Module G1

Electric Power Generation and Machine Controls

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Module G1: HW Probs 1, 4, 8, 9, 10, 11. Due: 3/14. (To turn in).

Overview

- Energy transformation into electrical form
- Generation operation
  - Revolving magnetic field
  - Phasor diagram
  - Equivalent Circuit
  - Power relationships
  - Generator pull-out power
- Excitation control
- Turbine speed control

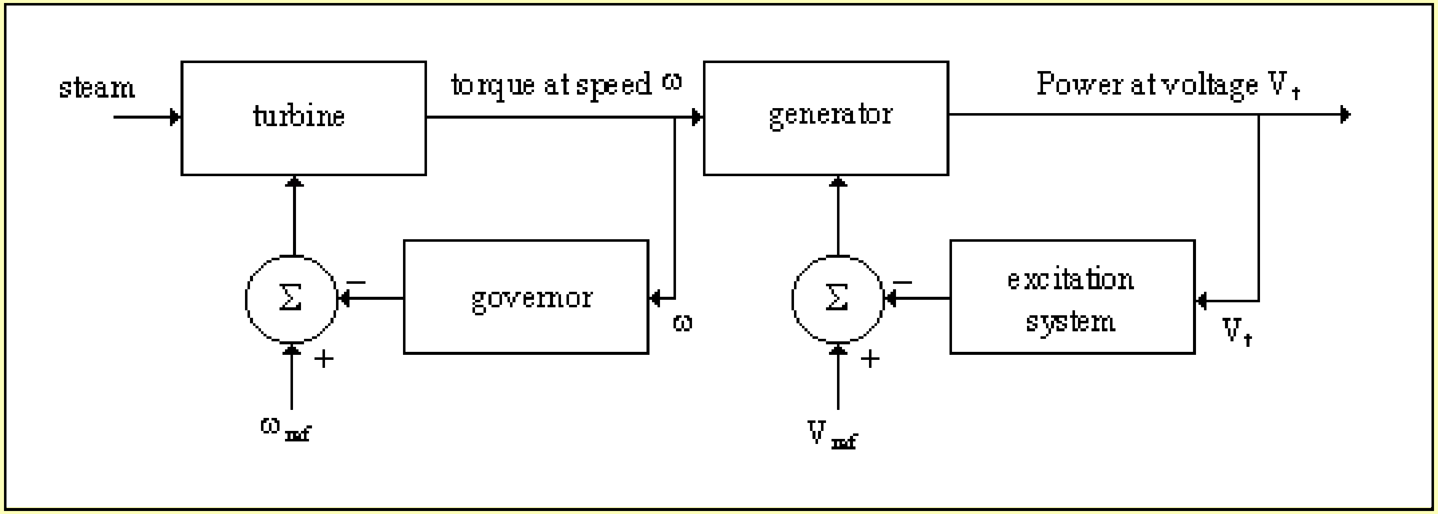
Energy Transformation

- Transformation processes:
  - Chemical
  - photovoltaic
  - electromechanical
- Electromechanical: conversion of energy from coal, petroleum, natural gas, uranium, water flow, geothermal, and wind into electrical energy
- Turbine-synchronous AC generator conversion process most common in industry today

Repairs to the overhand insulation of this 200MW generator rotor were carried out by experienced tradesmen working on shift to ensure the earliest possible return to service.

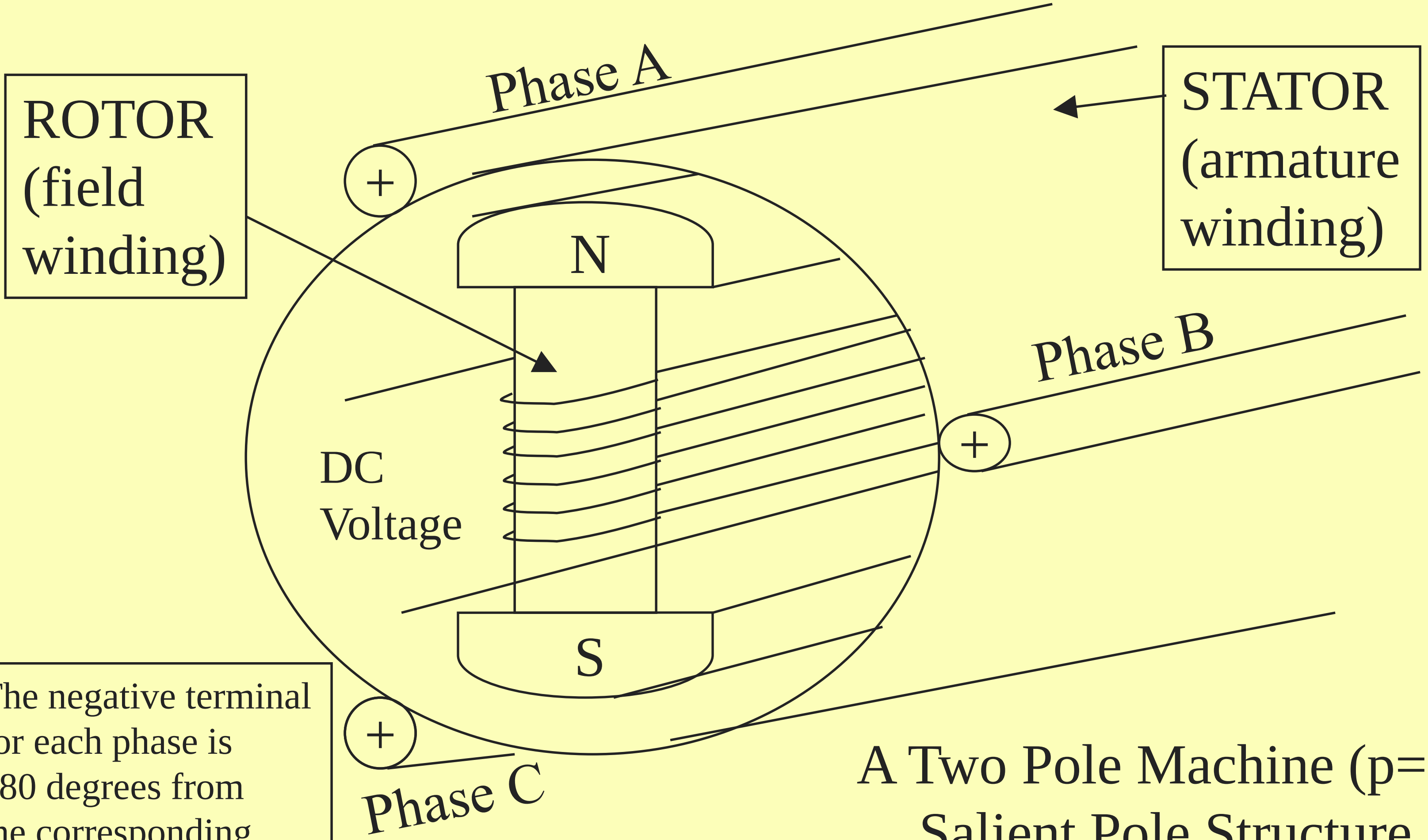
Feedback Control Systems for Synchronous Generators

