Principle of Operation

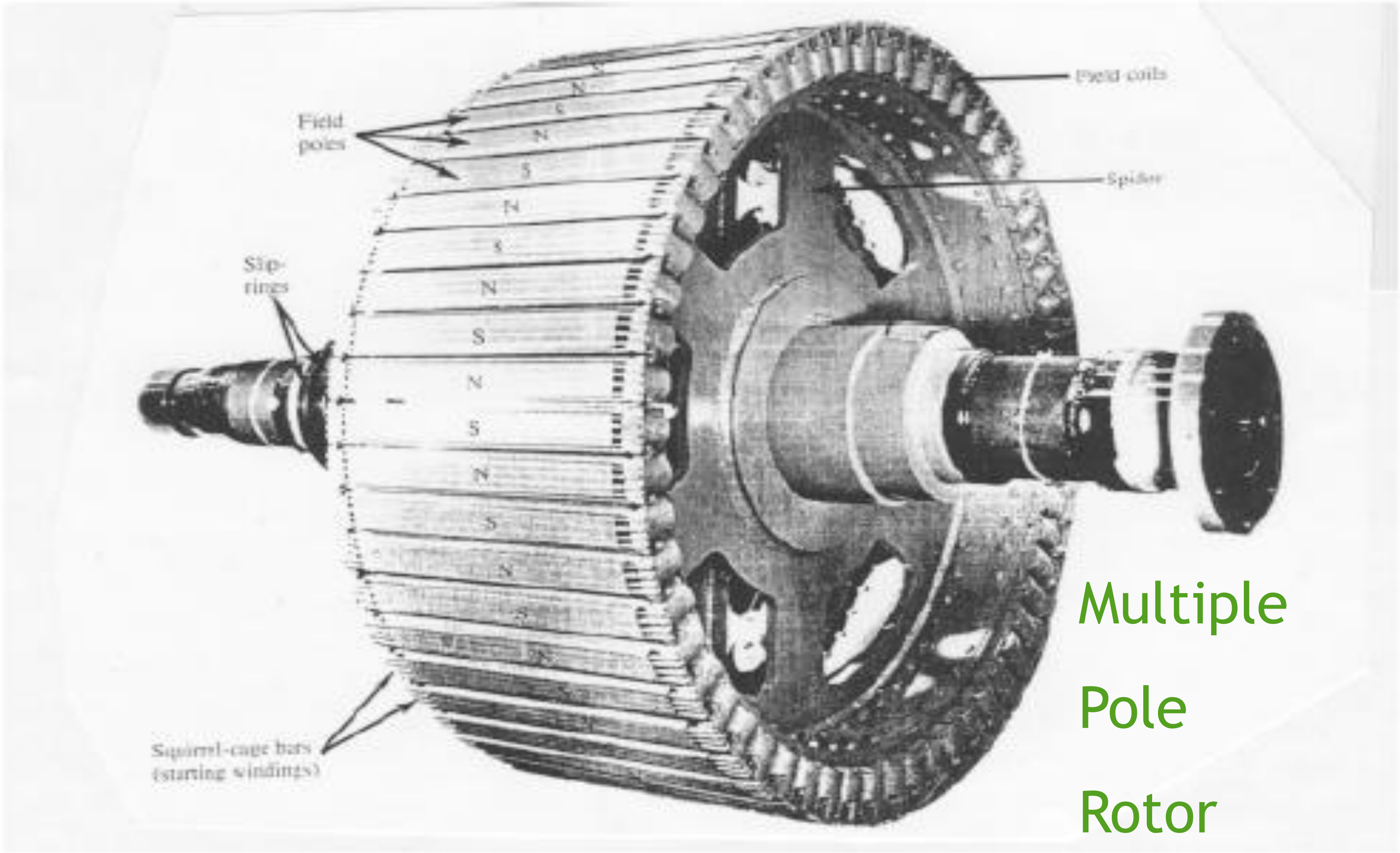
- The operation of a synchronous generator is based on Faraday's law of electromagnetic induction, and in an ac synchronous generator the generation of emf's is by relative motion of conductors and magnetic flux.

- These machines can be used as either motors or generators but their predominant use is in generation.

There are a number of sources of energy used to turn the turbines:-

(a) Gas
(b) Steam
(c) Combined cycle
(d) Nuclear
(e) Hydro
(f) Wind
(g) Wave
(h) Photovoltaic

Principle of Operation



Multiple

Pole

Rotor

Principle of Operation

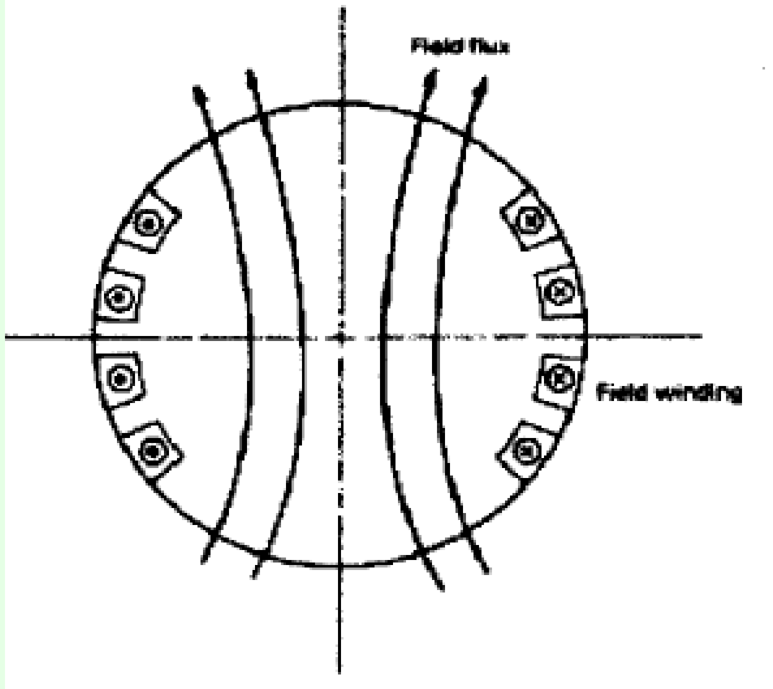
- In constructing a synchronous machine a point to note is that the stator is fixed and the poles rotate.

- There are two categories of Synchronous machines:

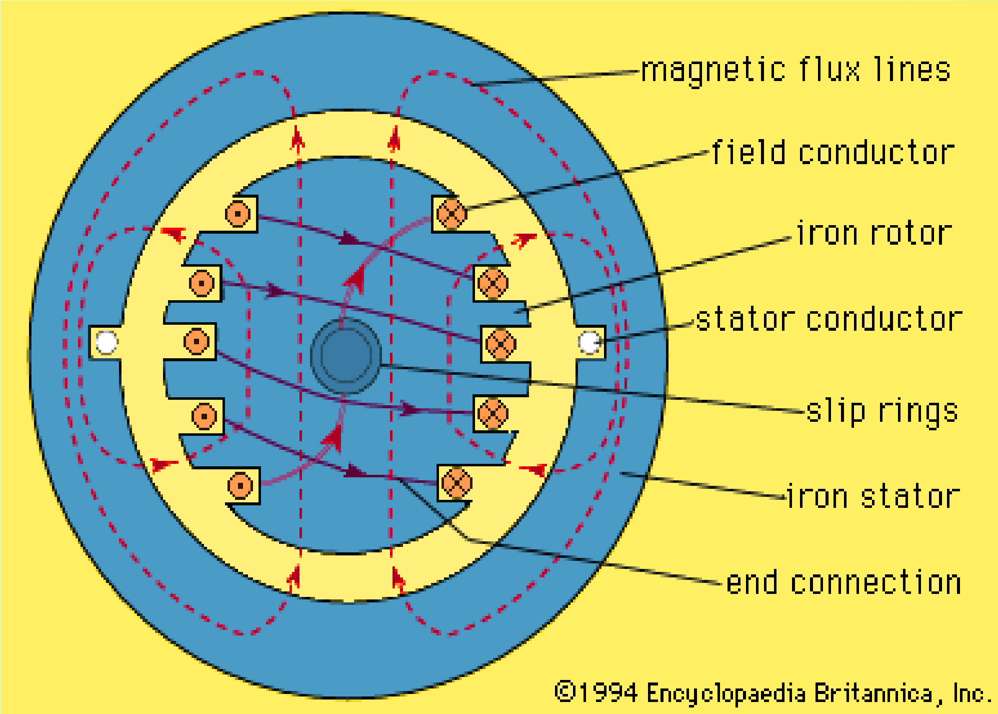
(a) those with salient or projecting poles

