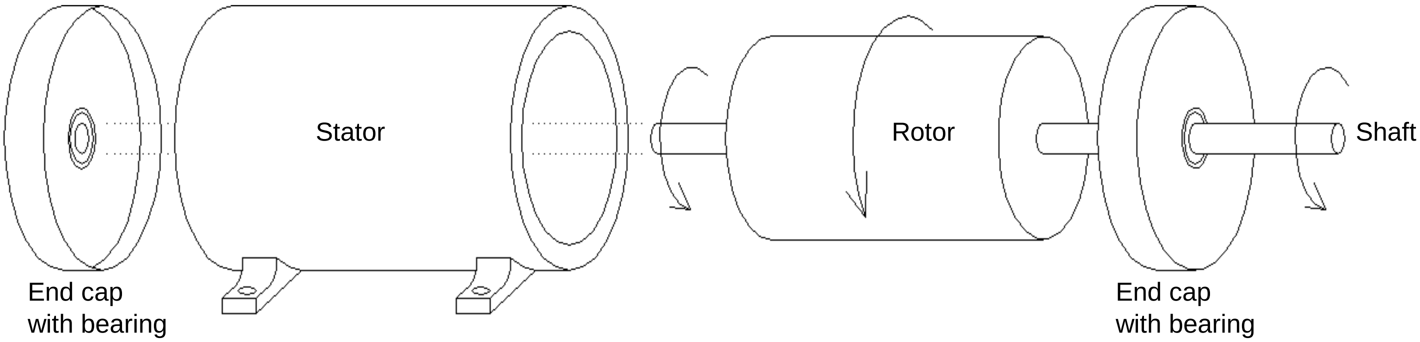
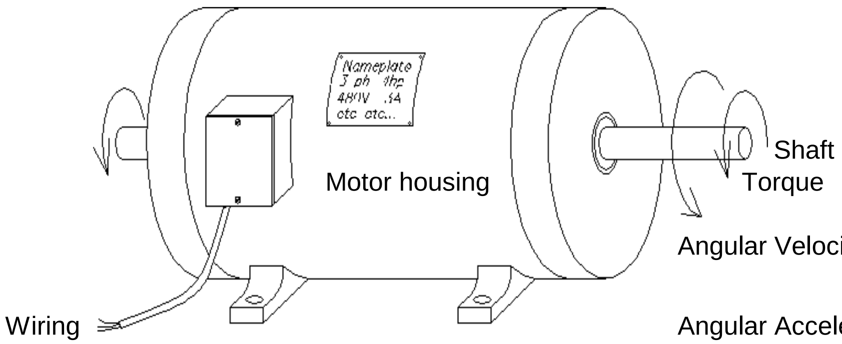
ECE 3600 Generator & Motor Basics

Simplified Drawing of a Motor or Generator (Exploded view)





Assembled Motor or Generator

Torque T or τ , $N \cdot m$

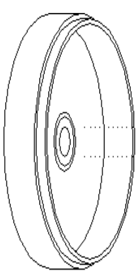
Angular Velocity ω , $\frac{rad}{sec}$ or n , $\frac{rev}{min}$ or rpm

Angular Acceleration α , $\frac{rad}{sec^2}$

Mechanical Power P_{shaft} or P_{out} $= \tau \cdot \omega$ W or hp (horse power)

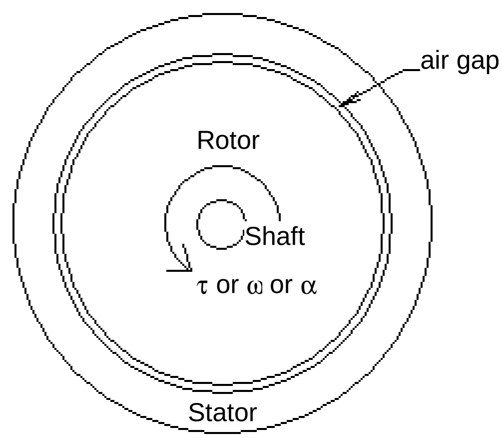
Generator: Torque as shown would come from some other rotating device, the *prime-mover* (not shown). The mechanical, shaft power would be into the generator.