- Turbine-generator basic form



- Governor and excitation systems are known as *feedback control systems;* they control the speed and voltage respectively

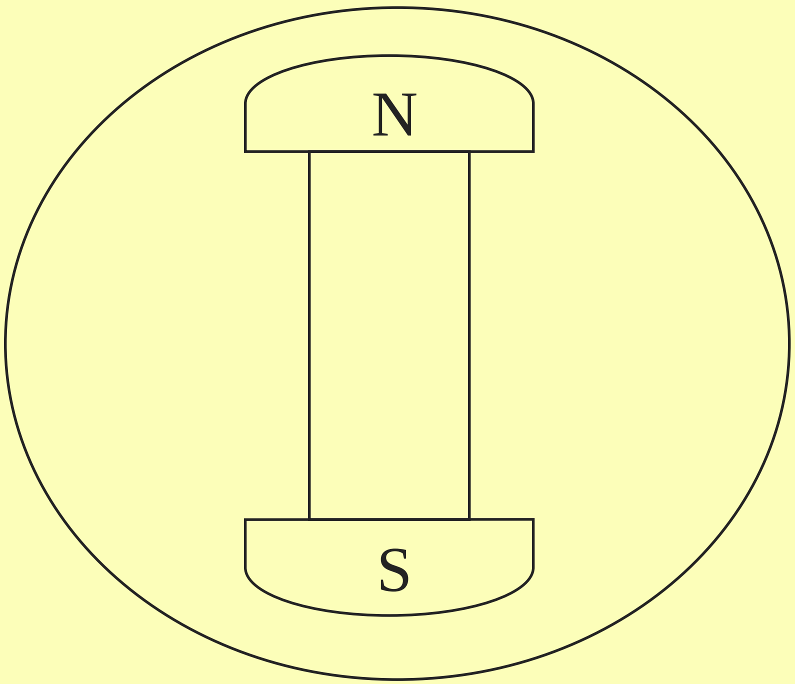
Synchronous Machine Structure



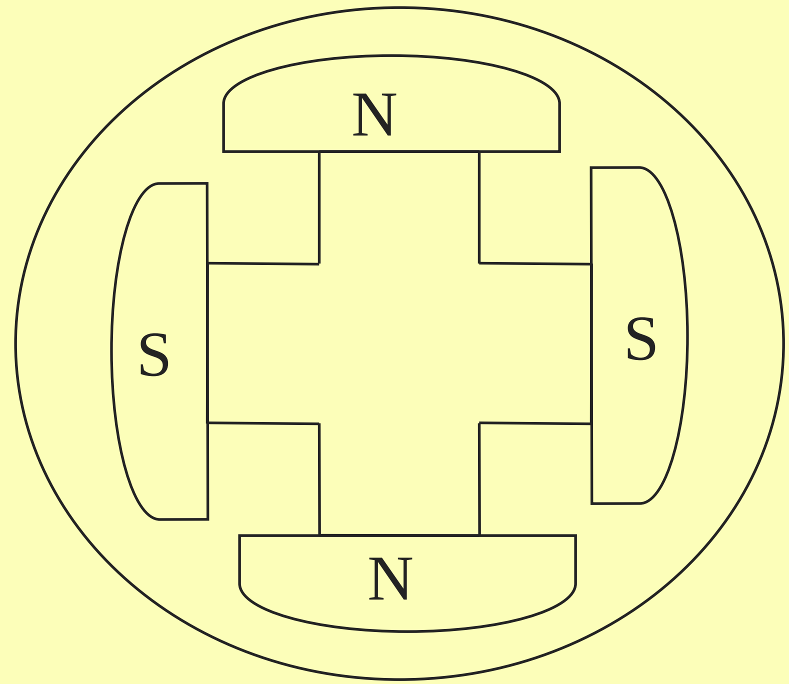
The negative terminal for each phase is 180 degrees from the corresponding positive terminal.