(b) those with cylindrical rotors

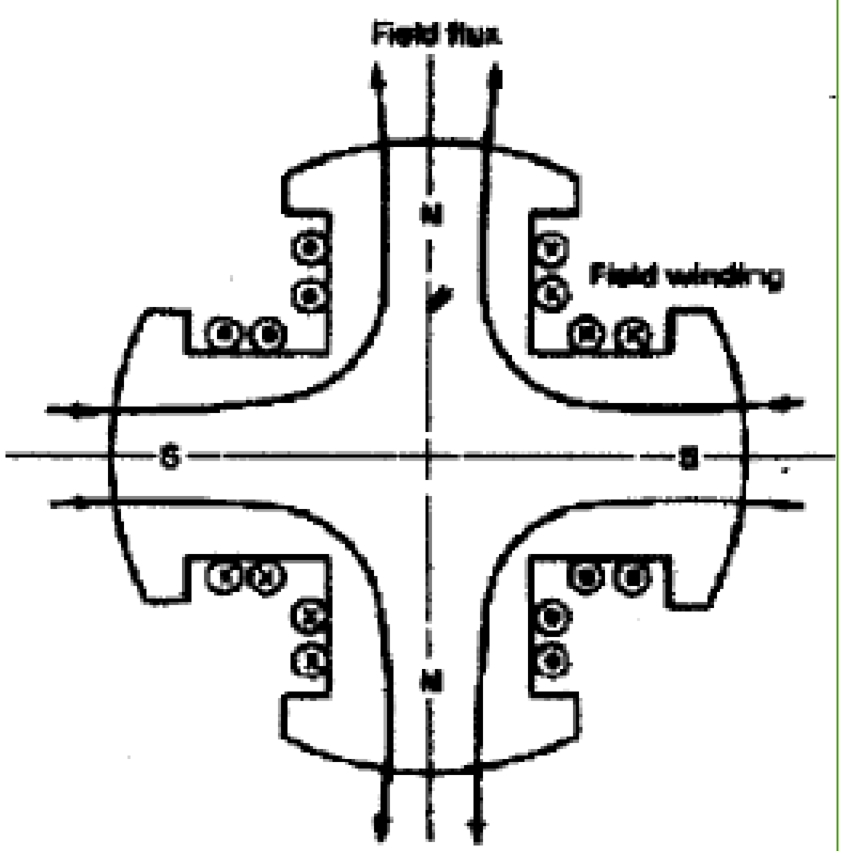
2-pole Cylindrical Rotor



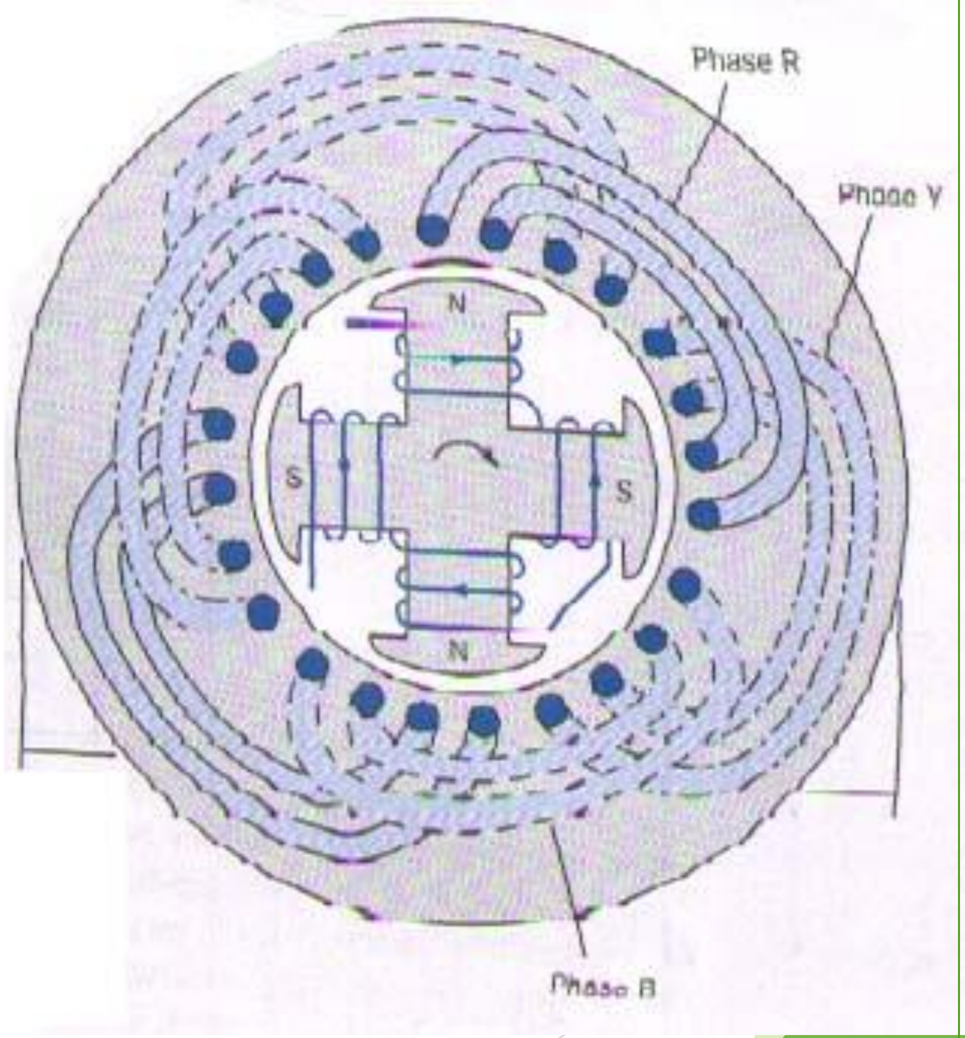
A Cylindrical Rotor



Principle of Operation

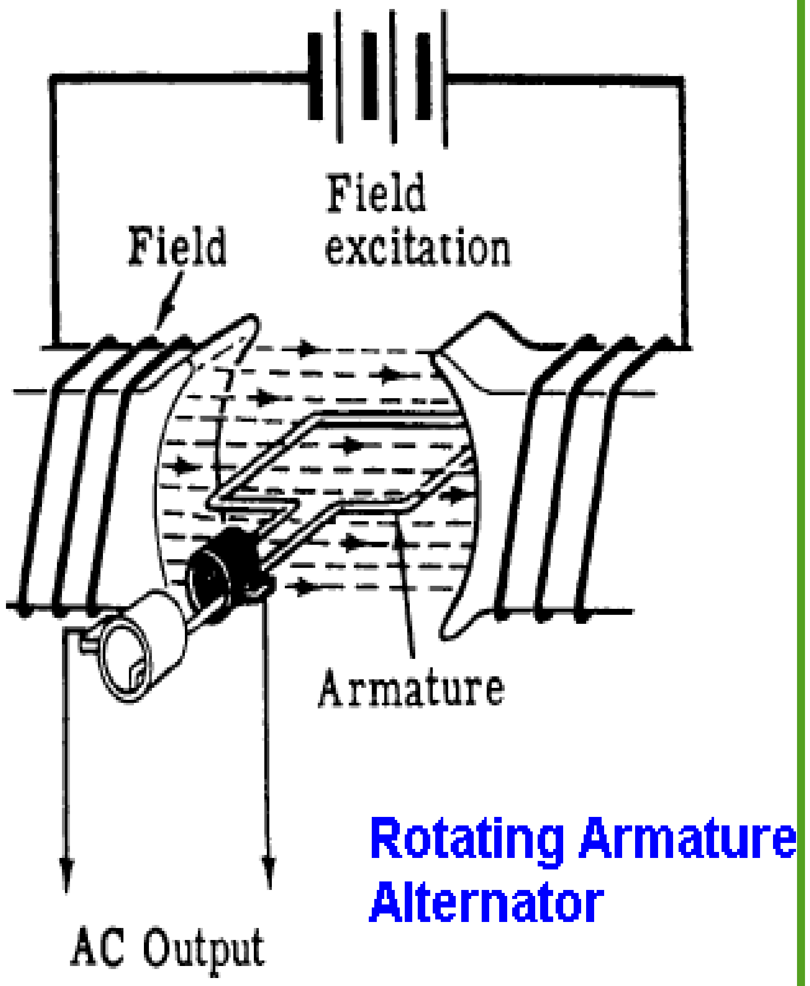


4-Pole Salient Rotor



A Salient Pole Rotor

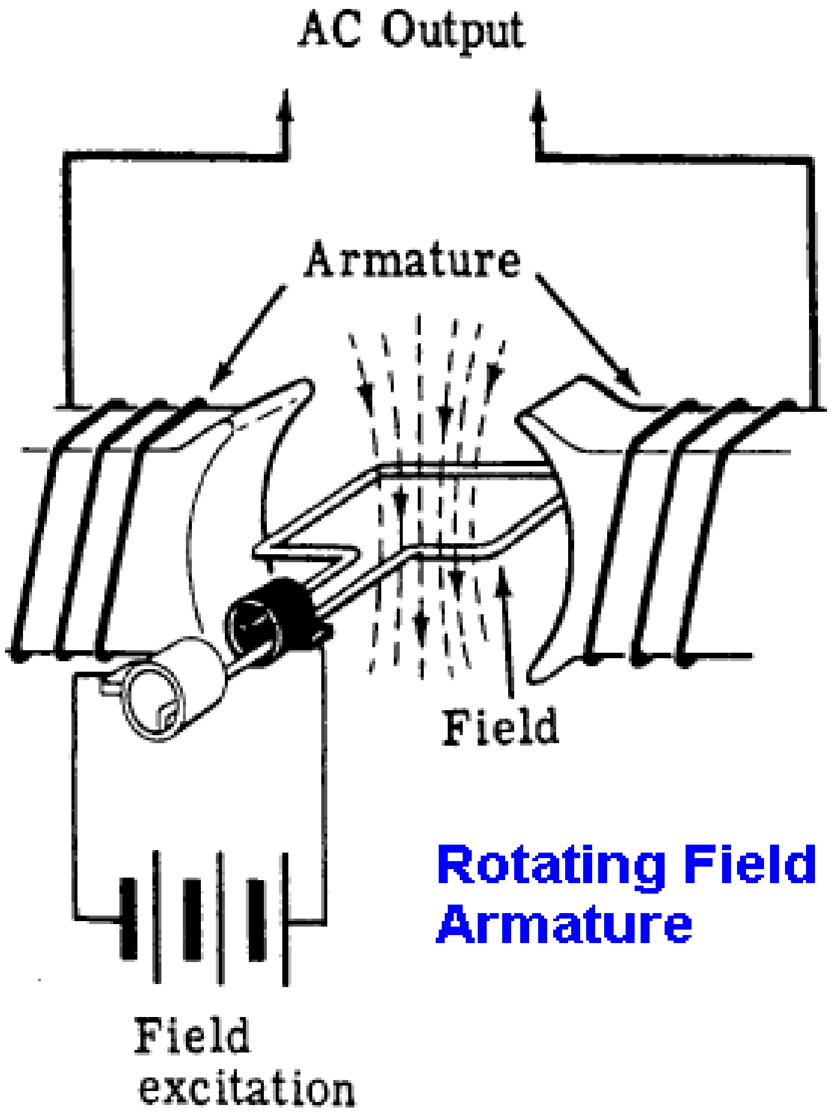
Principle of Operation



Its characteristic feature is that the armature rotates through a stationary magnetic field, and the generated AC is brought to the load by means of slip rings and brushes.

The revolving-armature alternator is found only in alternators of small power rating and is not generally used. This is because a rotating armature requires slip rings and brushes to conduct the current from the armature to the load.

Principle of Operation



