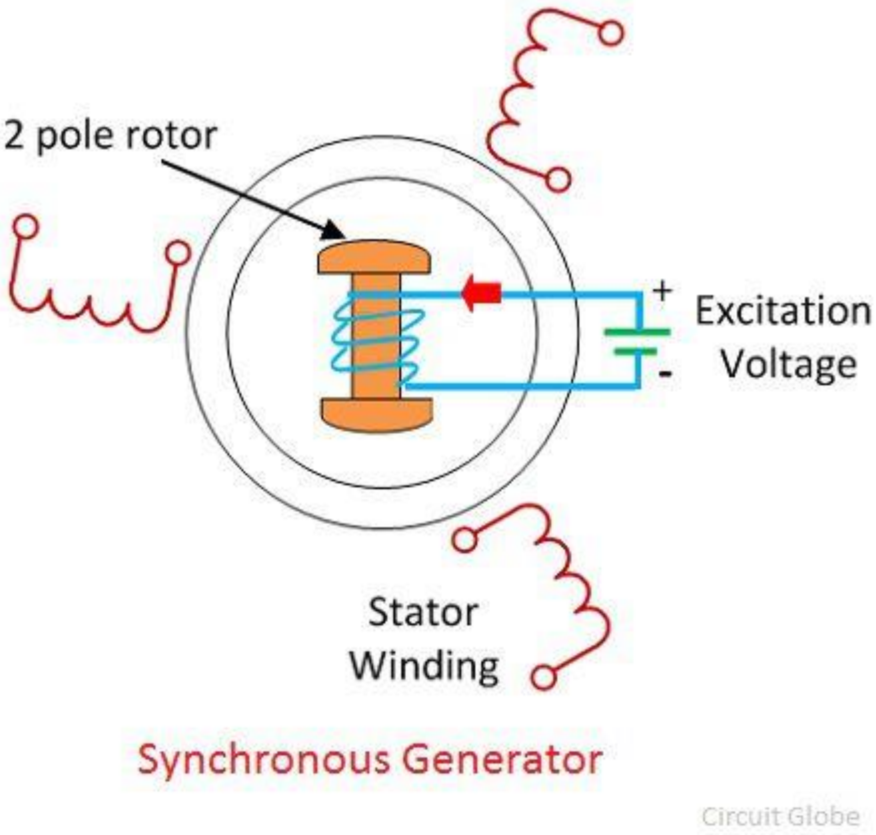
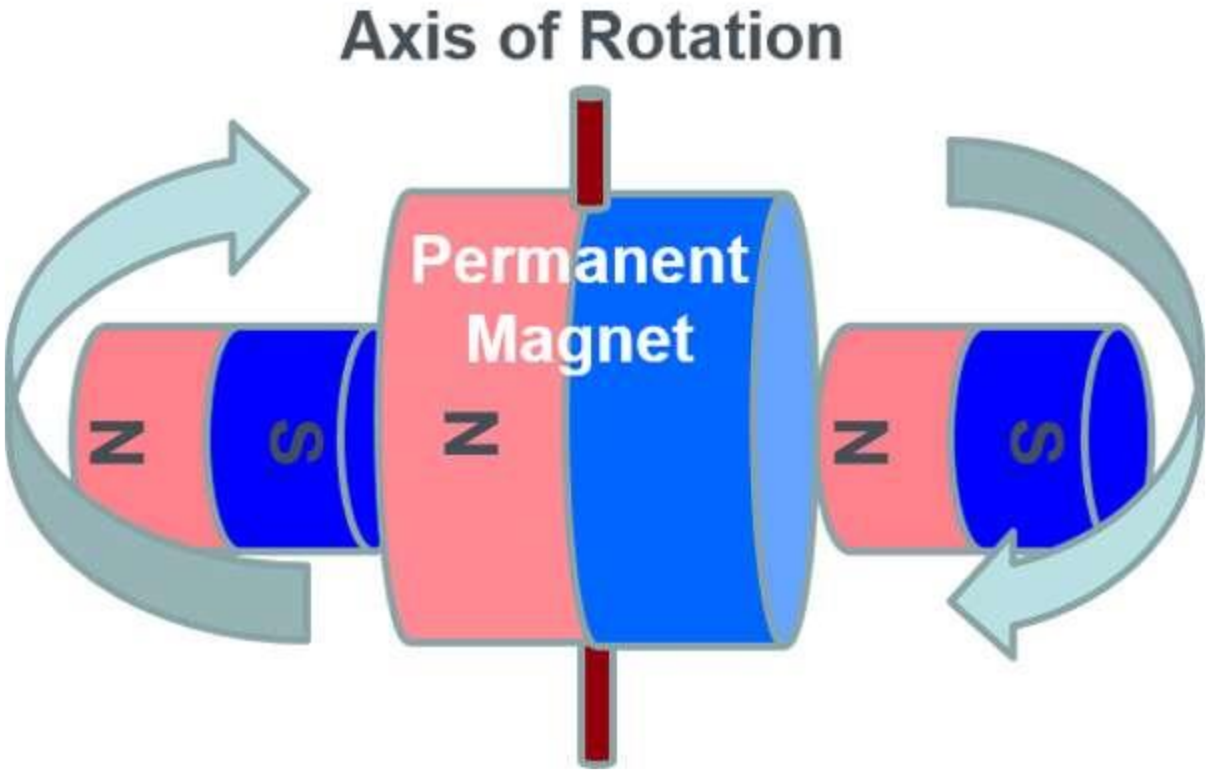
Synchronous Machines

