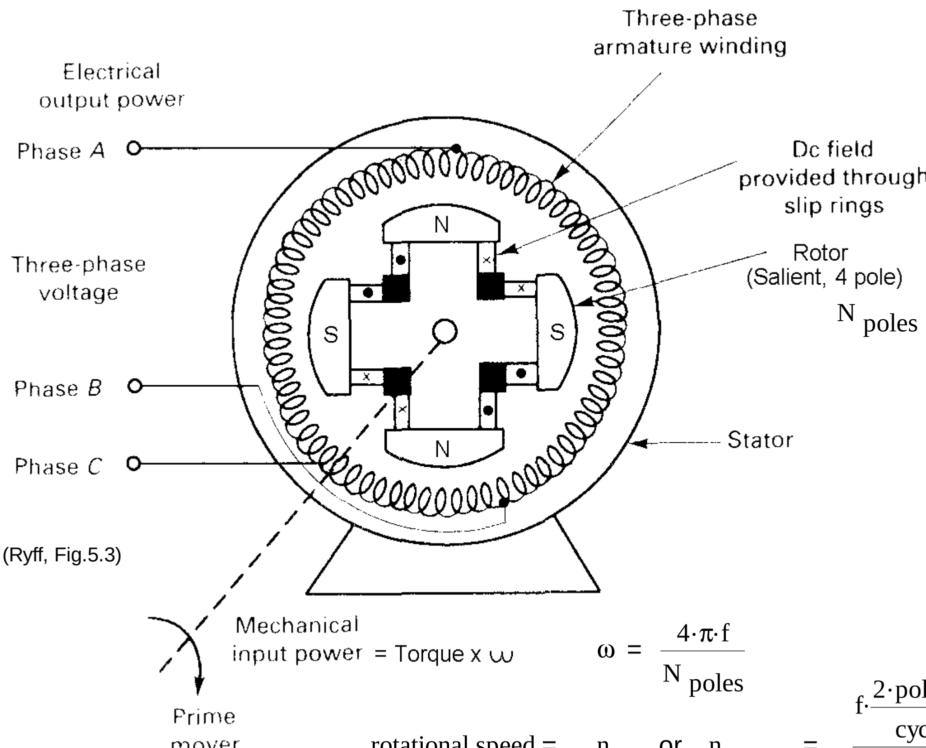


(Ryff, Fig.5.3)

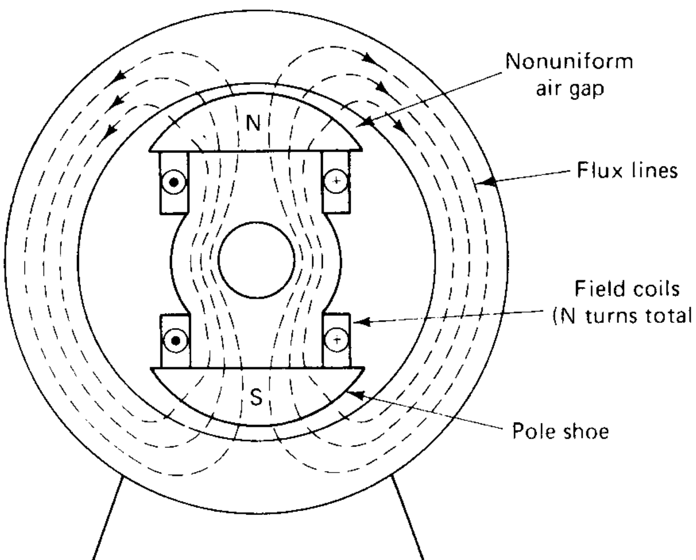
Sometimes the field current is generated and rectified right on the rotor.