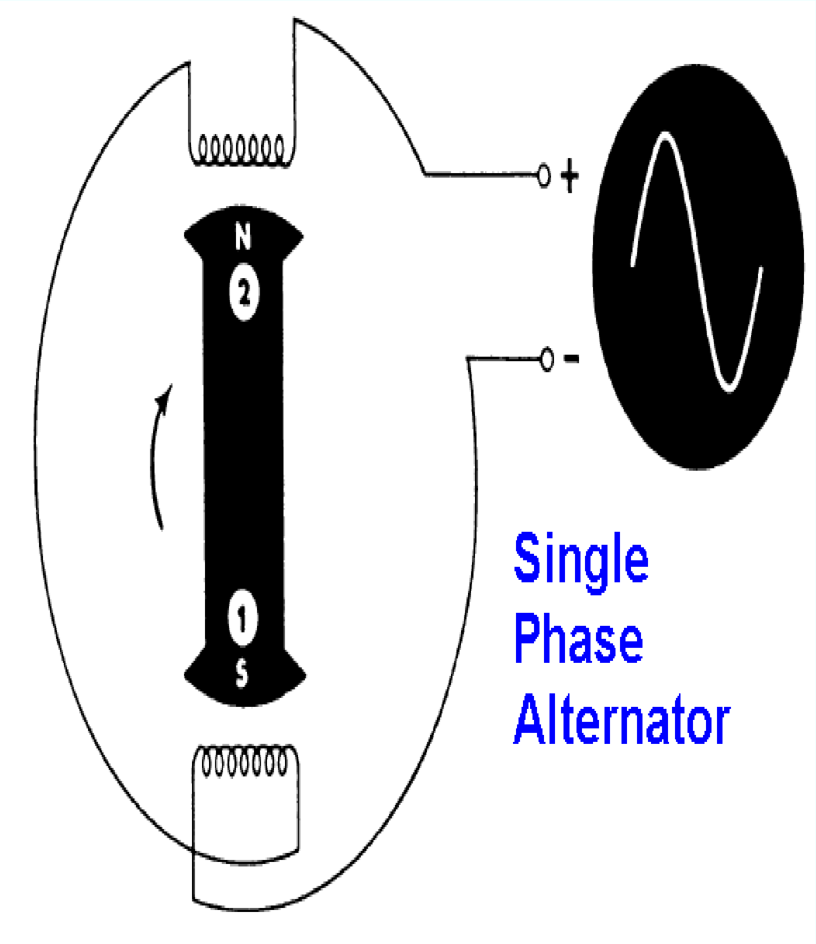
Rotating Field Armature

The revolving-field type alternator has a stationary armature and a rotating magnetic field.

The generated voltage can be connected directly to the load without having to pass across the slip rings and brushes.

The voltage applied to generate the rotating field is a small DC voltage (called a “field excitation” voltage)

Single Phase Alternator

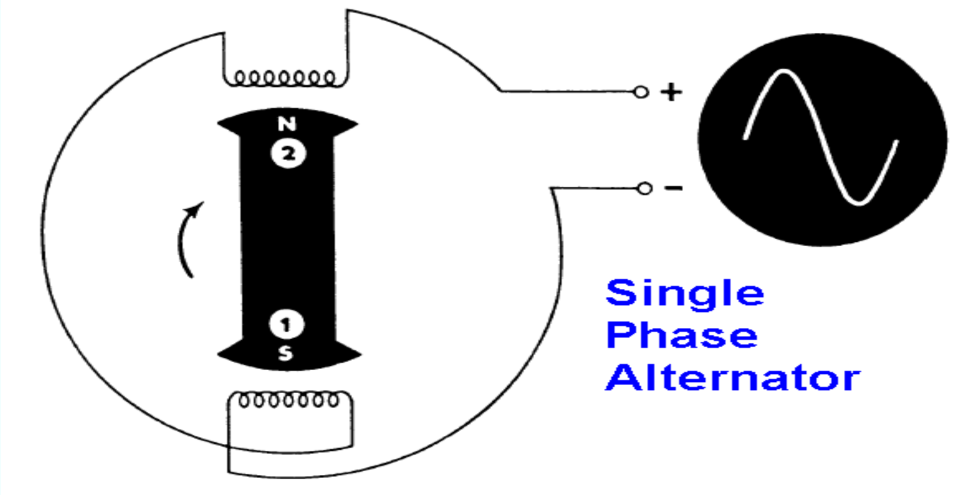


A single-phase alternator has all the armature conductors connected in series

The stator is two pole. The winding is wound in two distinct pole groups, both poles being wound in the same direction around the stator frame.

The rotor also consists of two pole groups, adjacent poles being of opposite polarity.