A Two Pole Machine (p=2)
Salient Pole Structure

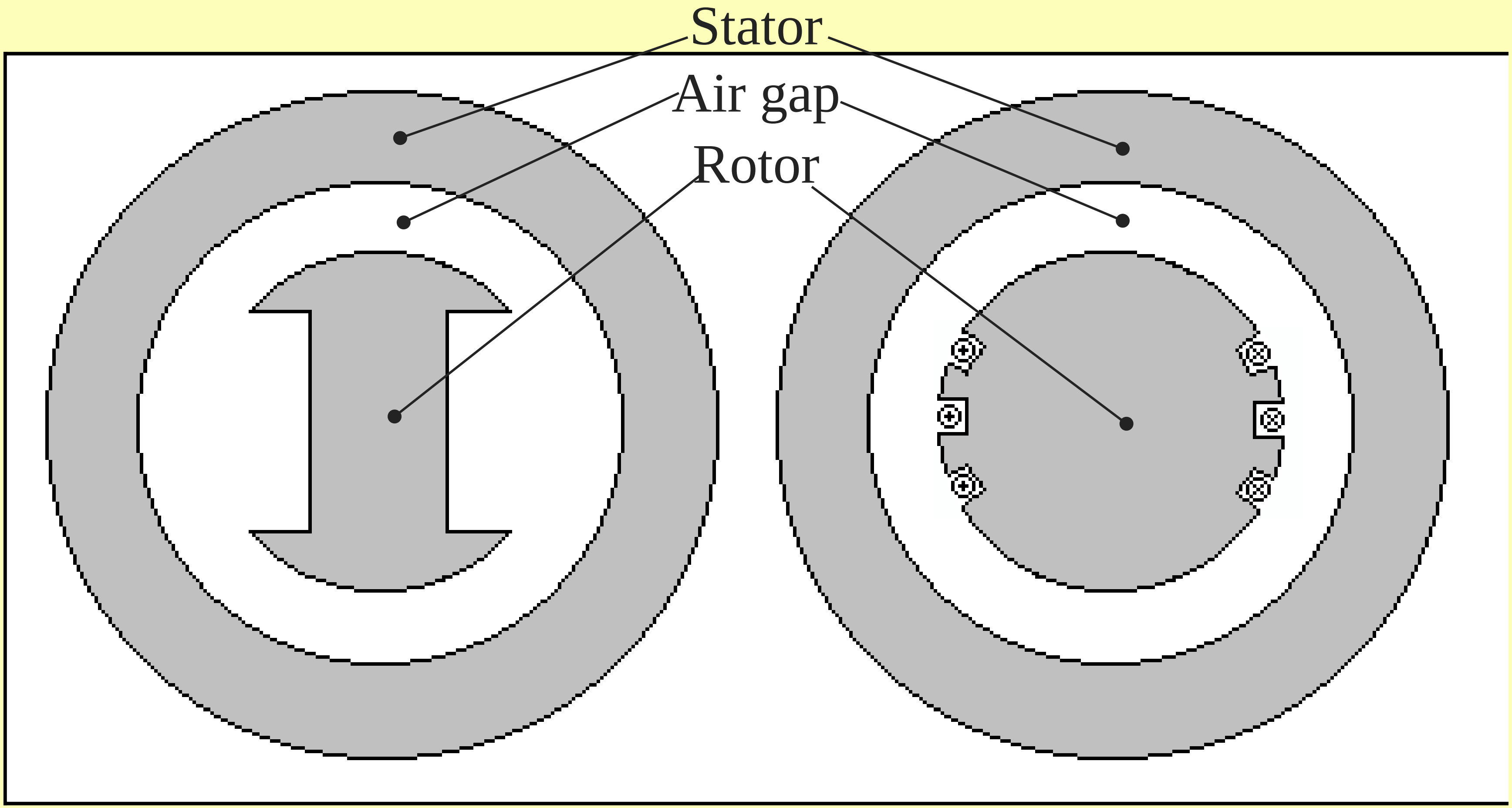
Synchronous Machine Structure



Two-pole
Salient pole construction



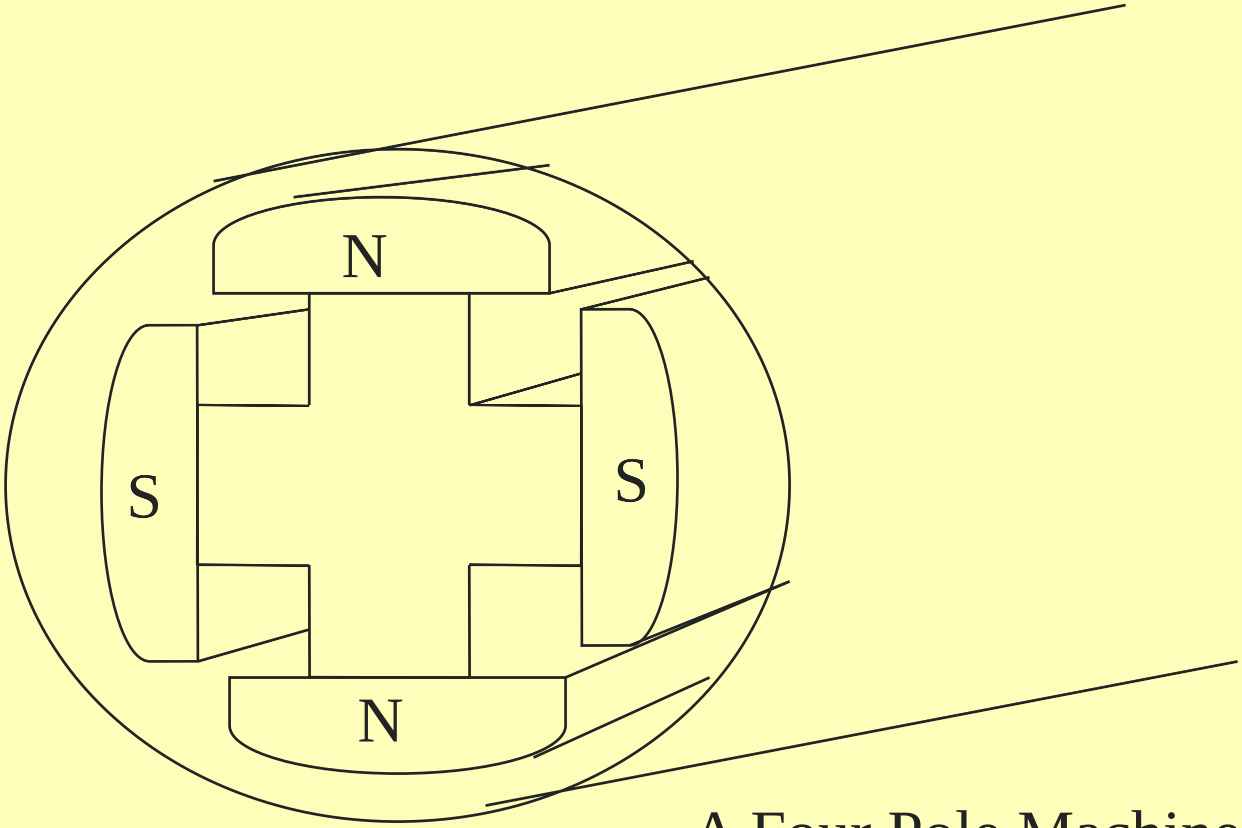
Four-pole
Salient pole construction



Salient Pole Construction

Smooth rotor Construction
Also known as round rotor or cylindrical rotor construction

Synchronous Machine Structure



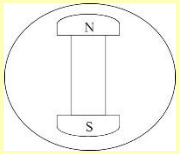
A Four Pole Machine (p=4)
(Salient Pole Structure)

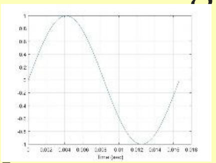
Generation Operation

- The generator is classified as a *synchronous machine* because it is only at synchronous speed that it can develop electromagnetic torque
- p = number of poles on the rotor of the machine
- $\omega_e = 2\pi f$ = electrical speed (frequency) in rad/sec
- $\omega_m = \dfrac{2}{p}(\omega_e)$ = mechanical speed in rad/sec

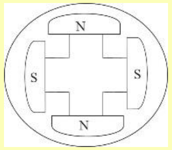
$$\omega_e = \frac{p}{2}(\omega_m)$$

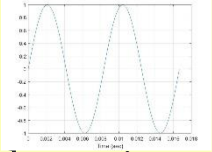
- p=2: 1 mechanical rotation gives 1 electrical rotation.





- p=4: 1 mechanical rotation gives 2 electrical rotations.





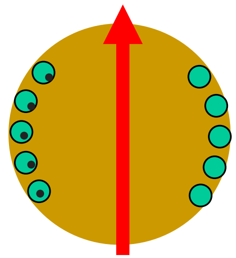
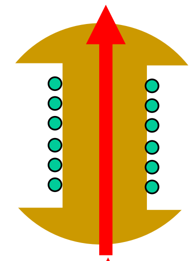
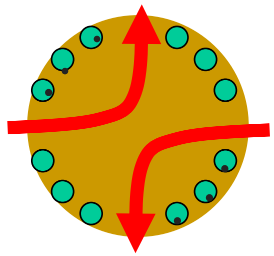
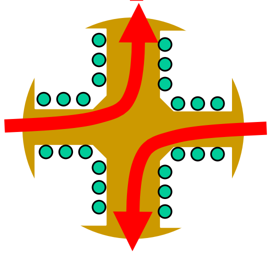
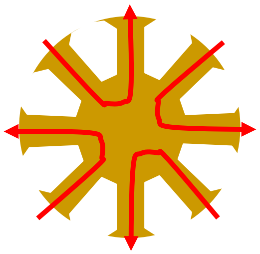
- p=6: 1 mechanical rotation gives 3 electrical rotations.
- …

- $N_s = (\omega_m)\dfrac{rad}{\sec} \times \dfrac{1rev}{2\pi rad} \times \dfrac{60\sec}{\min} = (\omega_m)\dfrac{30}{\pi} = \left(\dfrac{2}{p}\omega_e\right)\dfrac{30}{\pi} = \left(\dfrac{2}{p}2\pi f\right)\dfrac{30}{\pi} = \dfrac{120}{p}f$ = machine speed in RPM

For 60 Hz operation (f=60)

- Synchronous generator

Rotor construction

	Round Rotor		Salient Pole
Two pole		N_s = 3600 rpm	
Four Pole		N_s = 1800 rpm	
Eight Pole		N_s = 900 rpm	

For 60 Hz operation (f=60)

No. of Poles (p)		Synchronous speed (Ns)
2	Few poles ➔ High speed	3600
4		1800
6		1200
8		900
10		720
12		600
14		514
16		450
18		400
20	Many poles ➔ Slow speed	360

$$N_s = \frac{120}{p} f$$

<u>Fact</u>: hydro turbines are slow speed,
steam turbines are high speed.