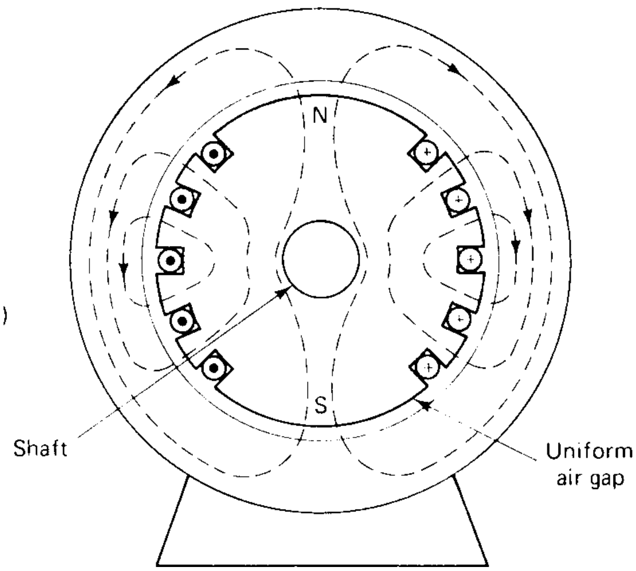
$N_{poles} := 4$

$\omega = \dfrac{4 \cdot \pi \cdot f}{N_{poles}}$

for 60Hz systems

rotational speed = n_m or n_{sync} $= \dfrac{f \cdot \dfrac{2 \cdot poles}{cyc} \cdot \dfrac{60 \cdot sec}{min}}{N_{poles}} = \dfrac{7200 \cdot rpm}{poles}$





(Ryff, Fig.5.6)

2 Salient poles

Typically low-speed, water turbine driven, short and large diameter
(typ diameter is 1.5xlength)

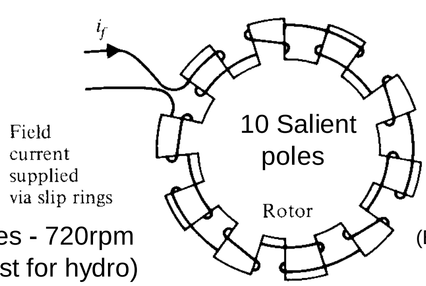
Say: 40-poles - 180rpm

2 Non-salient poles, Cylindrical rotor

Typically high-speed, steam turbine driven, long and small diameter
(typ length is 10xdiameter)

2-poles - 3600rpm

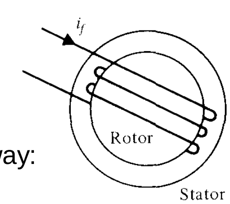
4-poles - 1800rpm



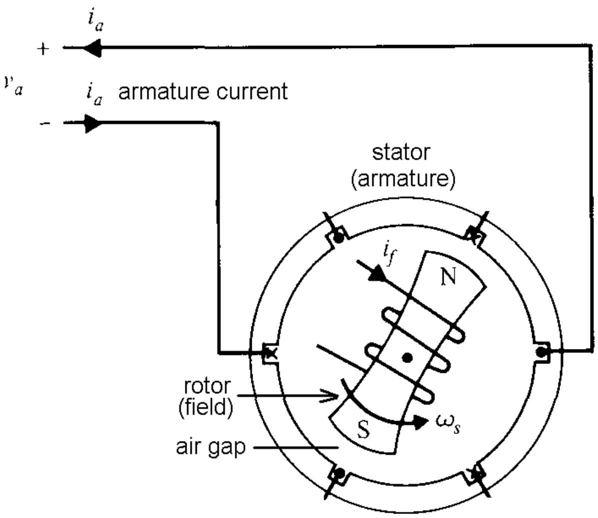
10-poles - 720rpm
(fast for hydro)

(Brown, Fig.4.3)

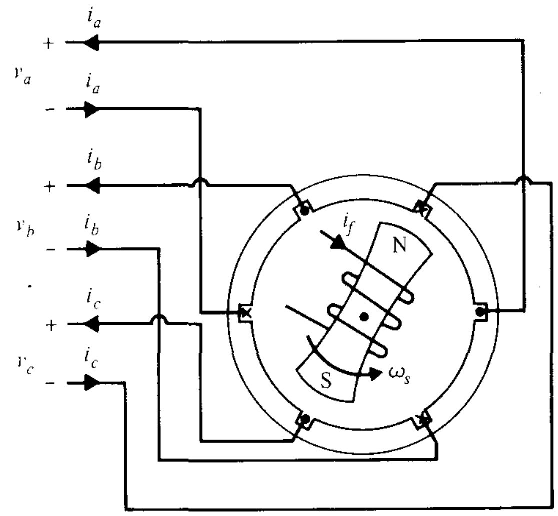
Sometimes shown this way:



(Brown, Fig.4.2)