Single Phase Alternator

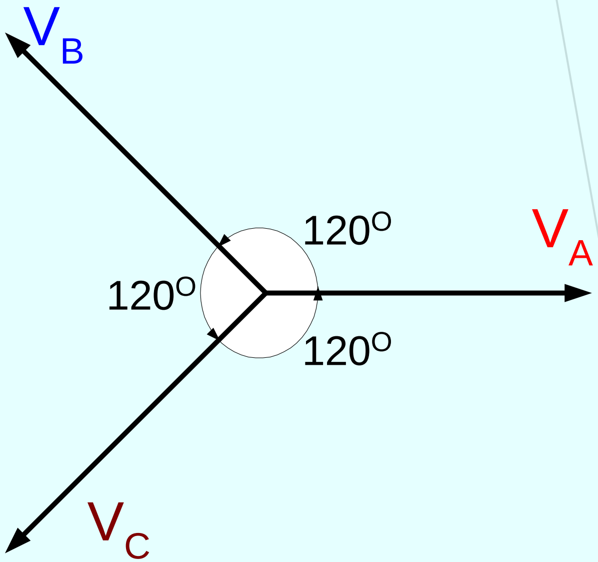


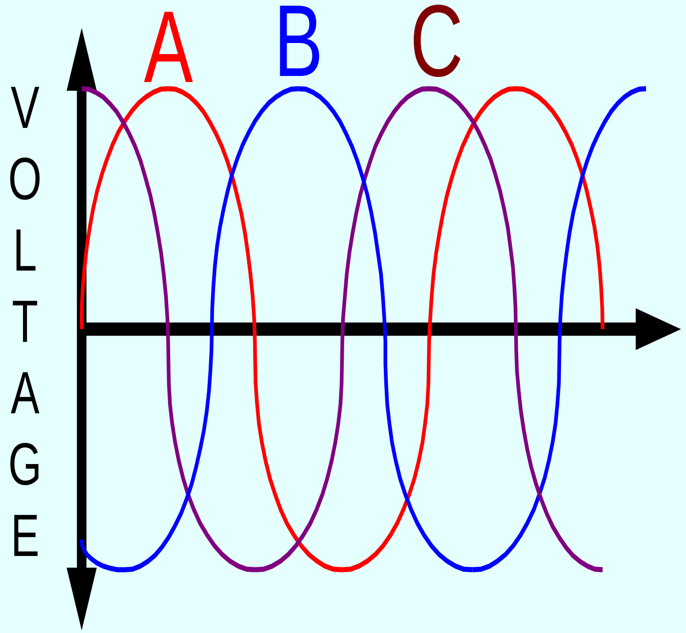
The two poles of the stator winding are connected to each other so that the AC voltages are in phase, so they add.

As the rotor (field) turns, its poles will induce AC voltages in the stator (armature) windings. Since one rotor pole is in the same position relative to a stator pole as any other rotor pole, both the stator poles are cut by equal amounts of magnetic lines of force at any time. As a result, the voltages induced in the two poles of the stator winding have the same amplitude or value at any given instant.

Three Phase Alternator

The three-phase alternator has three single-phase windings spaced so that the voltage induced in any one is phase-displaced by 120 degrees from the other two.





The voltage waveforms generated across each phase are drawn on a graph phase-displaced 120 degrees from each other.

Three Phase Alternator

- The three phases are independent of each other.

- One point from each winding can be connected to form a neutral and thus make a wye connection.

- The voltage from this point to any one of the line leads will be the phase voltage. The line voltage across any two line leads is the vector sum of the individual phase voltages. The line voltage is 1.73, ($\sqrt{3}$), times the phase voltage.

- Since the windings form only one path for current flow between phases, the line and phase currents are equal.

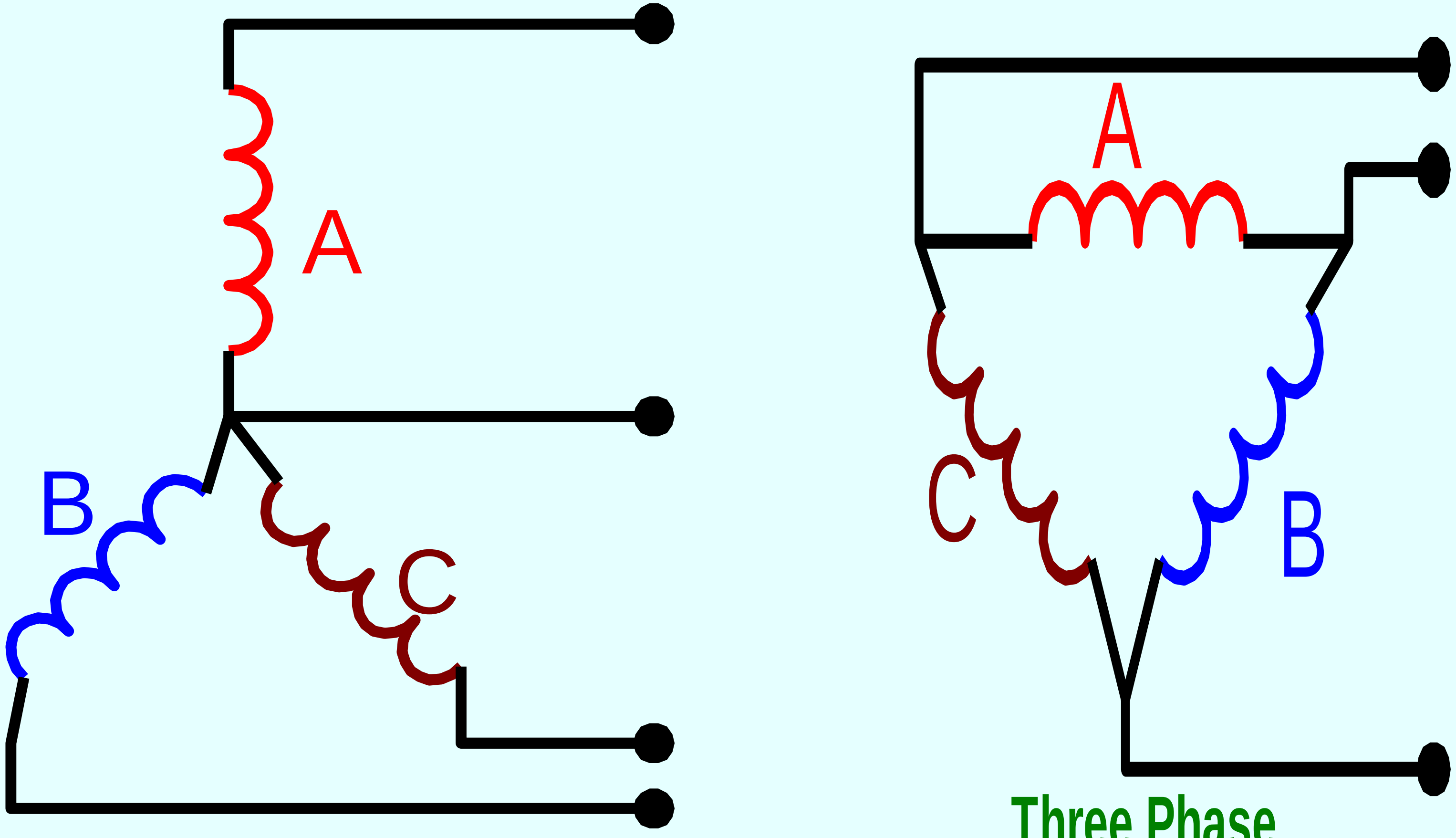
Three Phase Alternator

- A three-phase stator can also be connected so that the phases form a “delta” connection.

- In the delta connection the line voltages are equal to the phase voltages, but the line currents will be equal to the vector sum of the phase currents.

- Since the phases are 120 degrees out of phase, the line current will be 1.73, ($\sqrt{3}$), times the phase current. Both "wye" and the "delta" connections are used in alternators.

Three Phase Stator Connection



Three Phase STAR Connected

Three Phase DELTA Connected

Three Phase Alternator

- The frequency of the AC generated by an alternator depends upon the number of poles and the speed of the rotor

- When a rotor has rotated through an angle so that two adjacent rotor poles (a north and a south) have passed one winding, the voltage induced in that one winding will have varied through a complete cycle of 360 electrical degrees.

- A two pole machine must rotate at twice the speed of a four-pole machine to generate the same frequency.

- The magnitude of the voltage generated by an alternator can be varied by adjusting the current on the rotor which changes the strength of the magnetic field.

Three Phase Alternator

- A two pole alternator produces one electrical cycle for each complete mechanical rotation.
- A four pole alternator will produce two electrical cycles for each mechanical rotation because two north and two south poles move by each winding on the stator for one complete revolution of the rotor.