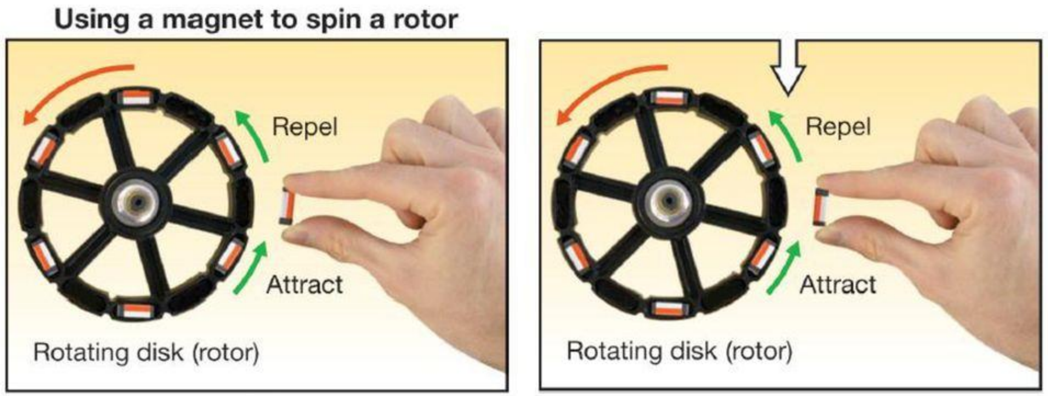
How do they look





Using magnets to spin a disk

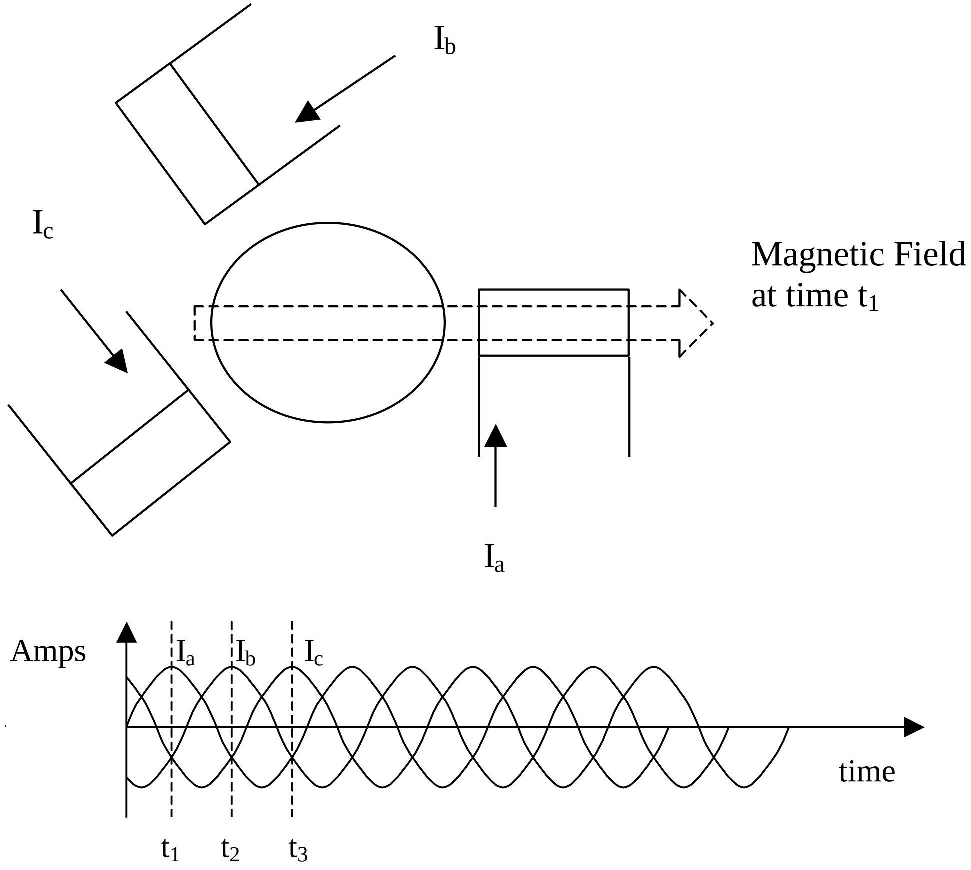
- Reversing the magnet in your fingers attracts and repels the magnets in the rotor, making it spin.



The Synchronous Machine

- An AC machine (generator or motor) with a stator winding (usually 3 phase) generating a rotating magnetic field and a rotor carrying a DC magnetic field which rotates in **synchronism** with the rotating stator field. The speed of a synchronous machine is locked in **synchronism** with the frequency of the AC supply.
- Large synchronous generators (Alternators) are used to generate the vast majority of the worlds electricity.
- Synchronous motors are less common but may be used where fixed or controlled speed operation is desirable:
  - Old Fashioned Electric Clocks
  - Precision motor drives (with electronic frequency converter)

A simplified view of the stator winding



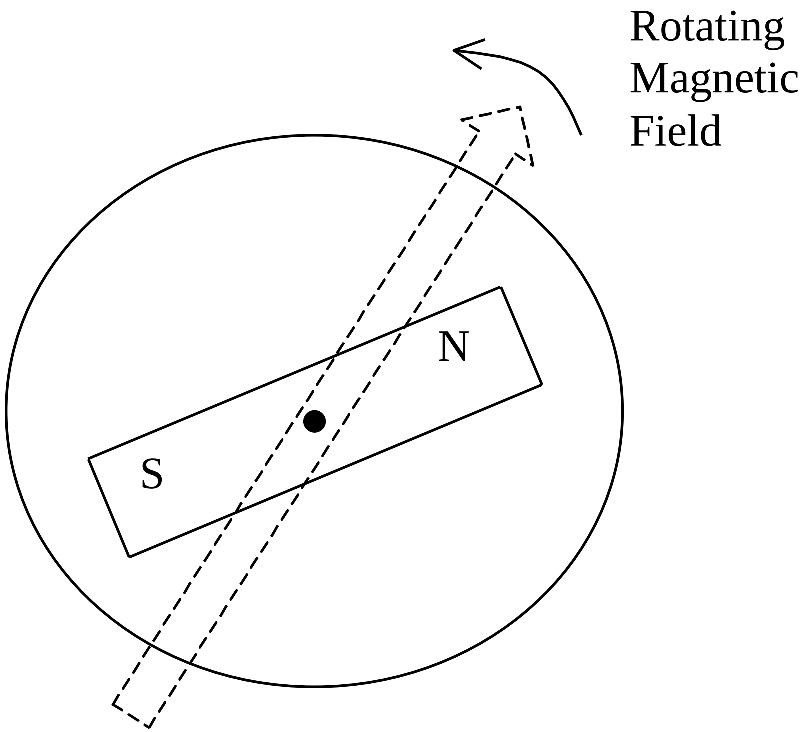
The Rotating field

- In a Real machine the windings are sinusoidally distributed and the fields due to all three phases add to produce a constant sinusoidally distributed rotating field that is 3/2 the peak magnitude of the stationary pulsating field that would result from any one winding acting on its own.
- In the simple machine shown on the last page the field rotates one revolution per cycle of the ac supply.
- The simple machine shown over is called a 2 pole machine (1 N and 1 S pole in magnetic field). Real life machine may have 2, 4, 6 or more poles.
- The speed of the rotating field is known as Synchronous speed (N_{sync})

  N_{sync} = 60.f .2/P **(P = pole number)**

$$f = \frac{pn}{120}$$

A Permanent Magnet Rotor



Intermediate question

- Synchronous speed – how do we calculate?
- Synchronising power – what factors depend upon?
- Voltage drop occurs in Synchronous generator due to ..?
- In an alternator, at lagging power factor, the generated voltage per phase, as compared to that at unity power factor…?
- With capacitive load what is expected of the terminal voltage of a S.G?
- Which kind of rotor is most suitable for turbo alternators which arc designed to run at high speed ?