Do hydro-turbine generators have few poles or many?

Many, because they rotate slowly.

Do steam-turbine generators have few poles or many?

Few, because they rotate very fast.

<u>Fact</u>: salient pole incurs significant
mechanical stress at high speed.

Do steam-turbine generators have salient poles or smooth?

Smooth, because salient pole creates too much mechanical stress at high speed.

<u>Fact:</u> Salient pole rotors are cheaper to build than smooth.

Do hydro-turbine generators have salient poles or smooth?

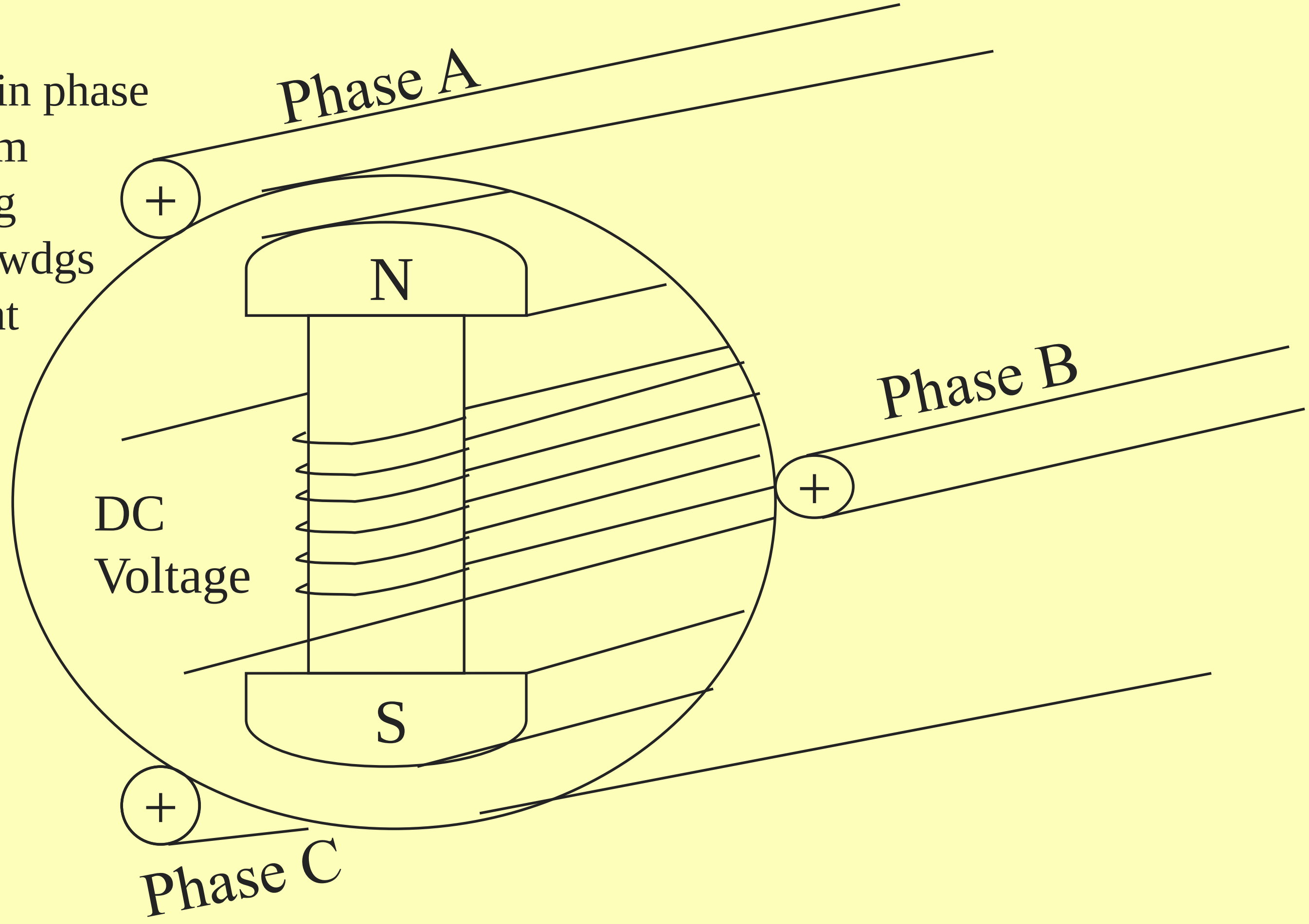
Salient, because it is cheaper.

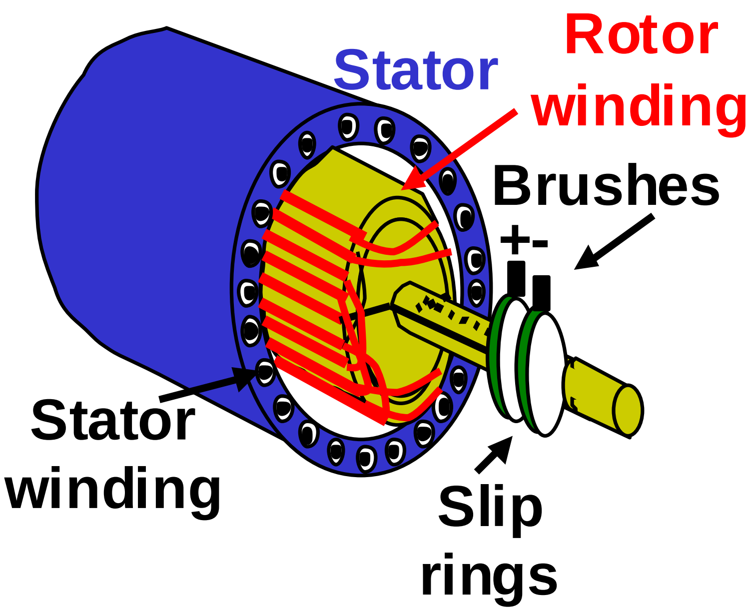
Generation Operation

- A magnetic field is provided by the DC-current carrying *field winding* which induces the desired AC voltage in the *armature winding*
- Field winding is always located on the rotor where it is connected to an external DC source via slip rings and brushes or to a revolving DC source via a special *brushless* configuration
- Armature winding is located on the stator where there is no rotation
- The armature consists of three windings all of which are wound on the stator, physically displaced from each other by 120 degrees

Synchronous Machine Structure

- voltage induced in phase wdgs by flux from rotating field wdg
- current in phase wdgs produces flux that also induces voltage in phase wdgs.