$f = (n_{Rotor})(p/2)/60 = (n_{Rotor}p)/120$

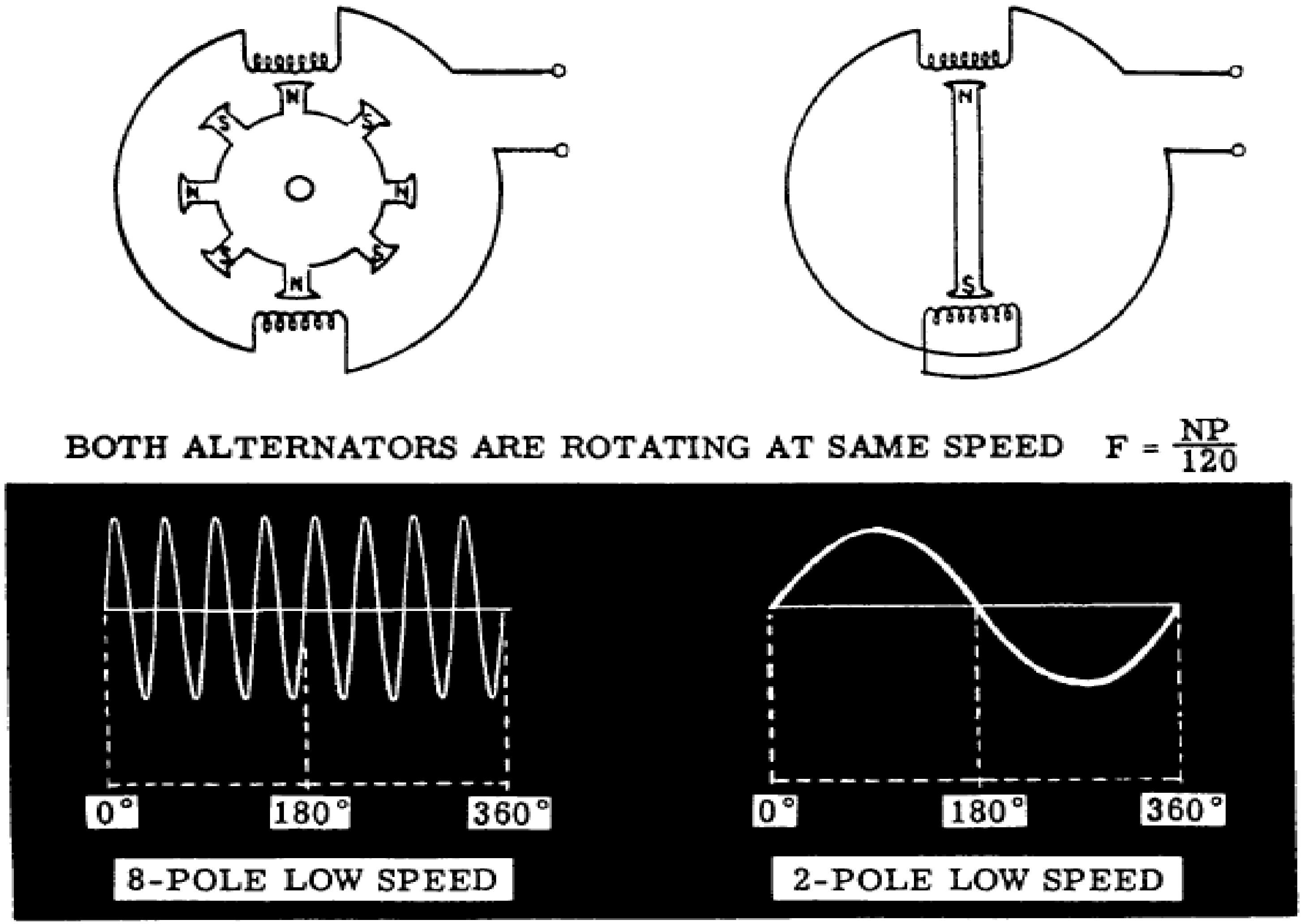
where n_{Rotor} is the speed of the rotor in revolutions per minute,

p is the number of poles

f is the electrical line frequency produced by the alternator.

The speed of the rotor must be divided by 60 to change from revolutions per minute to revolutions per second.

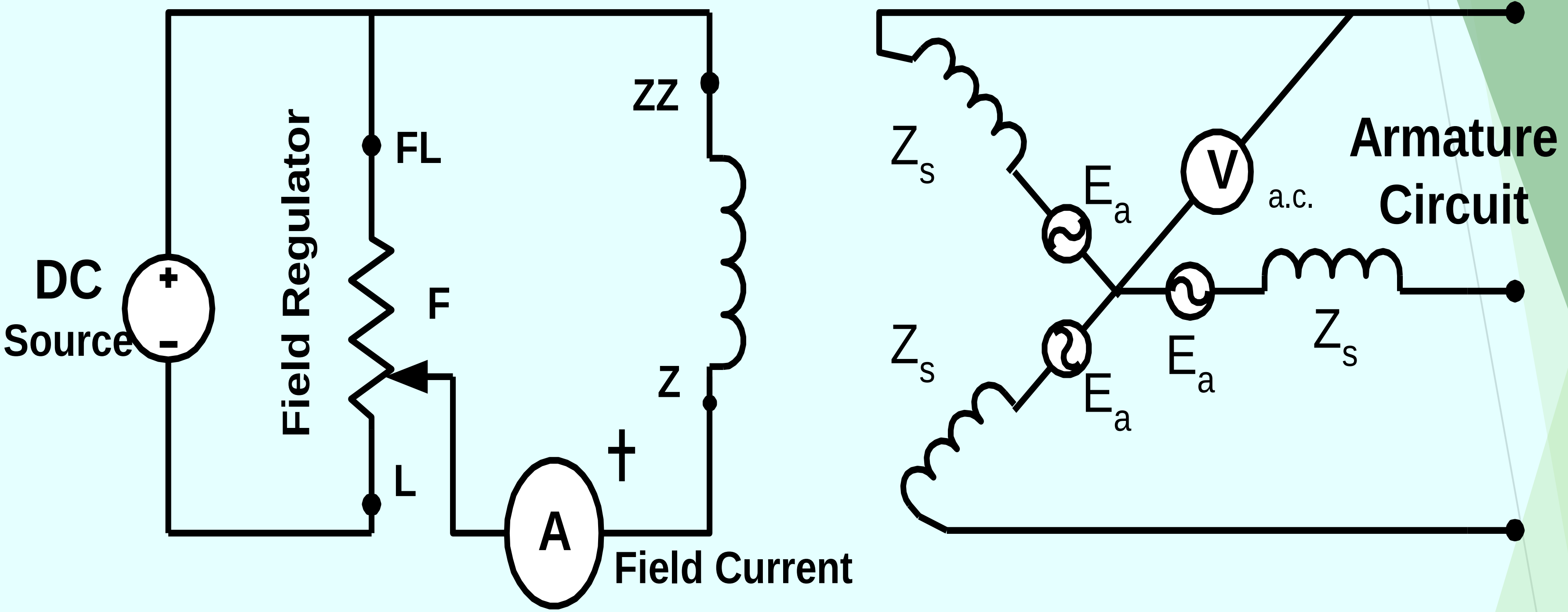
Three Phase Alternator



Three Phase Alternator

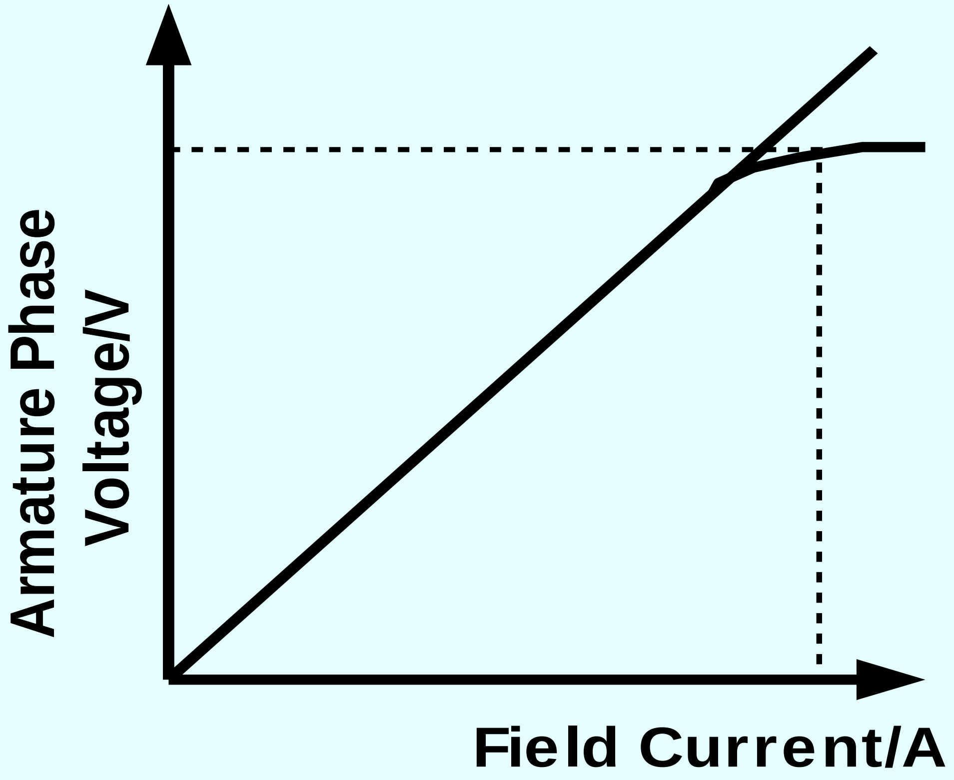
- In an alternator the output voltage varies with the load.
- There are two voltage drops.{ IR & IX_L }
- The IX_L drop is due to the inductive reactance of the armature windings.
- Both the IR drop and the IXL drop decrease the output voltage as the load increases.
- The change in voltage from no-load to full-load is called the “voltage regulation” of an alternator.
- A constant voltage output from an alternator is maintained by varying the field strength as required by changes in load.