The Rotor

- The North pole of the rotor will be attracted to the south pole of the rotating field and vice versa.
  - If the rotor lags slightly behind the rotating field it will be pulled along at synchronous speed => Synchronous motor.
  - If the Rotor is driven from an external source (eg turbine) it will tend to pull the field along slightly behind it => Synchronous generator.
- Note in both motoring and generating case the rotor speed = speed of the rotating field = N_{sync}
- In a typical Synchronous machine the permanent magnet rotor is replaced by a DC electromagnet called the excitation winding. This rotating winding is powered through slip rings. **The excitation current is DC.**

Synchronous Machine Equivalent Circuit

Synchronous Generator

- The Excitation Voltage

  The rotating d.c. field from the rotor cuts the stator windings inducing an a.c. voltage (E). If we neglect saturation $E \propto I_f$ where I_f is the d.c. field current.

  Note: E is also proportional to the rotational speed (compare for a d.c. machine $E_a = K_a \phi \omega_{mech}$) but in a synchronous machine the rotational speed is a fixed multiple of frequency.

- Armature Reaction

  DC Machine – Armature Current produces its own field acting against the field winding.

  Synchronous Generator – Stator current produces rotating field which tends to reduce the field from the excitation winding. This will reduce the excitation voltage by an amount $E_{ar.}$ E_{ar} is most easily modelled as the voltage drop across an inductive reactance $X_{ar.}$

Synchronous Generator (cont.)

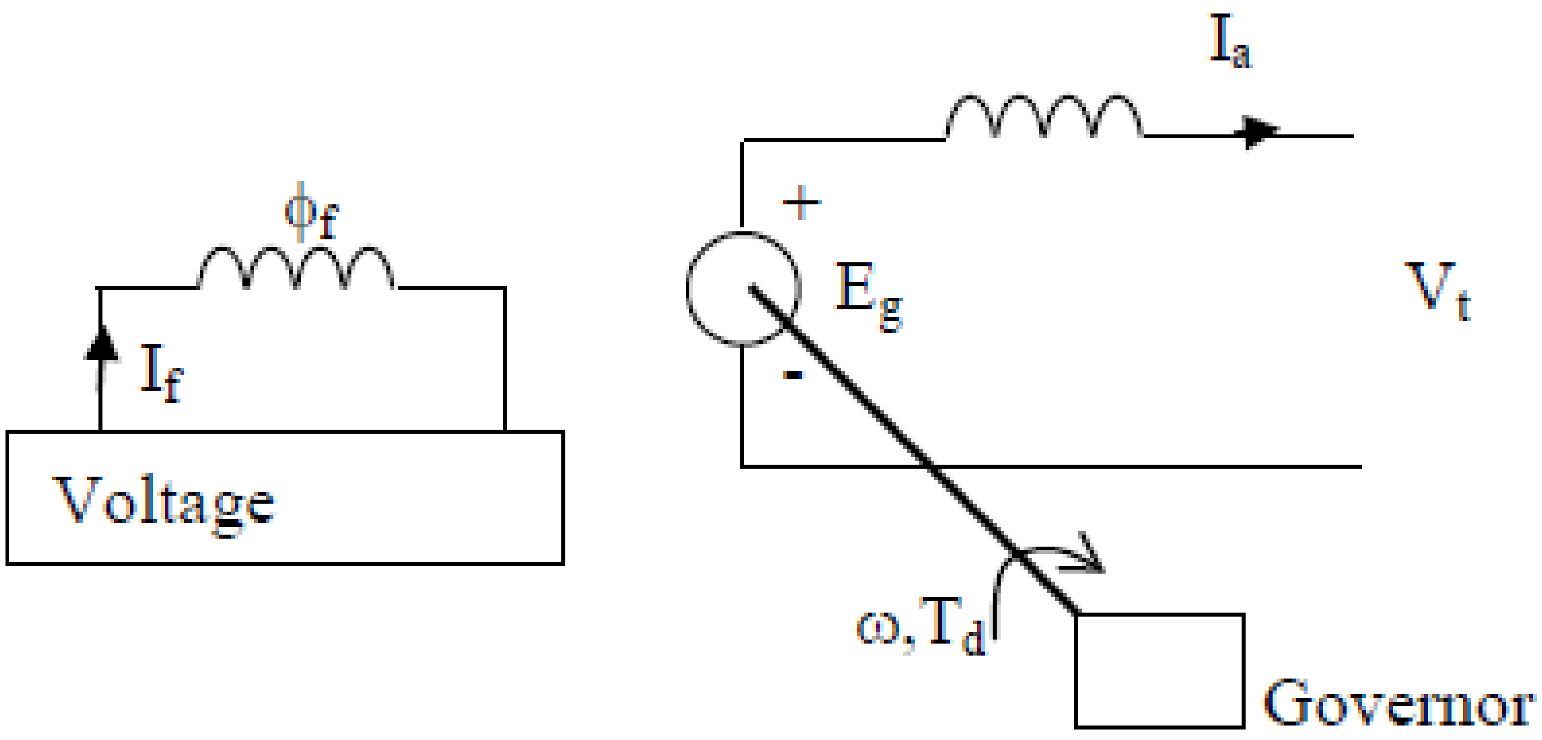
- Stator Leakage Reactance

  Not all of the stator flux links the rotor. Leakage flux which links the stator and not the rotor gives rise to a leakage reactance X_{al}.