Motor: Torque as shown would be caused by the motor overcoming a mechanical *load* resisting the motor's rotation (not shown). The mechanical, shaft power would be out of the motor. If the shaft were not coupled to some mechanical load the motor would spin freely (the no-load condition).

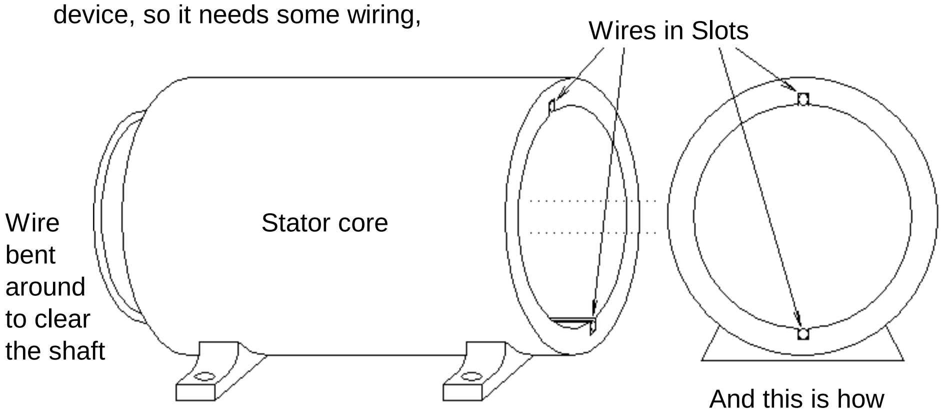


All of the parts are more complex than what I've shown. For instance, the end caps usually slip inside the main housing to insure good alignment.

Many drawings of motors, especially those designed to show how the motor works, show the motor from one end and only show the most important parts.