OPEN CIRCUIT CHARACTERISTICS



To obtain the open circuit characteristics the machine is driven at rated speed without the load. Readings of the line-to-line voltage are taken for various values of field current. The voltage, except in very low voltage machines, is stepped down by the means of a potential transformer.

OPEN CIRCUIT CHARACTERISTICS



If not for the magnetic saturation of the iron, the open circuit characteristics would be linear as represented by the air gap line

OPEN CIRCUIT CHARACTERISTICS

On open circuit $I_L = I_a = 0$

$$V_t = E - I_L Z_s$$

where $Z_s = R_a + jX_s$

and $X_s = X_L + X_{ar}$

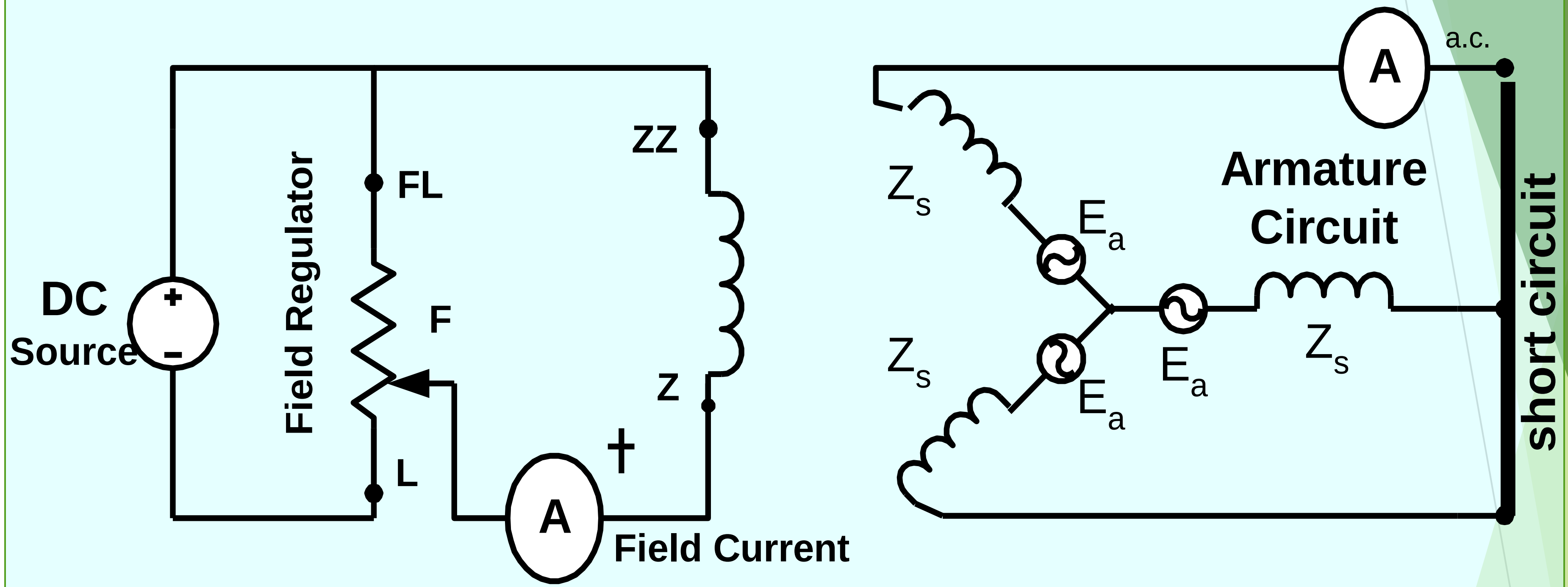
On open circuit $V_t = E$

Alternating current produces a flux which is proportional to I_L (reduces the total flux).

This is called the armature reactance effect represented by X_{ar}

On open circuit $X_{ar} = 0$.

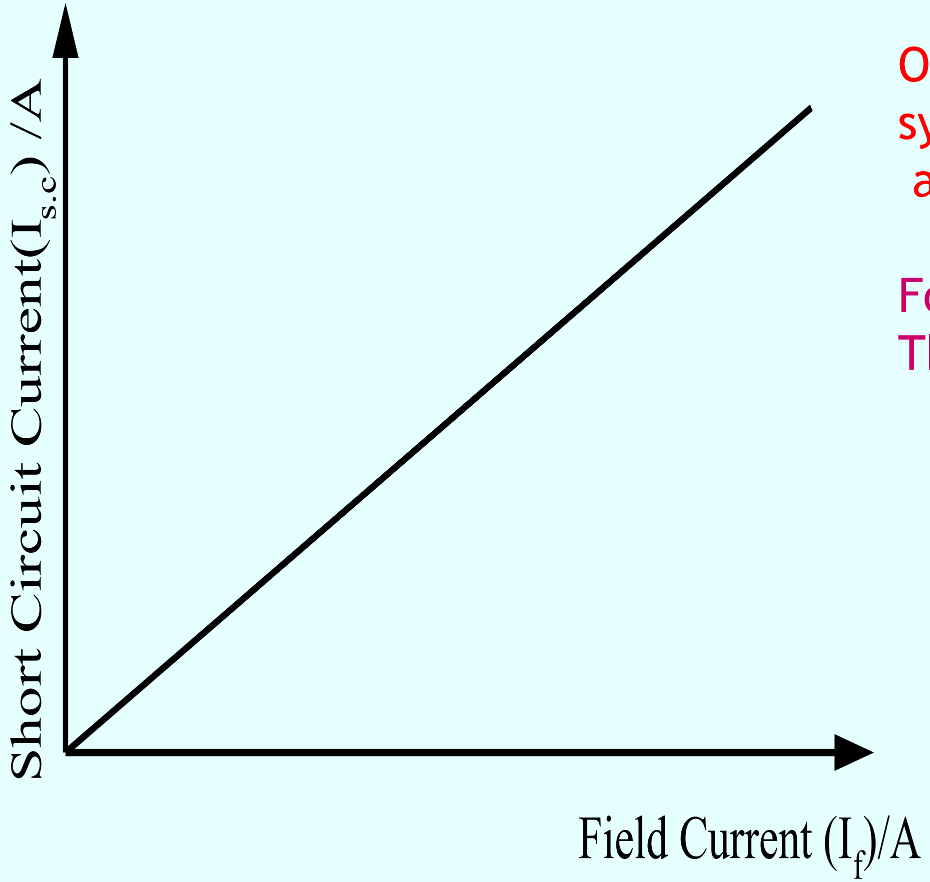
SHORT CIRCUIT CHARACTERISTICS



The three terminals of the armature are short circuited

The machine is driven at approximately synchronous rated speed and measurements of armature short circuit currents are made for various values of field currents usually up to and above rated armature current.