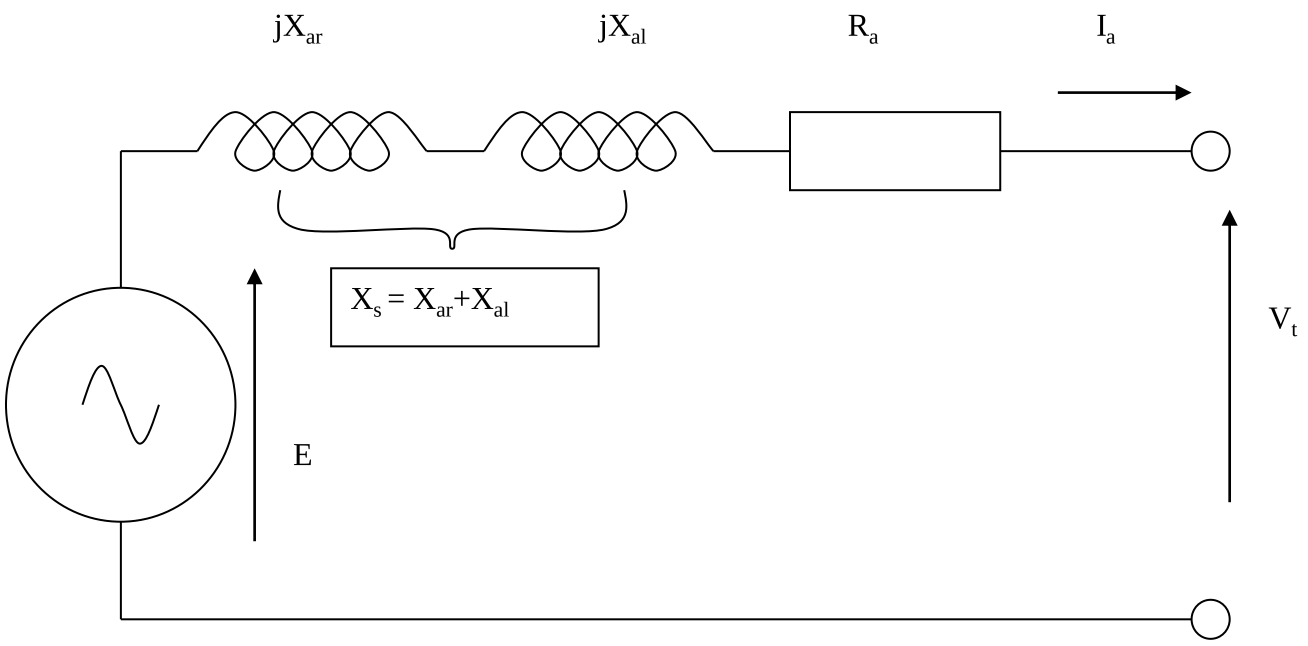
- Effective Stator Winding Resistance

  This models the resistance of the copper in the stator windings measured at operating frequency and operating temperature. It is usually higher than the DC resistance due to the combined effects of skin effect and temperature.

Per Phase Equivalent Circuit



Per Phase Equivalent Circuit



Per Phase Equivalent Circuit of a Synchronous Generator

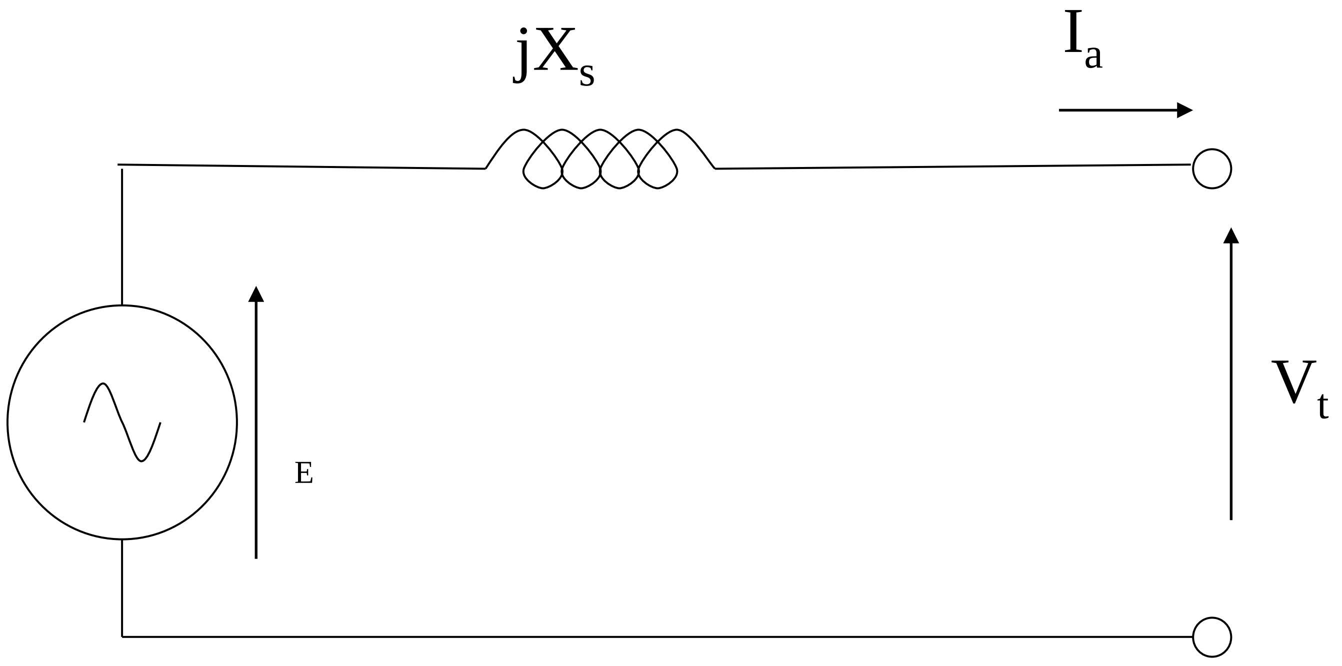
Typical Parameter Values

- Using the Per units systems a 1pu impedance would drop rated voltage at rated current

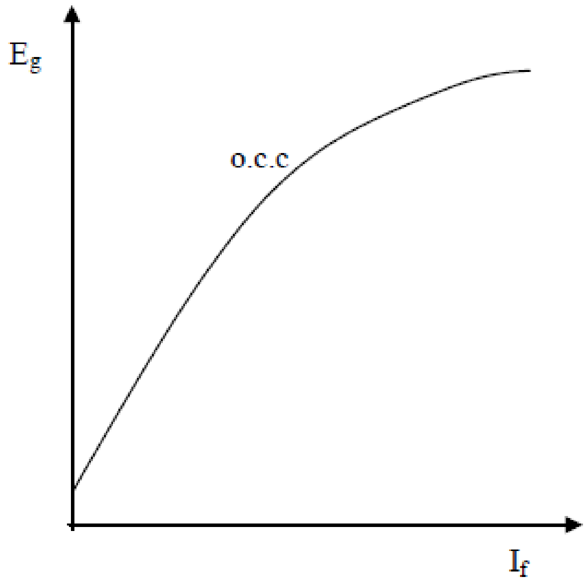
	Large Alternator (10MVA+)
R_a	0.01pu-0.005pu
X_s	1.0pu-1.5pu