This is, of course, an electrical device, so it needs some wiring,

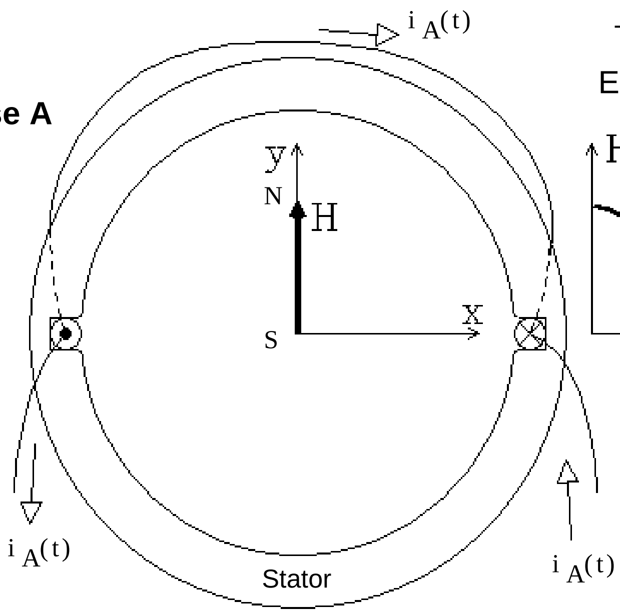


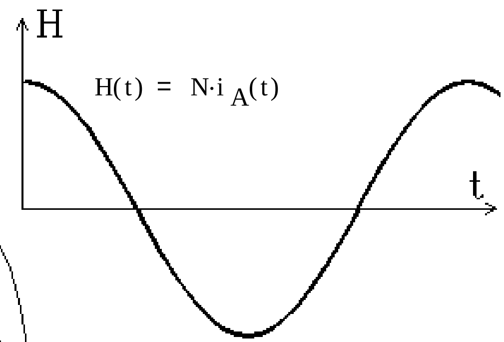
And this is how details will be shown

This is also an electromagnetic device

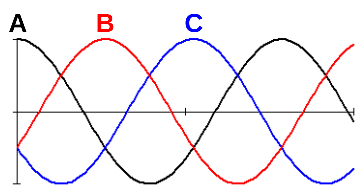
Establishing a Rotating Magnetic Field

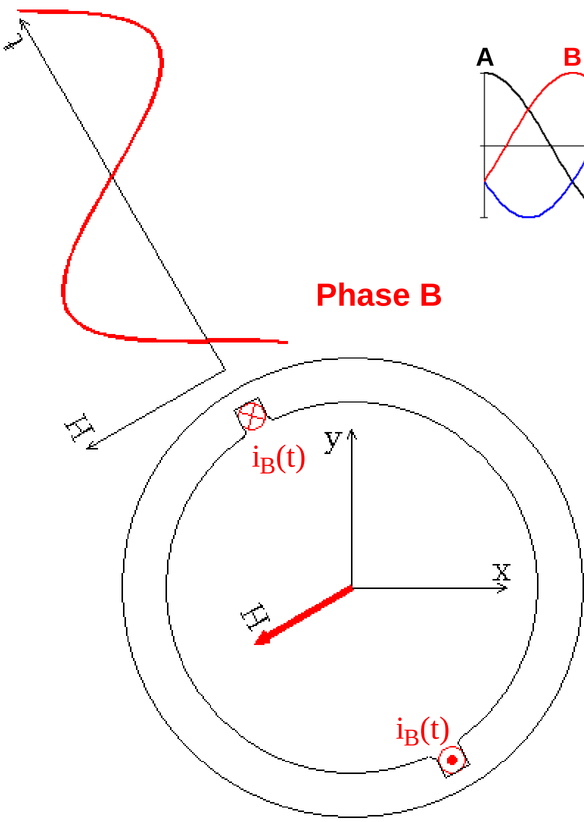
Phase A

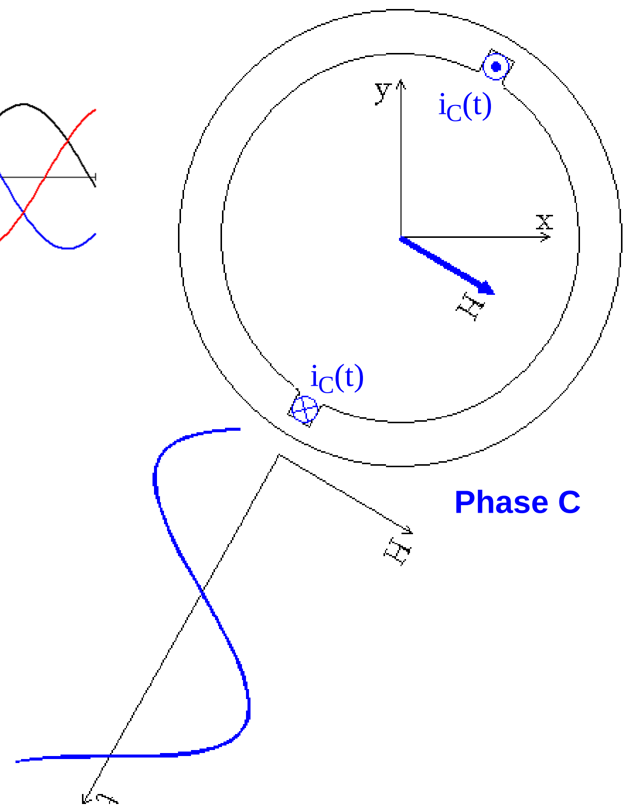


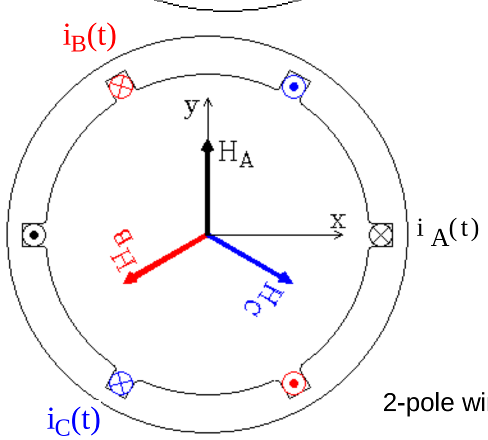


Field goes up and down, but no rotation

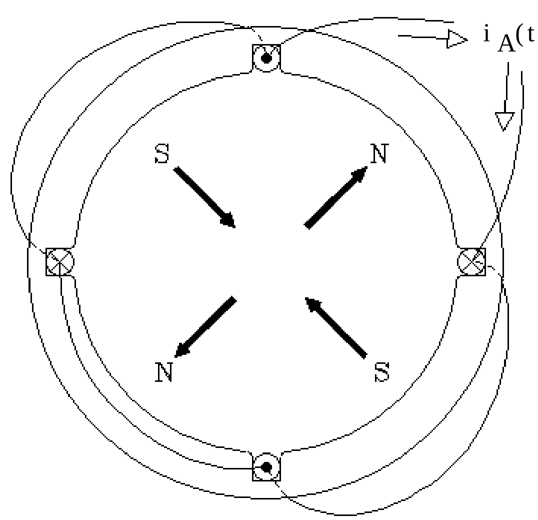








2-pole windings



All 3 phases create a counterclockwise rotating magnetic field.