Rotor
winding
Stator
Brushes
+-
Stator
winding
Slip
rings

Rotating magnetic field

- There are 3 stator windings, separated in space by 120°, with each carrying AC, separated in time by $\omega_0 t=120°$.
- Each of these three currents creates a magnetic field in the air gap of the machine. Let's look at only the a-phase:

temporal variation

spatial variation

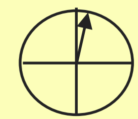
$$B_a(\alpha,t) = B'_{\max}\cos(\omega_0 t + \angle I_a)\cos\alpha$$

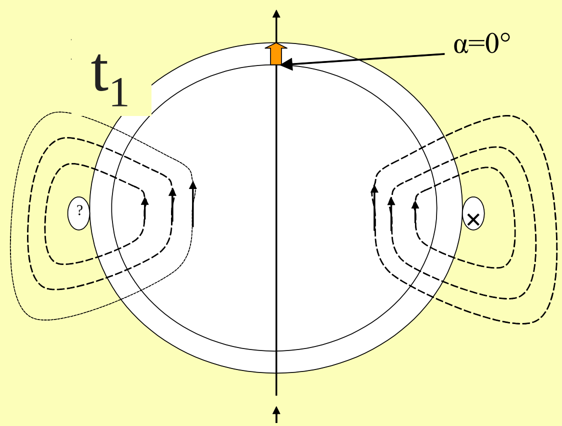
- B_a, in webers/m^2, is flux density from the a-phase current (We could also use H_a, which is magnetic field strength in amp-turns/m or Oersteds, related to B_a by $B_a=\mu H_a$)
- α is the spatial angle along the air gap
- For any time t, α=0,180 are spatial maxima (absolute value of flux is maximum at these points)

Rotating magnetic field – temporal characterization

$$B_a(\alpha,t) = B'_{\max}\cos\left(\omega_0 t + \angle I_a\right)\cos\alpha$$

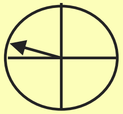
Let's fix $\alpha=0$ and see what happens at $\omega_0 t_1$, such that $\omega_0 t_1 + \angle I_a$ is just less than $\pi/2$





Rotating magnetic field – spatial characterization

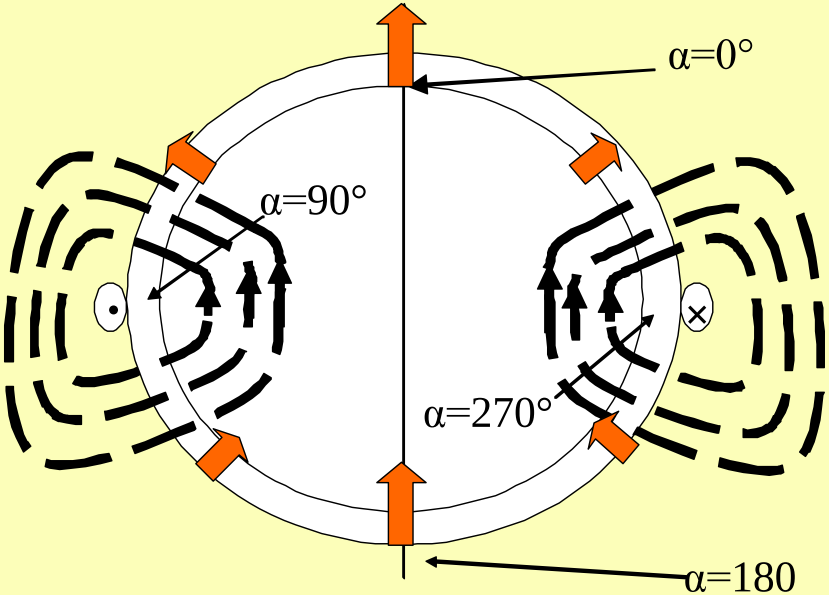
Now let's fix $t=t_4$ ($\omega_0 t_4 = \omega_0 t_1 + 270$):



$$B_a(\alpha,t) = B'_{\max}\cos\left(\omega_0 t_4 + \angle I_a\right)\cos\alpha$$

and see what happens at

α=0, α=45, α=90, α=135, α=180, α=225, α=270, α=315.



Radially outward is positive; radially inward is negative.

One observes that the magnetic field is sinusoidally distributed around the airgap.

Rotating magnetic field

- Now consider the magnetic field from all windings simultaneously.

$$B_a(\alpha,t) = B'_{\max}\cos(\omega_0 t + \angle I_a)\cos\alpha \qquad (1)$$

$$B_b(\alpha,t) = B'_{\max}\cos\left(\omega_0 t + \angle I_a - \frac{2\pi}{3}\right)\cos\left(\alpha - \frac{2\pi}{3}\right) \qquad (2)$$

$$B_c(\alpha,t) = B'_{\max}\cos\left(\omega_0 t + \angle I_a + \frac{2\pi}{3}\right)\cos\left(\alpha + \frac{2\pi}{3}\right) \qquad (3)$$

- Add them up, then perform trig manipulation to obtain:

$$B_{abc}(\alpha,t) = \frac{3B'_{\max}}{2}\cos(\omega_0 t + \angle I_a - \alpha) \qquad (4)$$

Notice that locations of the spatial maxima in (1), (2), and (3) do not vary w/time (i.e., although the value of the spatial maxima changes, their locations do not), indicated by:

$$B_a(\alpha,t) = B'_{\max}\cos(\omega_0 t + \angle I_a)\cos\alpha \Rightarrow \alpha = \{0,\pi\}$$

$$B_b(\alpha,t) = B'_{\max}\cos\left(\omega_0 t + \angle I_a - \frac{2\pi}{3}\right)\cos\left(\alpha - \frac{2\pi}{3}\right) \Rightarrow \alpha - \frac{2\pi}{3} = \{0,\pi\} \Rightarrow \alpha = \left\{\frac{2\pi}{3}, \frac{5\pi}{3}\right\}$$

$$B_c(\alpha,t) = B'_{\max}\cos\left(\omega_0 t + \angle I_a + \frac{2\pi}{3}\right)\cos\left(\alpha + \frac{2\pi}{3}\right) \Rightarrow \alpha + \frac{2\pi}{3} = \{0,\pi\} \Rightarrow \alpha = \left\{-\frac{2\pi}{3}, \frac{\pi}{3}\right\}$$

The location around the air gap (specified by α), at any given time, for which the field is max, **IS NOT** a function of t.