- R_a is usually << X_s so it can usually be neglected

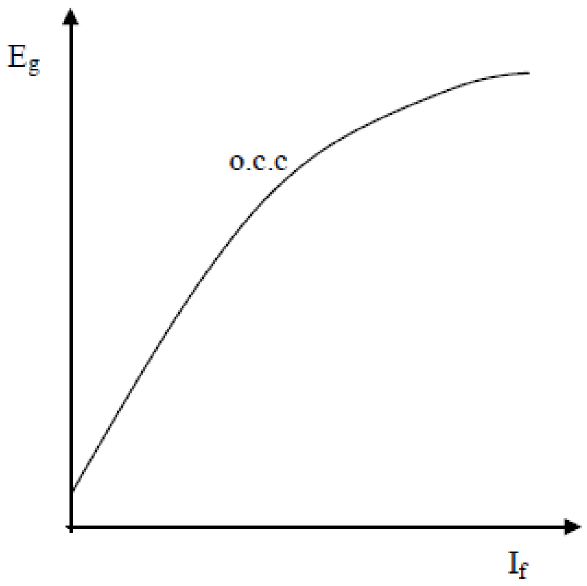
Simplified Per Phase Equiv. Circuit of a Synchronous Generator



$$E = V_t + jX_s . I_a$$



Determining Xs



<u>Open-circuit test:</u>

- Generator run at rated speed
- Exciting current is raised until rated voltage generated
- Exciting current and line-to-neutral voltage are recorded

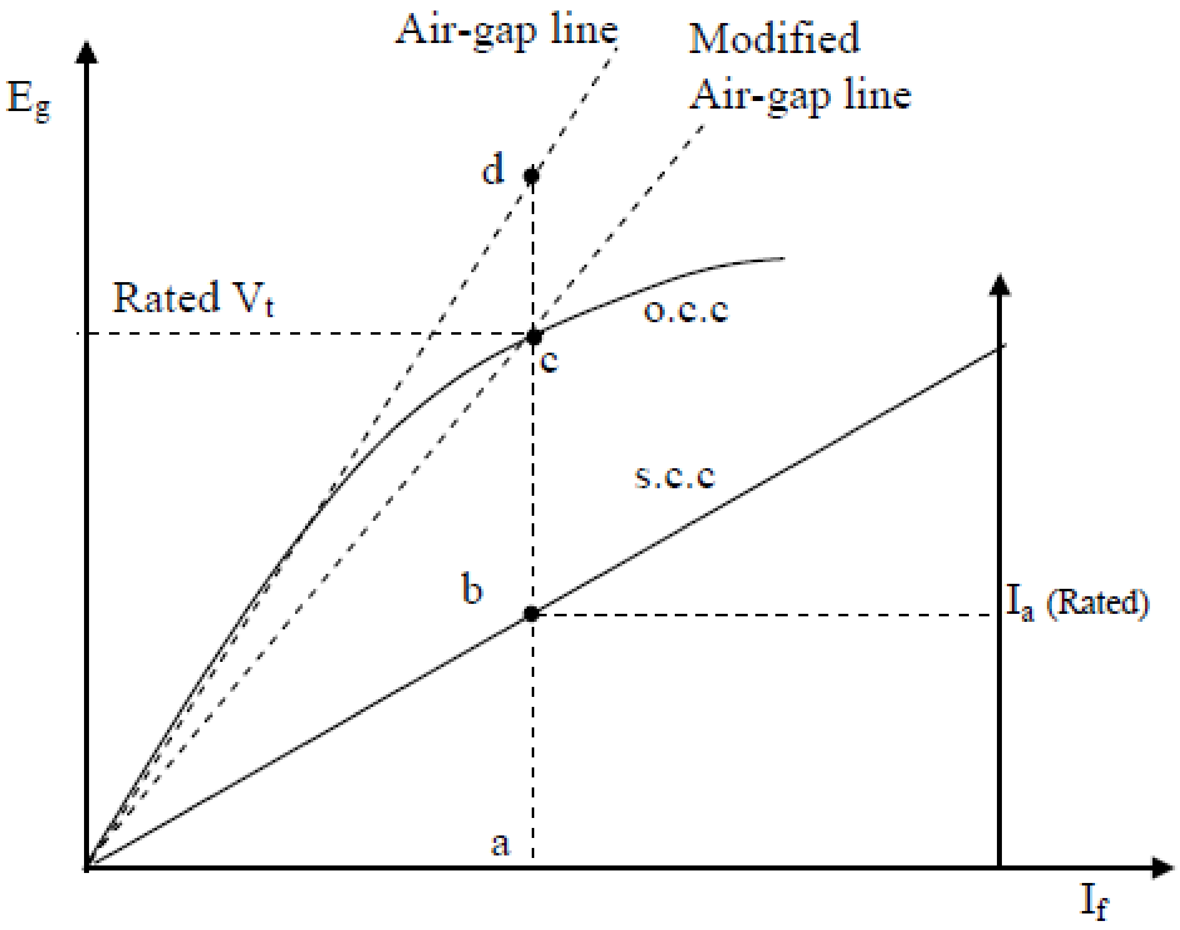
<u>Short circuit test:</u>

- Excitation is reduced to zero and armature is short-circuited
- Generator run at rated speed
- Excitation returned to value till rated stator current is achieved
- Short-circuit Isc in the stator is measured