SHORT CIRCUIT CHARACTERISTICS

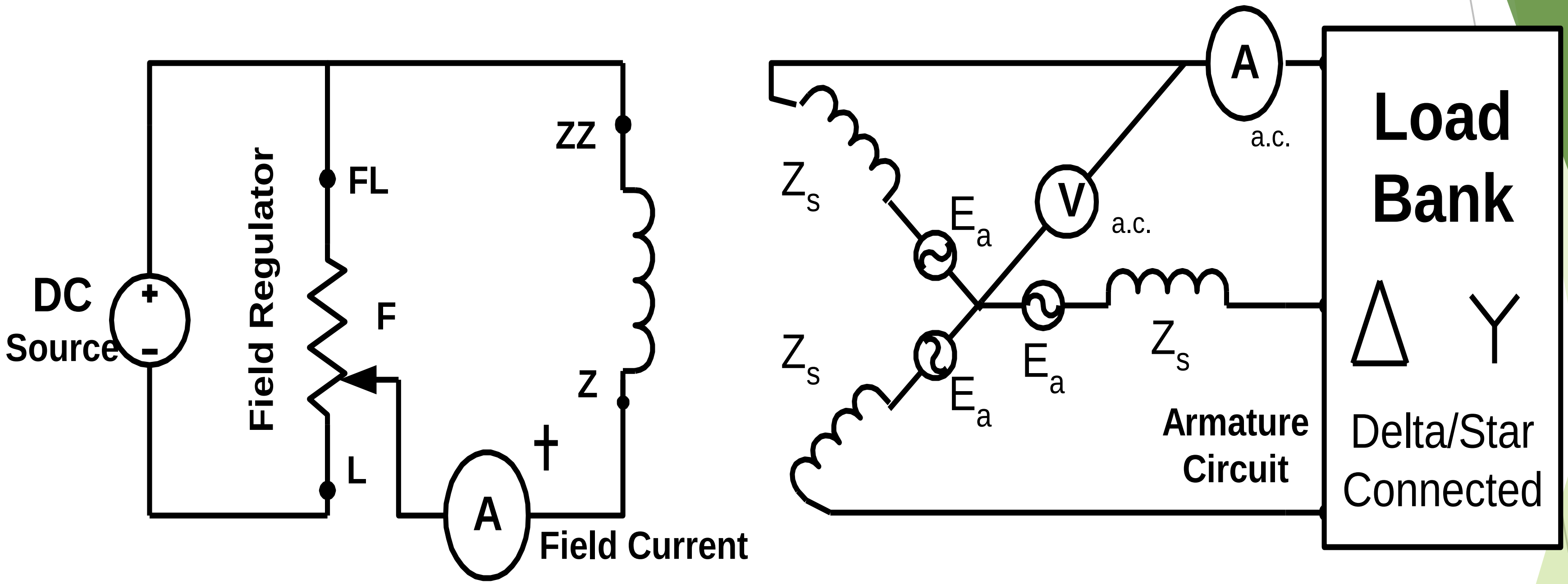


On short-circuit the machine runs at it synchronous speed ($n = n_s$)
and $I_L = I_{FL}$

For s/c $V_t = 0$,
Therefore $E / I_L = Z_s$
and $I_{sc} = I_L = E / Z_s$

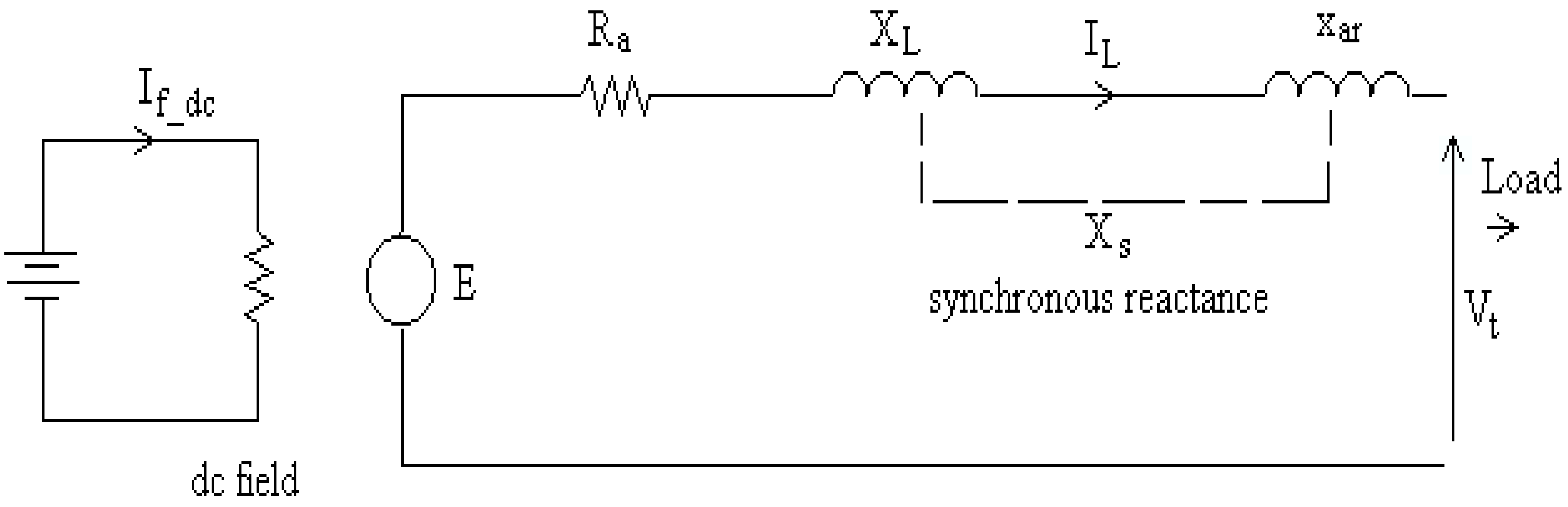
In conventional synchronous machines the short circuit characteristics is practically linear because the iron is unsaturated up to rated armature current

LOAD CONDITIONS



The machine is introduced to normal working conditions

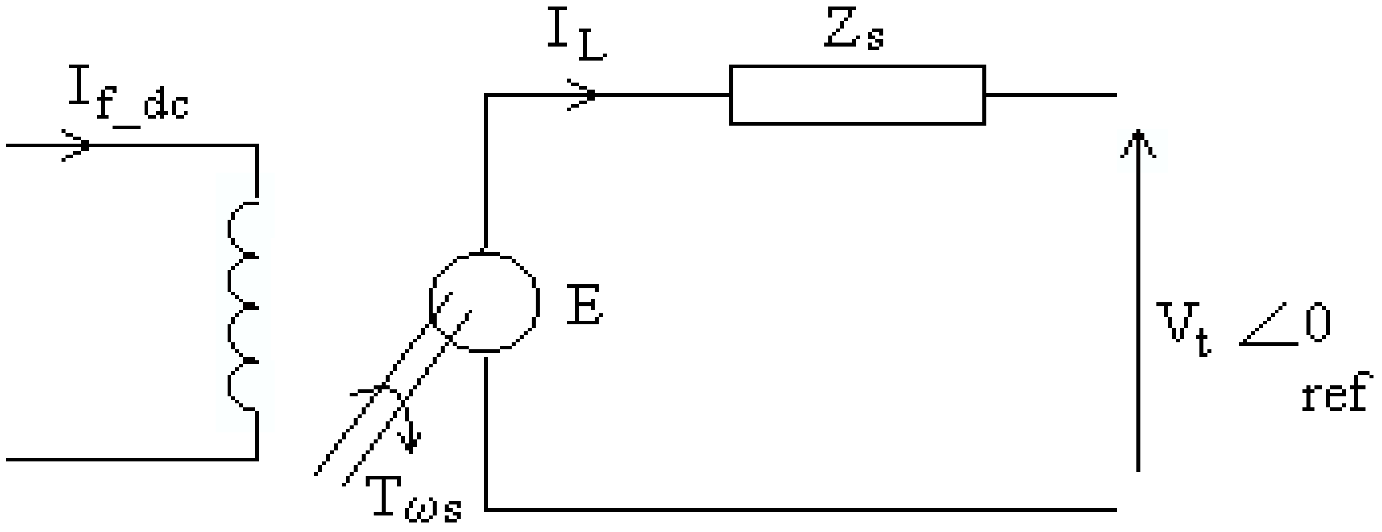
Per Phase Equivalent Circuit

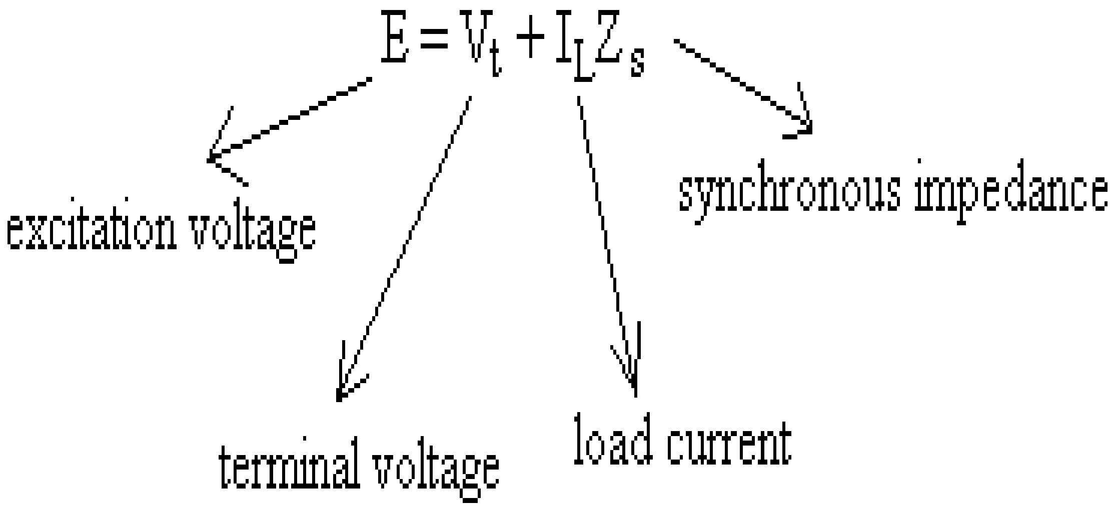


Per Phase Equivalent Circuit

R_a => armature resistance per phase
X_L => leakage reactance.

