keeps alternators in synchronism during parallel operation and maintains the compensated by stability. Any disturbances from equilibrium conditions are synchronizing power. For low value of SCR, Xs is very large and synchronizing power is very low. As synchronizing power decreases, tendency of alternators to remain in synchronism decreases. This decreases the stability. Thus low SCR puts the stability limit.
4. The SCR can be increased by increasing the air gap but this needs more m.m.f. to obtain same e.m.f. Hence the pole size increases which increases the overall size and cost of the machine.
5. Practically the SCR value is selected between 0.5 to 1.2.

The armature terminals are shorted through three ammeters. Care should we taken performing this test, and the field current should first decrease to zero before starting the alternator. Each ammeter should have range greater than the full rated value. The alternator runs at synchronous speed. Then the field current gradually increased in step, and the armature current is measured at each step.