Xs = En / Isc

Synchronous reactance is not constant, but varies with the degree of saturation

Characteristics of a Synchronous machine



Base Impedance / Per unit Xs

Use the rated line-to-line voltage E_B

Use the rated power of the generator S_B

Base impedance $Z_B = E_B^2 / S_B$

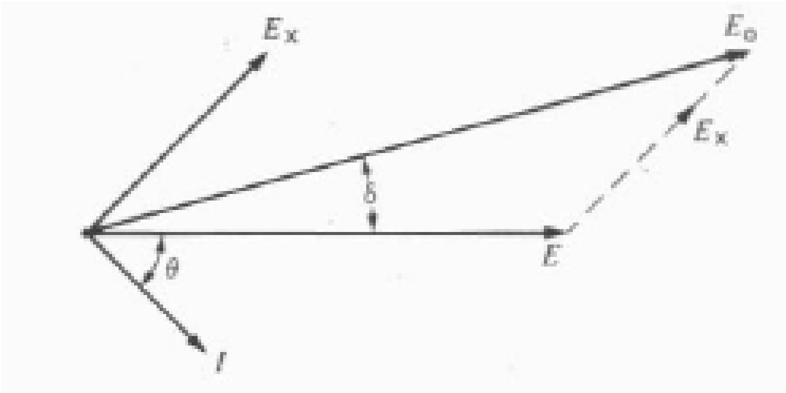
X_s (per unit) = X_s / Z_B

Synchronous Generator under Load

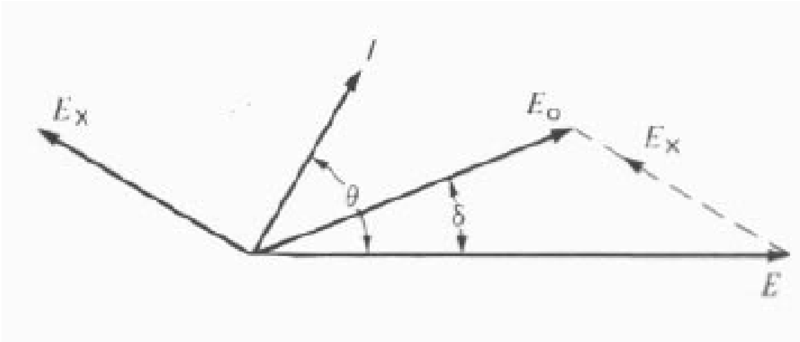
Two basic load categories:

- Isolated loads supplied by a single generator
- The infinite bus

Synchronous Generator under Load: Isolated Loads



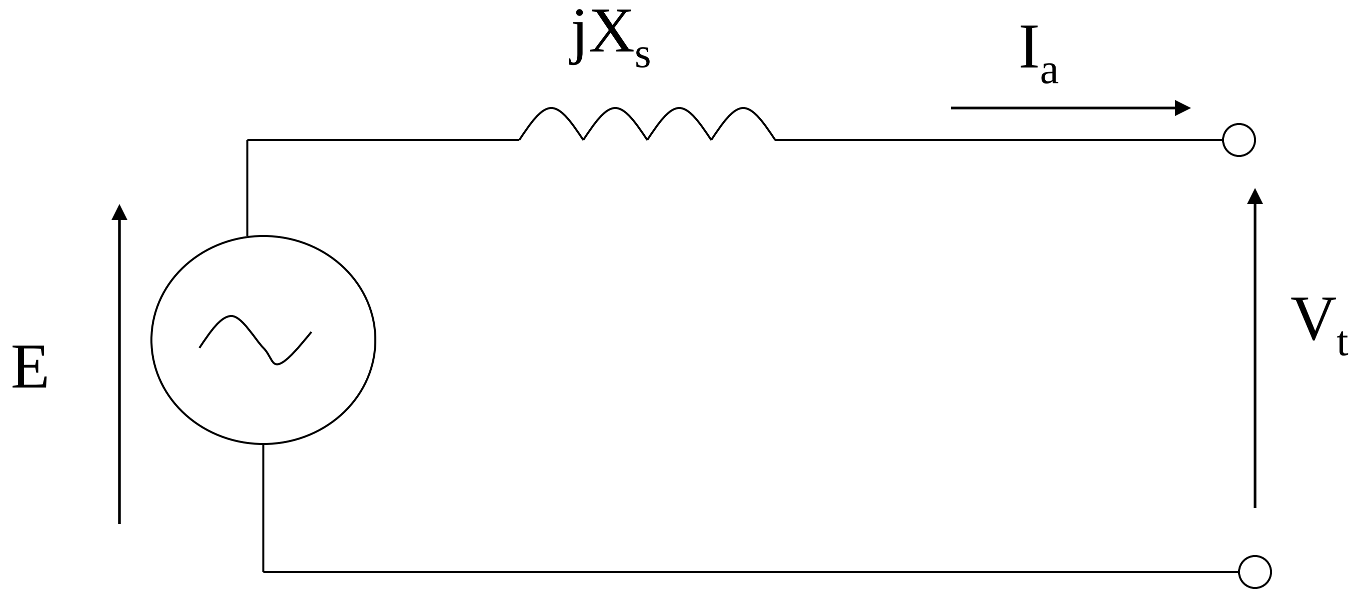
Lagging p.f. load



Leading p.f. load

Synchronous Machine Power and Torque

Synchronous Generator



Simplified Equivalent Circuit
(per phase)

Power Equation

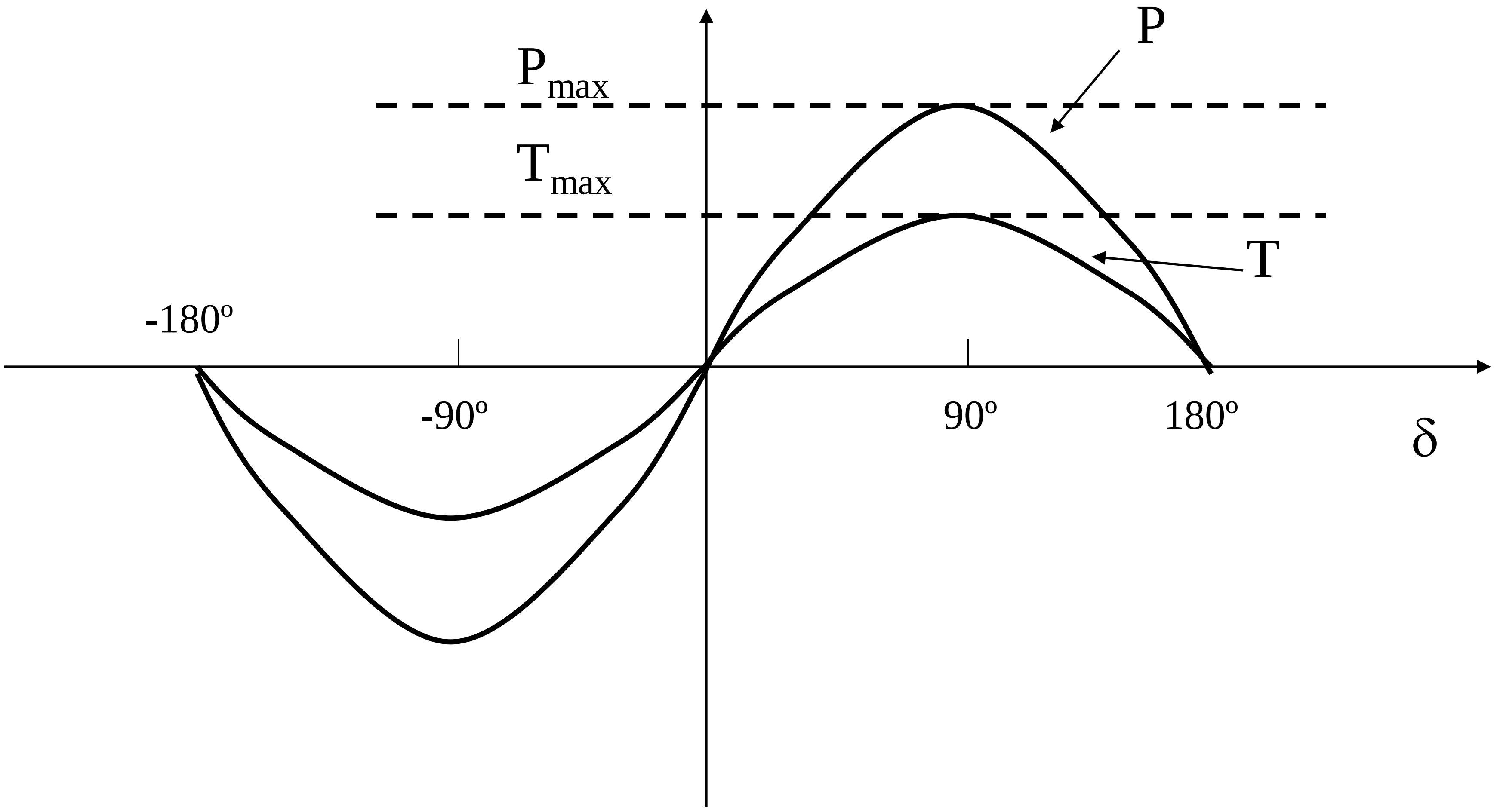
- $E = V_t + I_a.jX_s$
- $P_{elec} = 3.|V_t|.|I_a|.\cos(\phi)$
- $P_{elec} = 3.|V_t|.|E|.\sin(\delta) / X_s$
- Where ϕ is angle between V_t and I_a
- Where δ is the angle between E and V_t