Phase A of a 4-pole winding

Speed of the Rotating Magnetic Field

Depends on the number of poles $\omega = \frac{4\cdot\pi\cdot f}{N_{poles}} = \frac{2\cdot\left(377\cdot\frac{rad}{sec}\right)}{N_{poles}}$ for 60Hz systems

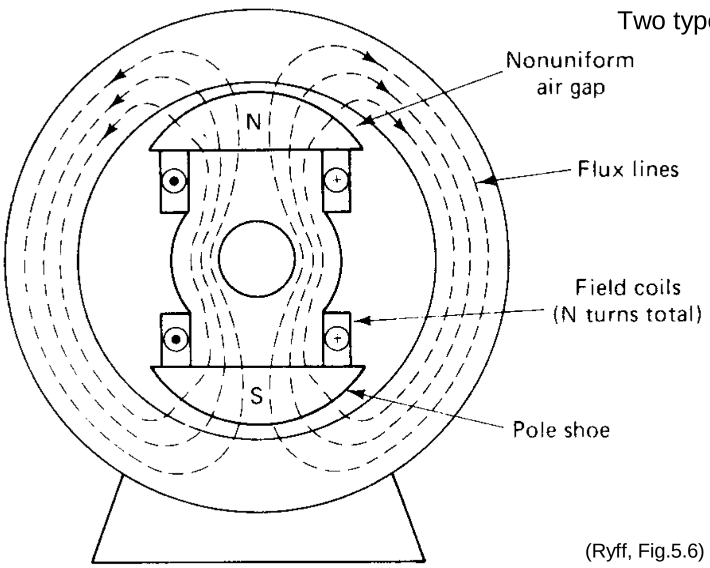
OR, n_m or $n_{sync} = \frac{f\cdot\frac{2\cdot poles}{cyc}\cdot\frac{60\cdot sec}{min}}{N_{poles}} = \frac{7200\cdot rpm}{N_{poles}}$ for 60Hz systems

The same stator windings are used for 3-phase Synchronous Machines and for Induction Motors.
In Synchronous Machines the stator is often called the "**armature**".

Synchronous Generators & Motors

Rotor The rotors in Synchronous Machines are magnets which want to follow the rotating magnetic fields, usually DC electromagnets. The DC current usually flows through brushes and slip rings to reach the moving rotor. Sometimes the field current is generated and rectified right on the rotor. This DC field current is called the field current (I_f).

Two types of rotors:

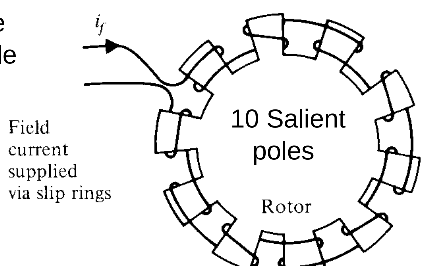


(Ryff, Fig.5.6)

2 Salient poles

Common for a motor or generator with many poles

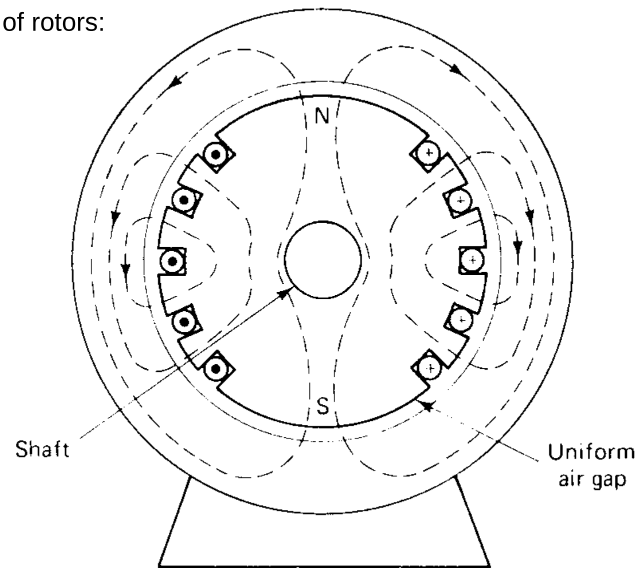
10-pole
example



(Brown, Fig.4.3)