But the spatial maxima of (4) has spatial location which does vary w/time, This is a characteristic of a rotating magnetic field.

$$B_{abc}(\alpha,t) = \frac{3B'_{\max}}{2}\cos(\omega_0 t + \angle I_a - \alpha)$$

$$\Rightarrow \omega_0 t + \angle I_a - \alpha = \{0,\pi\} \Rightarrow \alpha = \{\omega_0 t + \angle I_a, \omega_0 t + \angle I_a - \pi\}$$

The location around the air gap (specified by α), at any given time, for which the field is max, **IS** a function of t.

Rotating magnetic field

One observes this using the following:

http://educypedia.karadimov.info/library/rotating_field.swf

The shape of the individual winding fields B_a, B_b, B_c, throughout the air gap are spatially fixed, but their amplitudes pulsate up and down.

In contrast, the amplitude of the composite is fixed in time, but it rotates in space. What you see in the visualization are just the variation of the maximum flux point.

The plot on the middle right, is misleading. It should show a single period of a sinusoidal waveform rather than a square wave.

Equivalent circuit model for synchronous machine

- Each stator winding a,b,c will have a voltage induced in it proportional to the speed of rotation of the rotor, the number of turns of the winding N, and the flux produced by the field winding ϕ.
- Since the speed of rotation of the rotor must equal the synchronous speed, and since the synchronous speed is set by the grid frequency f according to $N_S=120f/p$ where p is number of poles, the induced rms voltage will be:

$$E_f = 4.44 K_w f N \phi$$

Here, K_w, called the winding factor, is a reduction factor between 0.85 to 0.95 that accounts for the distribution of the armature coils.

We call E_f the excitation voltage because it is produced by the field which is also known as the machine's excitation. It is also sometimes called the "internal voltage" because it is the voltage measured when the machine is unloaded (open-circuited).

Equivalent circuit model for synchronous machine

- The line-to-neutral rms terminal voltage of the a-phase winding is given by V_t. We will assume this is the reference, so that:

$$\bar{V}_t = V_t \angle 0°$$

- The excitation voltage is also a phasor, with magnitude and angle given by:

$$\bar{E}_f = E_f \angle \delta$$

- When the machine is unloaded, the terminal voltage equals the excitation voltage, i.e.,

$$\bar{V}_t = \bar{E}_f \Rightarrow E_f = V_t, \qquad \delta = 0°$$

Equivalent circuit model for synchronous machine

- However, when the machine is loaded, i.e., when there is a current flowing through the a-phase winding, then the terminal voltage will differ from the excitation voltage due to voltage drops caused by:

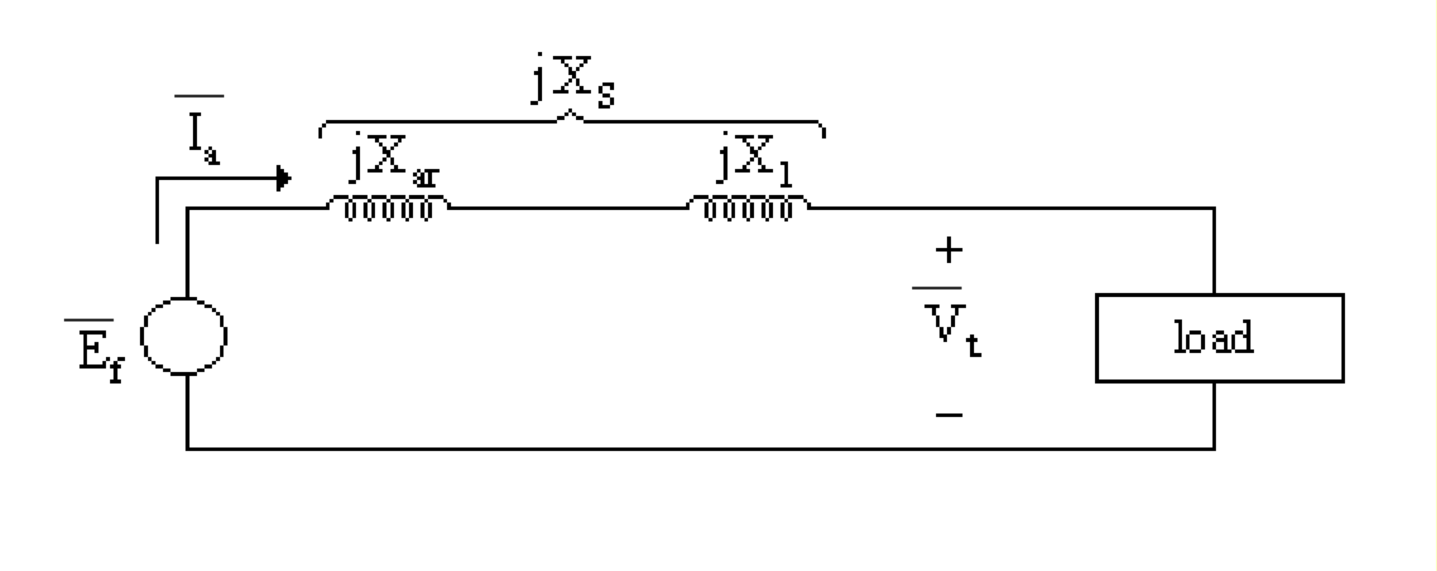
    1. Resistance of the phase winding; we will ignore this.
    2. Armature reaction: This is the interaction of the flux from the (rotating) field winding and the flux from the a-phase winding current. It tends to decrease the terminal voltage. It is represented by a reactance X_{ar}.
    3. Flux leakage: There is some flux developed by the field winding which does not link with the armature winding. This leakage is captured by a reactance X_l.