  Note: These equations are derived in class using phasor diagrams

Torque Equation

- Ignoring losses $P_{mech} = P_{elec}$
- $P_{mech} = T.\omega_{mech} = 3.|V_t|.|E|.\sin(\delta) / X_s$
- $T = 3.|V_t|.|E|.\sin(\delta) / (X_s.\ \omega_{mech})$
- Note: $\omega_{mech} = N_{sync}.(2\pi/60)$
- The maximum value $\sin(\delta)$ can have is 1.0 so:
- $P_{max} = 3.|V_t|.|E| / X_s$
  $T_{max} = 3.|V_t|.|E| / (X_s.\ \omega_{mech})$

Power and Torque versus δ



Stability Limits

- $P = 3.|V_t|.|E|.\sin(\delta) / X_s$
- In a synchronous generator connected to the AC mains $|V_t|$ is fixed by the mains (an infinite bus), $|E|$ is set by the Rotor Field current. We can control the power into the generator by feeding more or less juice into our turbine.
- As we increase the input power from 0 to P_{max} then δ increases from 0 to 90º. If we try to increase the power above P_{max} (or the Torque above T_{max}) then the generator will speed up and break out of synchronism.
- P_{max} and T_{max} are known as the static stability limits
- T_{max} is also known as the pull out torque.
- Increasing the rotor field current (I_f) will increase $|E|$ and increase the stability limit.

- Question:

  What is the significance of negative δ ?

  How might you get the machine to run in this region?

δ

- δ is called the Power angle or the Torque angle
- δ is the phase shift between E and V.

- E is the voltage induced by the rotor cutting the stator windings so the phase of E is locked to the position of the rotor shaft. Therefore we can "see" δ if we draw a mark on the rotor shaft and shine a stroboscope on it that is synchronised to the zero crossing of V_t.. The apparent position of the mark should be noted when power is zero (δ = 0º). As power is increased δ will increase and the apparent position of the mark on the shaft will move by an angle equal δ*2/P.

Question

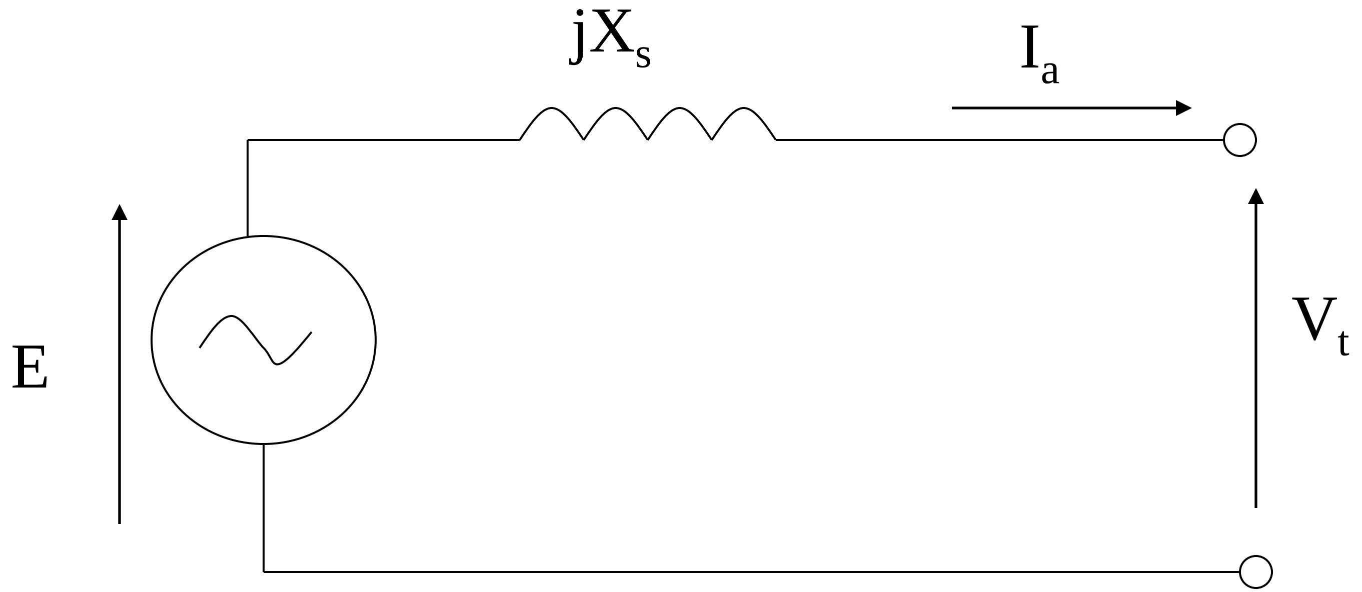
- A 3ϕ, 5kVA, 400V, 4 pole, 50Hz star connected synchronous machine has negligible stator winding resistance and a synchronous reactance of 30Ω per phase at rated terminal voltage. It is connected to a 400V, 3ϕ supply and operated as a generator.
  1. Determine the excitation voltage and the power angle when the machine is delivering rated kVA at 0.8PF lagging. Draw the phasor diagram for this condition
  2. With the same field current as above the prime mover power is slowly increased. What is the static stability limit? If rotational losses may be ignored what is the torque under this condition? What are the corresponding values of stator current, power factor and reactive power (Q) under this maximum power condition?