10-poles - 720rpm
(fast for hydro)

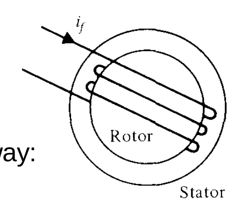
Typically low-speed motor or water turbine driven generator. Typically short in length and large in diameter. (typ diameter is 1.5xlength)



2 Non-salient poles, Cylindrical rotor

Common for a motor or generator with few poles

Sometimes
shown this way:



(Brown, Fig.4.2)

Typically high-speed motor or steam turbine driven generator, long and small diameter. (typ length is 3xdiameter)

2-poles - 3600rpm 4-poles - 1800rpm

Motor

If the stator currents flow in from a 3-phase power source and the rotor is a magnet, the rotor will follow the rotating magnetic field at the synchronous speed (in sync with the rotating field). That would be a synchronous motor. However, when the magnetic rotor is spinning within the stator windings it will induce voltages on those windings, just like a generator. The induced voltages (called the back EMF, E_A) will oppose the input voltages that caused the original currents to flow.

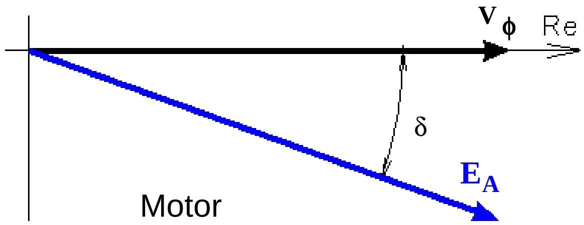
When the motor shaft is connected to a mechanical load (spins something which resists spinning), the rotor tries to slow down, but it only succeeds in lagging behind the rotating magnetic field a little (unless the motor is overloaded). When the rotor lags behind the field, the induced voltages ($\mathbf{E_A}$)s will also lag the input voltages.

Generator

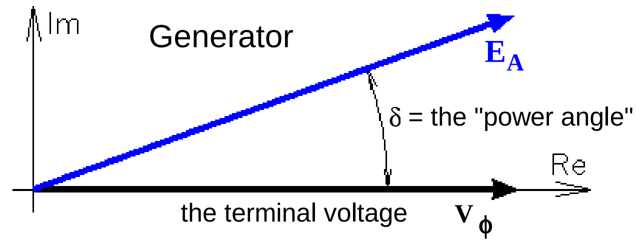
If, instead of a mechanical load, the shaft of this same device is connected to a source of mechanical power which tries to make it spin faster than the synchronous speed, it will act as a generator. If the generator is connected to the power grid (as they usually are) the only way the mechanical power source (the prime mover) can increase the speed would be to push the frequency of the entire grid higher than 60 Hz -- not likely. So all it succeeds in doing is to make the rotor lead the rotating magnetic field a little and along with it the induced voltages ($\mathbf{E_A}$)s will also lead the grid voltages..

Phasor diagrams of one phase.

We usually consider the the terminal or phase voltage ($\mathbf{V_\phi}$) be set and held constant by the entire power grid.

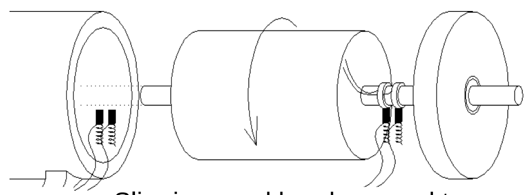


When operated as a motor, the induced armature voltage ($\mathbf{E_A}$) lags the terminal voltage, $\mathbf{V_\phi}$.