Stator (armature) winding

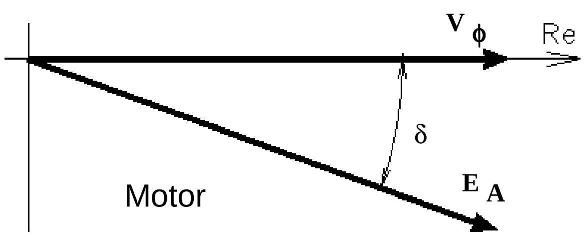


2-pole, 3-phase synchronous machine

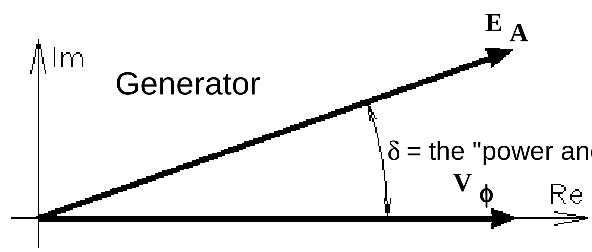
(Brown, Fig.4.1)

Electrical analysis on a per-phase basis

When spinning, the induced armature voltages ($\mathbf{E_A}$ for our phase) depends on the field current, I_f .
I_f cause the field flux (call **excitation**).



When operated as a motor, the induced armature voltage ($\mathbf{E_A}$) lags the terminal voltage, $\mathbf{V_\phi}$.

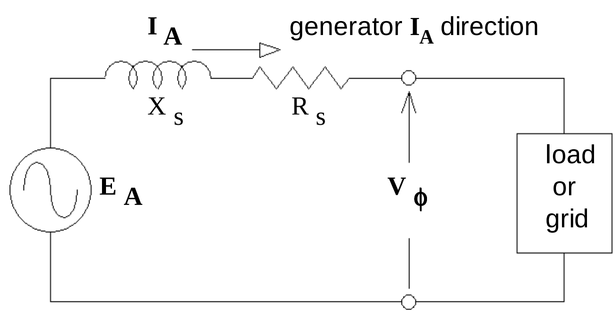


When operated as a generator, the induced armature voltage ($\mathbf{E_A}$) leads the terminal voltage, $\mathbf{V_\phi}$.

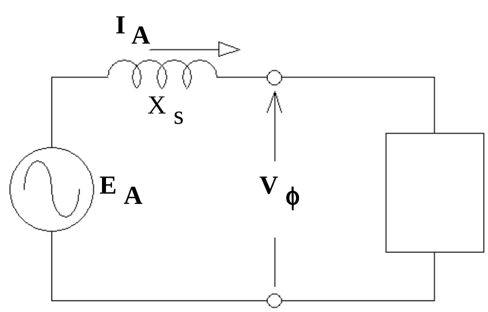
The electrical model of an armature winding:

$\mathbf{X_s}$ is the armature inductance
(armature windings and leakage)
(magnetization)

$\mathbf{R_A}$ is the armature winding resistance

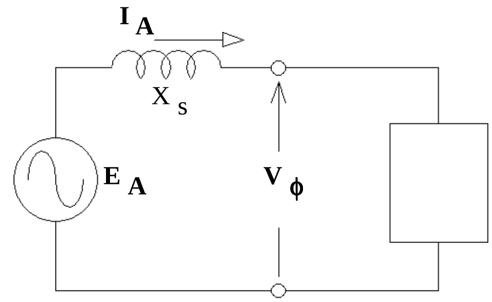


This is almost always simplified to this:

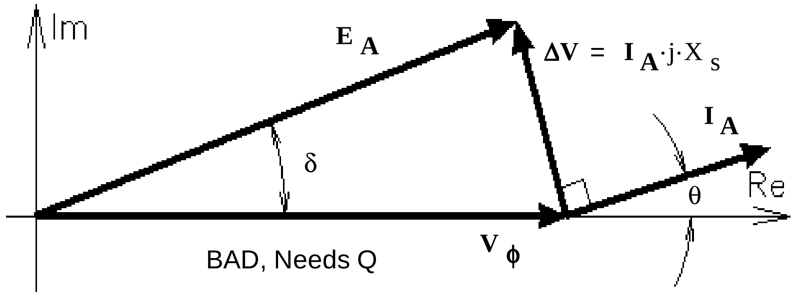


Per-phase Synchronous Generator Model

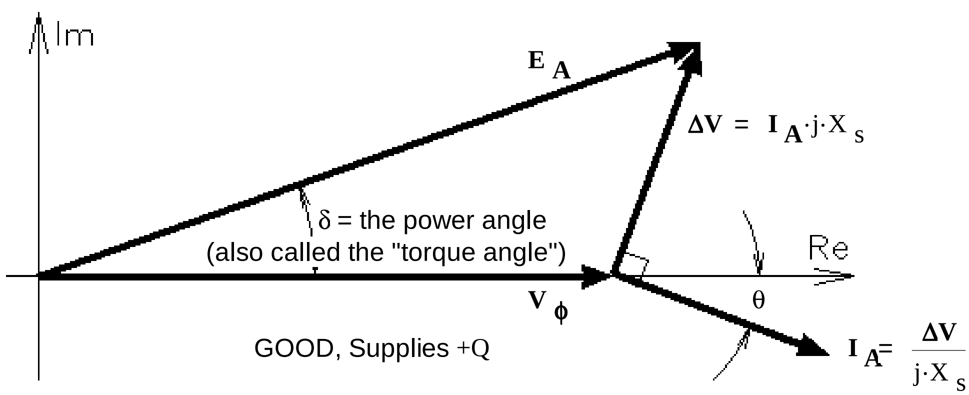
Synchronous Generators



$E_A = I_A \cdot j \cdot X_s + V_\phi$



The **under-excited** condition, the current leads the terminal voltage, V_ϕ. The generator supplies -Q (-VARs), that is, it absorbs +Q (+VARs), just like an inductive load. Usually not desirable.



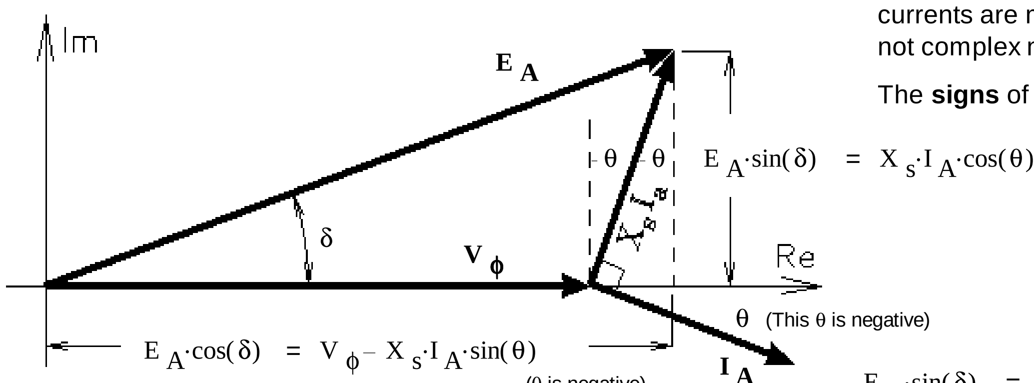
Note: if δ reaches 90°, the generator will lose synchronization.

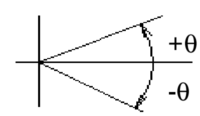
The **over-excited** condition, the current lags the terminal voltage, V_ϕ. The generator supplies +Q (+VARs), that is, it absorbs -Q (-VARs), just like an capacitive load. Usually desirable.

Important relations

Note: Voltages and currents are magnitudes, not complex numbers

The **signs** of the angles are **important!**





$$E_A \cdot \sin(\delta) = X_s \cdot I_A \cdot \cos(\theta)$$ <----

$$-I_A \cdot \sin(\theta) = \frac{E_A \cdot \cos(\delta) - V_\phi}{X_s} \qquad I_A \cdot \cos(\theta) = \frac{E_A \cdot \sin(\delta)}{X_s}$$

$$Q_{1\phi} = -V_\phi \cdot I_A \cdot \sin(\theta) \qquad P_{1\phi} = V_\phi \cdot I_A \cdot \cos(\theta)$$

----> $$Q_{1\phi} = \frac{V_\phi \cdot E_A \cdot \cos(\delta) - V_\phi^2}{X_s} \qquad P_{1\phi} = \frac{V_\phi \cdot E_A \cdot \sin(\delta)}{X_s}$$ <----

Pullout power

Pullout power is the maximum power a generator can produce for a given excitation, at $\delta := 90 \cdot deg$

$$P_{po} = \frac{E_A \cdot V_\phi}{X_s} \cdot \sin(90 \cdot deg) = \frac{E_A \cdot V_\phi}{X_s}$$

To Bring a Synchronous Generator "On Line"

1. Bring speed to the correct rpm so that the generator frequency matches the line frequency.
2. Adjust the field current, I_f so that the generator voltage matches the line voltage.
3. Readjust speed if necessary, check that the phases are in the correct sequence if necessary.
4. Wait until the phases align (0 volts difference between generator terminal and the line phase). Connect to the line at just the right moment.
5. Increase input torque to produce real electrical power and and field current to produce reactive power.