$$\bar{V}_t = \bar{E}_f - j\left(X_{ar} + X_l\right)\bar{I}_a$$

- We define the synchronous reactance as $X_s = X_{ar} + X_l$, so that

$$\bar{V}_t = \bar{E}_f - jX_s\bar{I}_a$$

Equivalent circuit model for synchronous machine

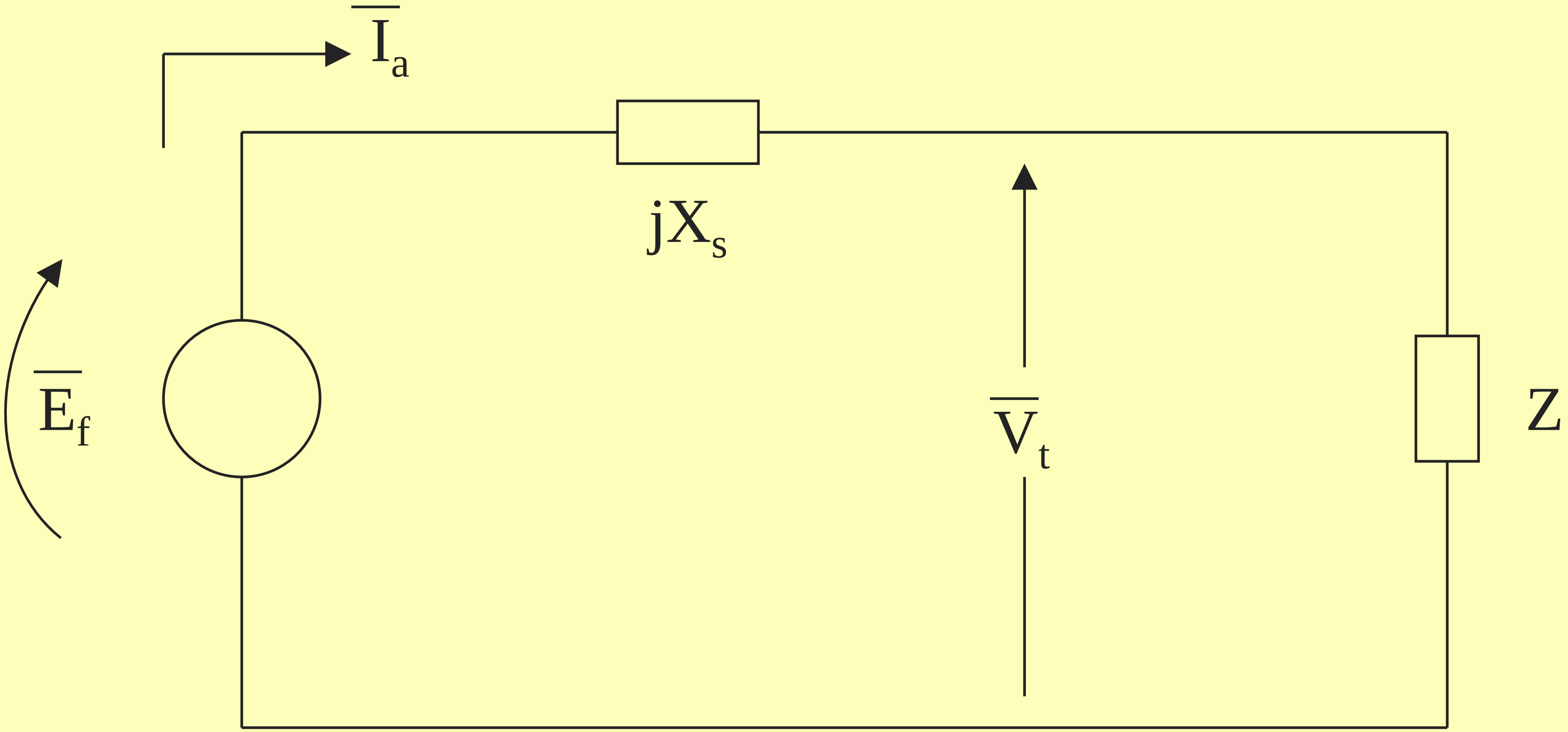


$$\bar{V}_t = \bar{E}_f - j\left(X_{ar} + X_l\right)\bar{I}_a$$

$$\bar{V}_t = \bar{E}_f - jX_s\bar{I}_a$$

All voltages and currents on the above diagram are phasors.

Equivalent circuit model for synchronous machine



All voltages and currents on the above diagram are phasors.

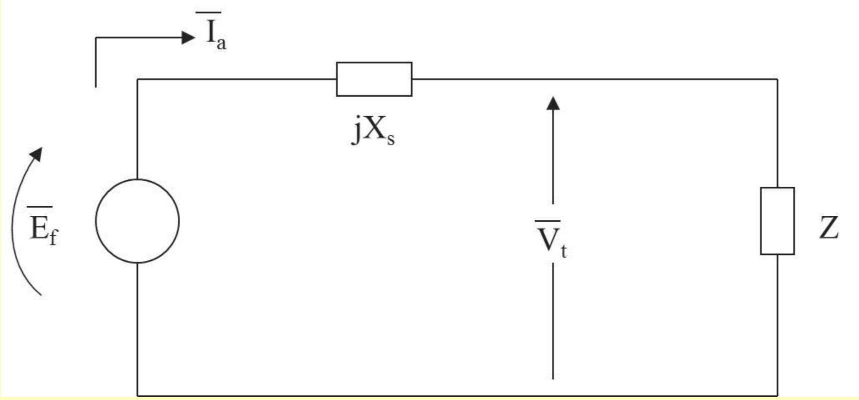
Equivalent circuit model for synchronous machine

You can perform per-phase equivalent analysis or you can perform per-unit analysis.

In per-phase, $\overline{E}_f$ and $\overline{V}_t$ are both line to neutral voltages, $\overline{I}_a$ is the line current, and Z is the impedance of the equivalent Y-connected load.

In per-unit, $\overline{E}_f$ and $\overline{V}_t$ are per-unit voltages, $\overline{I}_a$ is the per unit current, and Z is the per unit load impedance.

Leading and Lagging Generator Operation



Let $Z = R + jX = |Z|\angle\theta, \qquad \bar{V}_t = V_t\angle\theta_V$

From the equivalent circuit,

$$\bar{I}_a = \frac{\bar{V}_t}{Z} = \frac{V_t\angle\theta_V}{|Z|\angle\theta} = \frac{V_t}{|Z|}\angle(\theta_V - \theta)$$

So here we see that $\theta_i = \theta_V - \theta \quad \Rightarrow \quad \theta = \theta_V - \theta_i$

Leading and Lagging Generator Operation

Assign $\overline{\mathrm{V}}_{\mathrm{t}}$ as the reference: $\theta_V = 0$

Then,

$$\bar{I}_a = \frac{\bar{V}_t}{Z} = \frac{V_t}{|Z|}\angle(\theta_V - \theta) = \frac{V_t}{|Z|}\angle(-\theta)$$

So here we see that $\theta_i = -\theta$

This gives an easy way to remember the relation between load, sign of current angle, leading/lagging, and sign of power angle.