Operating a Synchronous Machine on an infinite bus

The Infinite Bus

- Most Synchronous Generators (also called Alternators) are connected to the AC mains. No one generator can affect the voltage or frequency of the national grid. We call the grid voltage (V_t) an infinite bus and it is considered to be fixed.
- The alternator is now connected to an infinite bus.
  - The terminal voltage (V_t) is locked to the mains voltage.
  - The speed of the machine is locked to synchronous speed.
- What happens if:
  - You increase the power fed in from the prime mover?
  - You vary the field current I_f?

Synchronous Generator



Generator Simplified Equivalent Circuit (per phase)

$$E = V_t + jX_s.I_a$$

Vary the Power from the prime mover

- This power must be fed back to the AC mains (Generating)

- $P = 3. |V_t|.|I_a|.\cos(\phi)$
  $|V_t|$ is fixed so $|I_a|.\cos(\phi)$ varies to feed the correct power back to the mains

- See on a phasor diagram that for a given value of power the operating point of the machine must be somewhere on a straight line (The locus of constant power).

Vary the field current

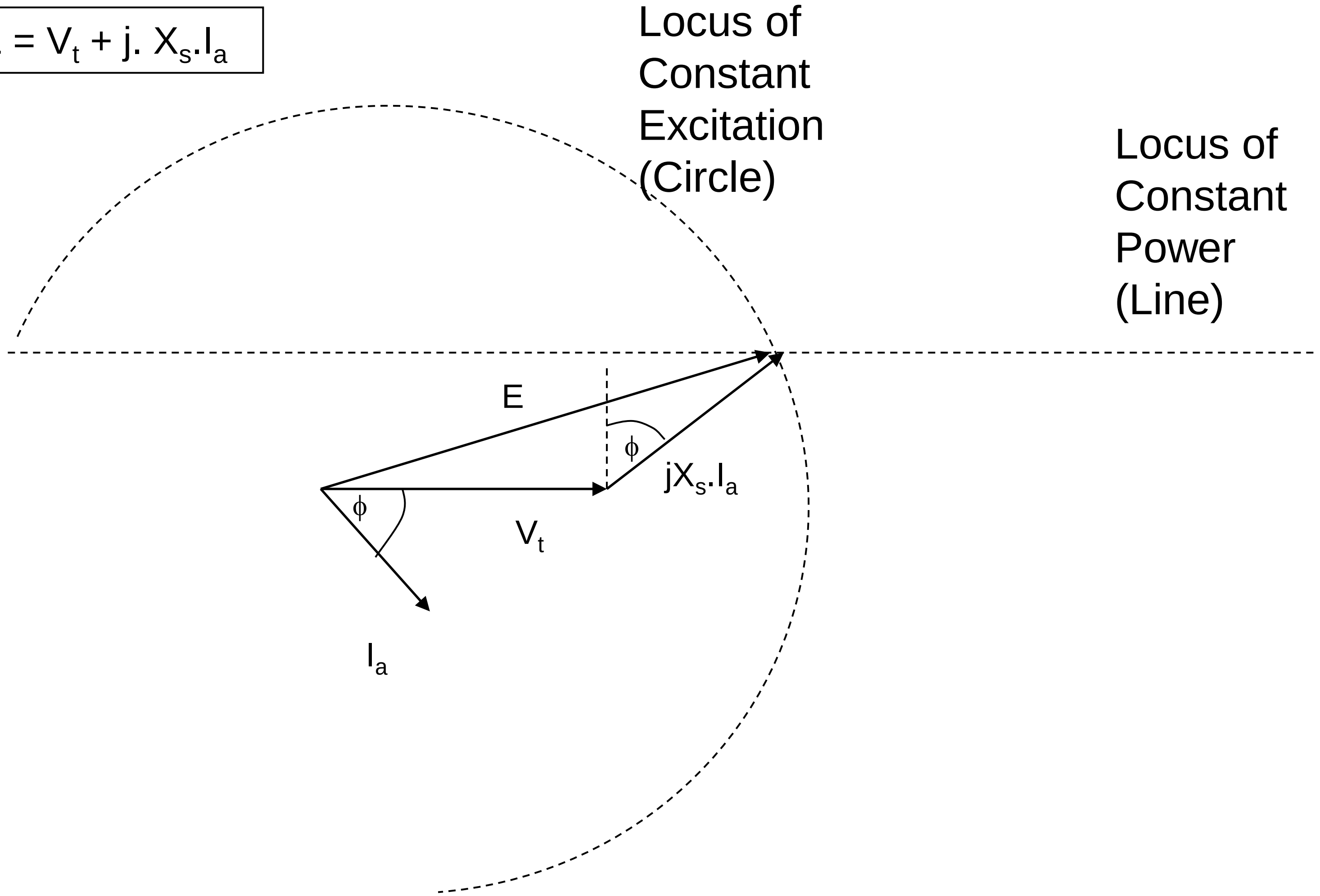
- $|E|$ is proportional to the field current (often called the excitation)

- For a given value of excitation the operating point must lie somewhere on a circle (The Locus of Constant Excitation)
- NB. Notice that varying the excitation will not affect the power but it will change the phase angle of the current (ϕ).

- We can vary the phase shift (ϕ) of a synchronous alternator by varying the excitation.
  - Increasing the excitation will generate more inductive current (I_a lags V_t).
  - Reducing the excitation will generate more capacitive current (I_a leads V_t).

Phasor Diagram

$\boxed{E = V_t + j.\ X_s.I_a}$



Network voltage and frequency control

- On an electricity network the power stations must generate real power to supply the real energy drawn by the network. It must also generate reactive power (usually inductive) to supply all of the reactive loads on the network. By varying the turbine power and the excitation of the synchronous alternators the power generating utility (ESB) can independently vary the amounts of real power and reactive power.

- Note the power utility (e.g. ESB) will monitor the frequency and voltage of the grid to make sure that enough real power (P) and Reactive Power (Q) are being generated.
  - P tends to affect the frequency
  - Q tends to affect the voltage level