Most (~99%) of the world's electrical energy is produced by 3-phase synchronous generators.

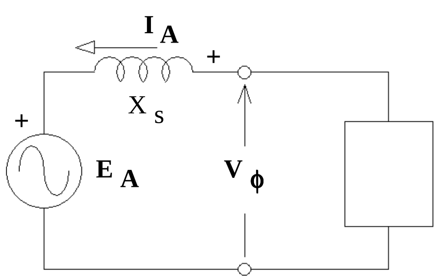
Mechanical speed, torque, and power

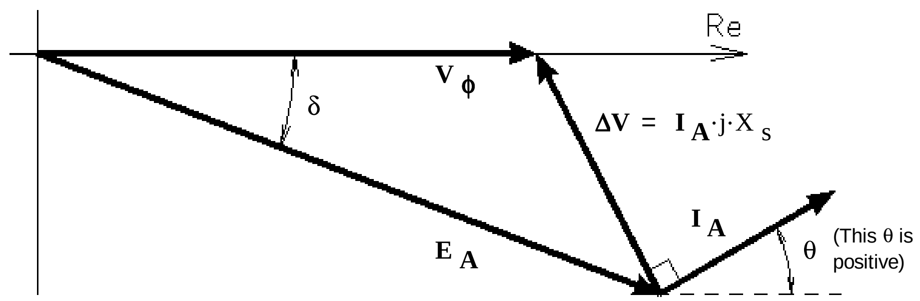
Shaft speed in rad/sec $\omega_{mech} = \frac{4 \cdot \pi \cdot f}{N_{poles}}$ neglecting friction: $T_{mech} \cdot \omega_{mech} = P_{3\phi}$

T_{mech} = mechanical torque

$$\text{rotational speed} = \frac{f \cdot \frac{2 \cdot poles}{cyc} \cdot \frac{60 \cdot sec}{min}}{N_{poles}} = \frac{7200 \cdot rpm}{poles}$$ for 60Hz systems

Synchronous Motors

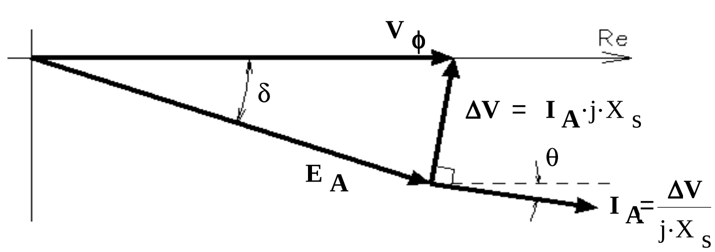




Over-excited condition, GOOD, supplies +Q (+VARs).

(θ is measure in opposite direction to a regular load)

$$Q = V_\phi \cdot I_A \cdot \sin(-\theta)$$



Under-excited condition, BAD, absorbs +Q (+VARs).

Important relations

$$E_A \cdot \sin(|\delta|) = X_s \cdot I_A \cdot \cos(\theta)$$

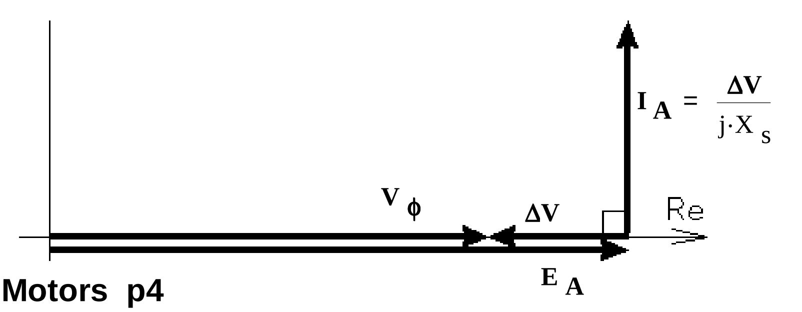
$$P_{1\phi} = \frac{E_A \cdot V_\phi}{X_s} \cdot \sin(|\delta|)$$

$$Q_{1\phi} = \frac{V_\phi^2 - E_A \cdot V_\phi \cdot \cos(\delta)}{X_s}$$

(Bigger E_A makes Q negative (good))