Leading and Lagging Generator Operation

Circle the correct answer in each of the six rows for each column

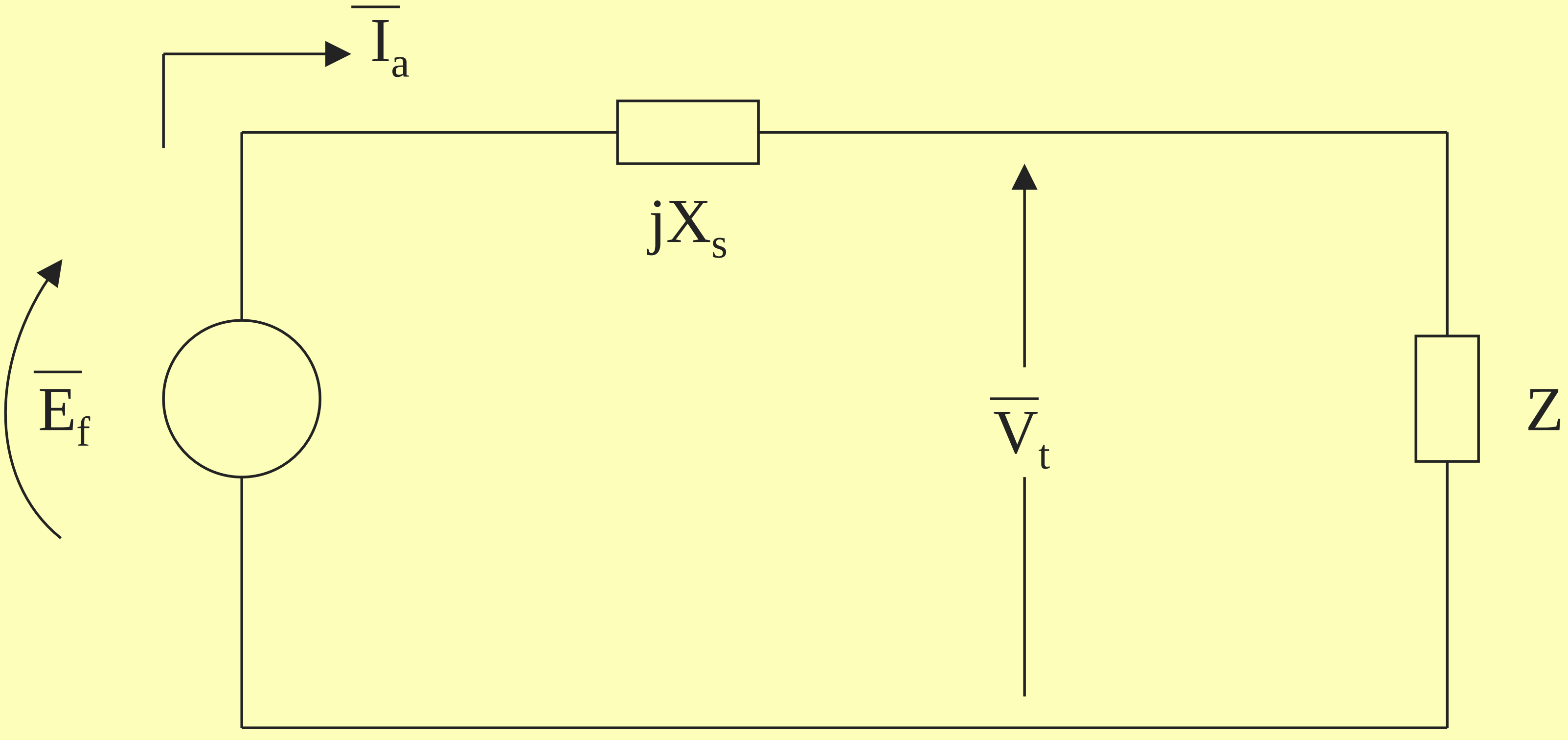
Inductive load	**Capacitive load**
load absorbs/supplies Q	load absorbs/supplies Q
gen absorbs/supplies Q	gen supplies/absorbs Q
$X > ? < 0$	$X > ? < 0$
$\theta > ? < 0$	$\theta > ? < 0$
$\theta_i > ? < 0$	$\theta_i > ? < 0$
current is leading/lagging	current is leading/lagging

Leading and Lagging Generator Operation

Answers

Inductive load	**Capacitive load**
load **absorbs**/supplies Q	load absorbs/**supplies** Q
gen absorbs/**supplies** Q	gen **absorbs**/supplies Q
$X \mathbf{>} ? < 0$	$X > ? \mathbf{<} 0$
$\theta \mathbf{>} ? < 0$	$\theta > ? \mathbf{<} 0$
$\theta_i > ? \mathbf{<} 0$	$\theta_i \mathbf{>} ? < 0$
current is leading/**lagging**	current is **leading**/lagging

Equivalent circuit model for synchronous machine



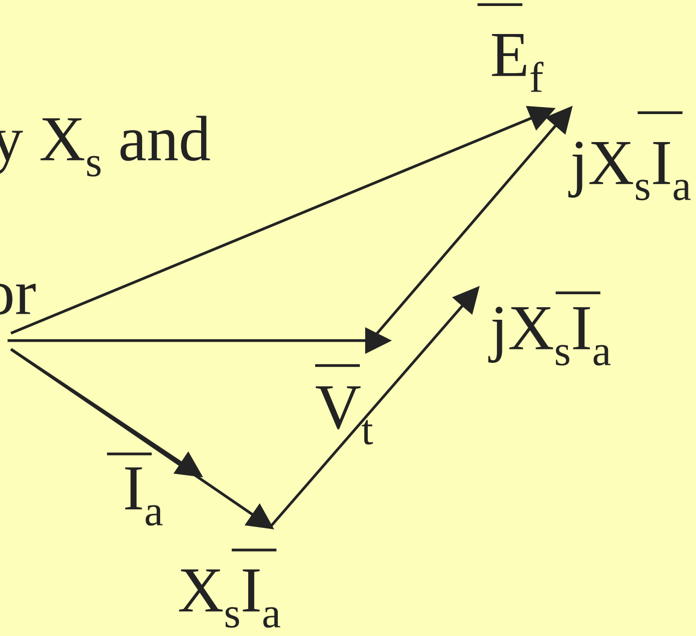
From KVL: $\bar{E}_f = \bar{V}_t + jX_s\bar{I}_a$

Phasor Diagram for Equivalent Circuit

$$\bar{E}_f = \bar{V}_t + jX_s\bar{I}_a$$

This equation gives directions for constructing the phasor diagram.

1. Draw $\bar{V}_t$ phasor
2. Draw $\bar{I}_a$ phasor
3. Scale $\bar{I}_a$ phasor magnitude by X_s and rotate it by 90 degrees.
4. Add scaled and rotated vector to $\bar{V}_t$



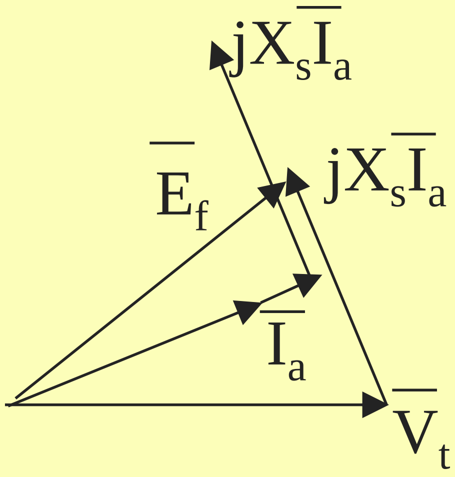
Try it for lagging case.

Phasor Diagram for Equivalent Circuit

$$\bar{E}_f = \bar{V}_t + jX_s\bar{I}_a$$

This equation gives directions for constructing the phasor diagram.

1. Draw $\bar{V}t$ phasor
2. Draw $\bar{I}a$ phasor
3. Scale $\bar{I}a$ phasor magnitude by Xs and rotate it by 90 degrees.
4. Add scaled and rotated vector to $\bar{V}t$



You do it for leading case.

Question: What does the condition (leading or lagging) imply about the magnitude of the internal voltage $\bar{E}_f$.

Phasor Diagram for Equivalent Circuit

$$\bar{E}_f = \bar{V}_t + jX_s\bar{I}_a$$

Let's define the angle that E_f makes with Vt as δ

$$\bar{E}_f = E_f \angle \delta$$

For generator operation (power supplied by machine), this angle is always positive.

For motor operation, this angle is negative.