Power flow out of a Synchronous Machine





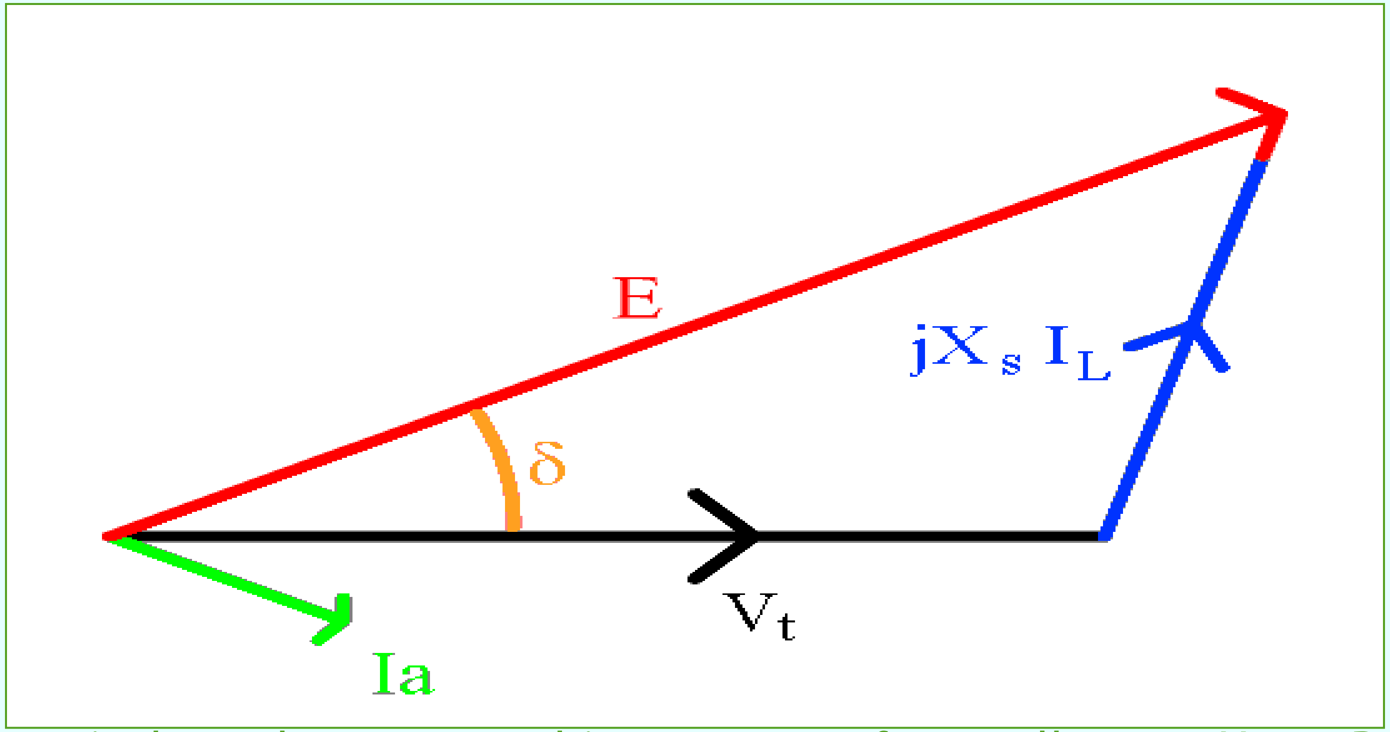
Generator power flow => out

Motor power flow => in

Power flow out of a Synchronous Machine

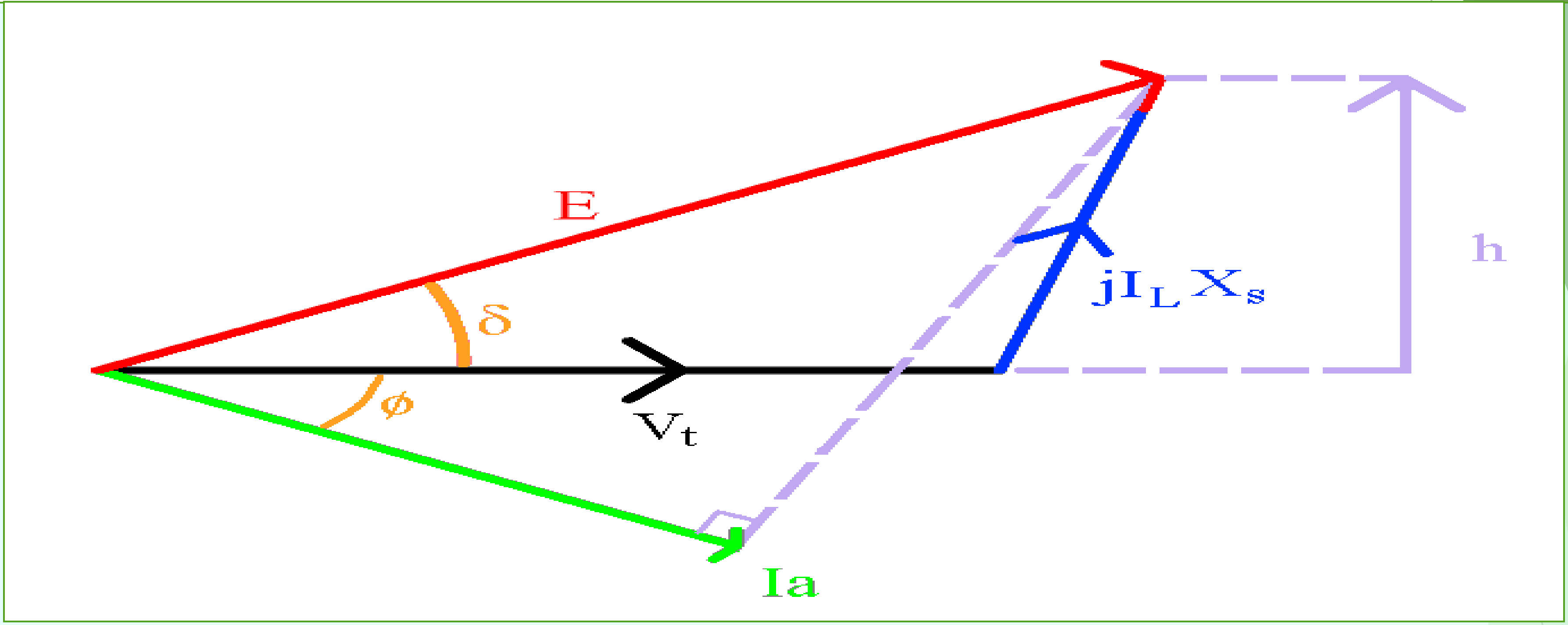
δ = Load angles

$$E\angle\delta = V_t\angle 0 + I_L\angle\phi .\ jX_s$$



In practical synchronous machines, except for small ones, $X_s >> R_a$ so we could assume that $Z_s = jX_s$ in the analysis.
Therefore we get $E = V_t + jI_LX_s$

Power flow out of a Synchronous Machine



Power = VIcosϕ

Considering the diagram $h = I_L X_s \cos\phi = E \sin\delta$

Therefore $I_L X_s \cos\phi = E \sin\delta$

Power flow out of a Synchronous Machine

$$\text{so } I_L \cos\phi = \frac{E \sin\delta}{X_s}$$

$$\text{Now } P_{out} = VI\cos\phi$$

$$\text{from the two equations we can get } P_{out} = \frac{E \sin\delta}{X_s} V$$

$$= \frac{EV}{X_s} \sin\delta$$

For maximum power sinδ = 1

Therefore δ = 90

In which case

$$P_{out} = \frac{EV}{X_s}$$