Synchronous Condenser (Capacitor)

A special case of the over excited motor with no mechanical load (and neglecting friction)



ECE 3600 Synchronous Generators & Motors p5

Core losses

In steady-state synchronous operation, the rotor of a synchronous machine does not experience a changing magnetic flux so there are no core losses in the rotor and it can be made of solid ferromagnetic material. The stator, on the other hand, *does* experience a changing magnetic flux (at 60 Hz) so there are both hysteresis and eddy-current core losses in the stator. The stator is constructed of laminated, silconized material to minimize the eddy currents.

Stator windings in practice

The nonlinearity of the stator core also causes the stator current to be nonsinusioidal, including a significant third-harmonic (just like in a transformer). The reduce the harmonics, the phase windings are designed to overlap each other a little and don't always span exactly 180^{o} of flux.

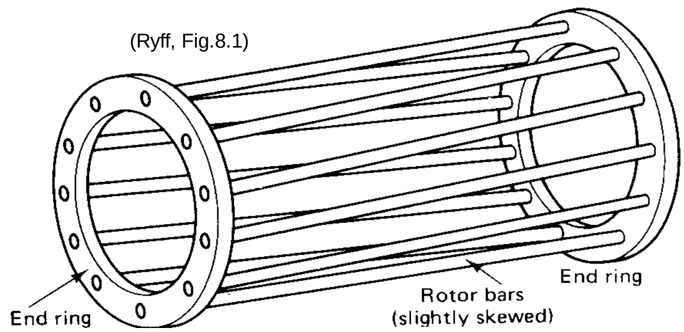
Effect on the network (grid)

Our analysis regularly assumes that the generator feeds an "infinite" network bus. Then we can assume the network voltage, or the terminal voltage, is constant in magnitude, frequency and phase (The slack-bus idea). In reality, large generators *do* affect the network (the larger the generator, the larger the effect). Increasing the prime-mover torque will raise the network voltage (especially in the local area) and slightly increase the entire network frequency. Matching the generation of reactive power to the local needs will help to optimize the network power flow.

Damper Bars

The rotor of an induction motor includes a number of thick conductors called "rotor bars". Current is induced in these bars because the rotor normally turns at speed which is slower than the synchronous speed (the speed of the rotating flux caused by the stator windings). The interaction between the induced current and the rotating flux provides the motor torque.

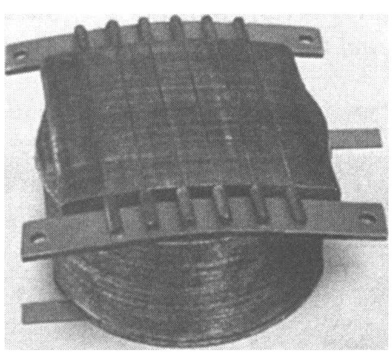
(Ryff, Fig.8.1)



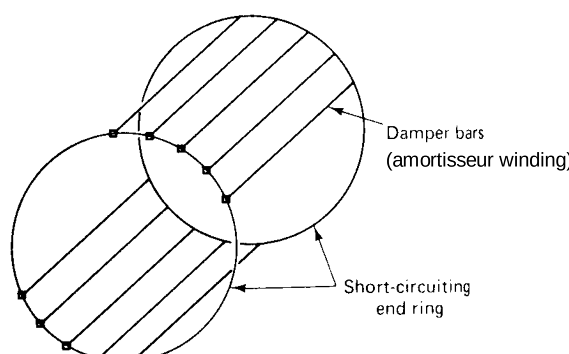
Synchronous machines usually have very similar bars in their rotors. In steady-state synchronous operation, they have no affect. The purpose of these bars is to resist, or dampen, transients. Currents will be induced in these windings when the stator current magnitudes change or when the input rotational shaft speed changes. By Lenz's law, those currents will be induced in a direction to oppose the change that caused them. In solid iron rotors, the eddy currents have the same effect. Without damping, the shaft speed can oscillate.

See textbook section 5.11, p.243 for more details.

See also textbook fig 5.41, p.245



(Ryff, Fig.10.3)



(Ryff, Fig.10.3)

Note: These notes and Chapter 5 of our textbook assumes that the DC supply of the field current is robust enough to withstand high voltage transients. It also assumes the source resistance and the field winding resistance are so small that the field winding itself can perform the transient damping function. It is more reasonable to assume that the synchronous machine is constructed with damper bars, but the results of the different assumptions is about the same.

Transient Conditions

The armature currents normally create a rotating flux in sync with the rotor motion and the flux through the rotor is constant. These steady-state currents see large synchronous reactances (X_s) due in large part to the low reluctance of the rotor. X_s can be 1 per-unit based on the machine's bases. When armature current magnitudes change, the armature flux has to change as well. A rotor with damping bars (or other low-resistance windings or eddy current paths), will strongly resist any changes in flux through the rotor, so much of the changing flux will go around the rotor, taking a much higher reluctance path. A higher reluctance path results in a lower inductance and a lower reactance.

X_s = steady-state synchronous reactance, nearly all flux goes through rotor

X''_s = sub transient synchronous reactance, no additional flux goes through rotor
first few cycles only

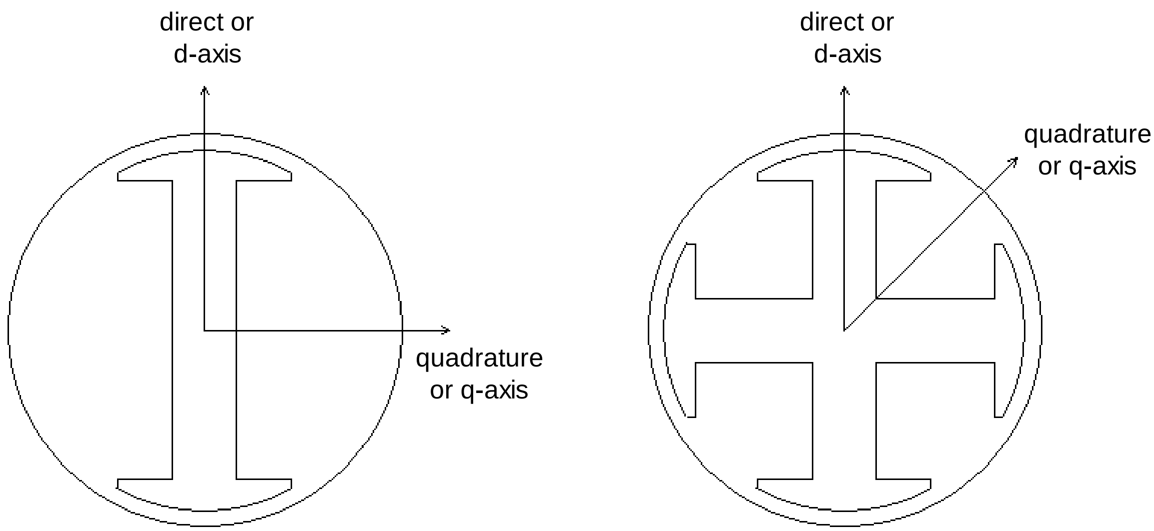
$= \frac{X_s}{7}$ to $\frac{X_s}{7}$

X'_s = transient synchronous reactance, some additional flux goes through rotor
after first few cycles until new steady-state.

$\simeq 2 \cdot X''_s$

Variations of the magnetizing reactance in salient pole machines

A large part of the synchronous reactance (X_s) is the magnetizing reactance (X_m) and arises from the rotating magnetic flux produced by the armature current. Our analysis up to this point, assumes that the rotating flux depends proportionally on the current magnitude alone. That, in turn, assumes that the magnetic reluctance is the same for all angles of the rotor. This is a bad assumption for a salient-pole rotor. The reluctance along the "direct" or "d"-axis of the rotor is less than the reluctance along the "quadrature" or "q"-axis.



To fully analyze the salient-pole machine, the armature magnetizing reactance (X_m) needs to be broken up into X_{md} and X_{mq}, corresponding to the direct and quadrature axes. The armature voltages and currents are then also broken up into v_d and v_q, and i_d and i_q, respectively. We will not cover this in this class.