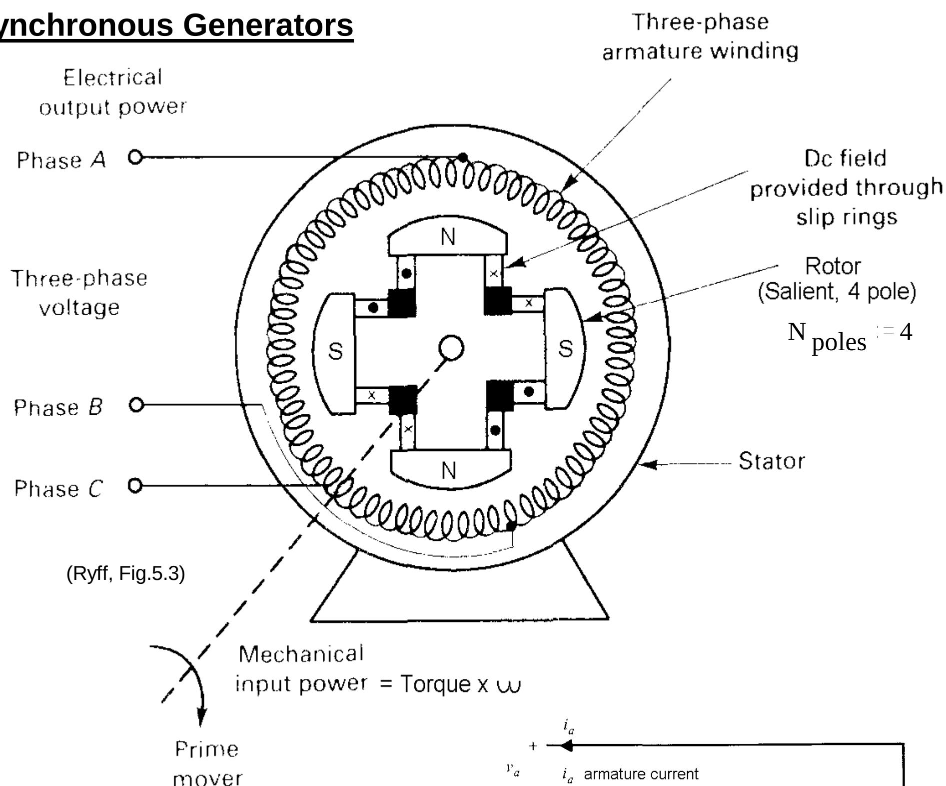
When operated as a generator, the induced armature voltage ($\mathbf{E_A}$) leads the terminal voltage, $\mathbf{V_\phi}$.

The magnitude of the induced armature voltages ($\mathbf{E_A}$ for our phase) depends on the field current, I_f . I_f causes the field flux (called **excitation**). The DC current may come from an external supply or it may be generated on the rotor. Either way there are usually brushes and slip rings, if not for DC current, then for control of that current.



Slip rings and brushes used to connect a DC supply to the rotor. (brushes shown twice)

Synchronous Generators

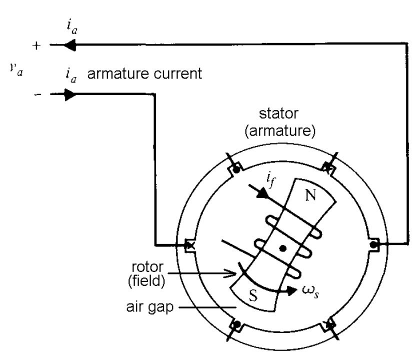


(Ryff, Fig.5.3)

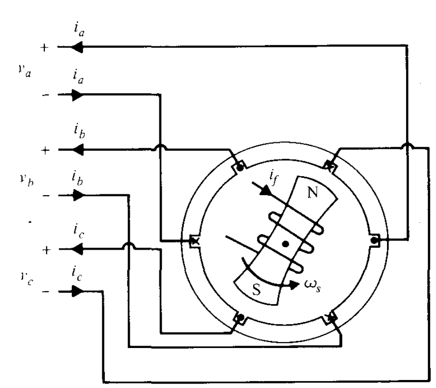
$N_{poles} := 4$

$$\omega = \frac{377 \cdot \frac{rad}{sec}}{2} = 188.5 \cdot \frac{rad}{sec}$$

$$n = \frac{7200 \cdot rpm}{4} = 1800 \cdot rpm$$



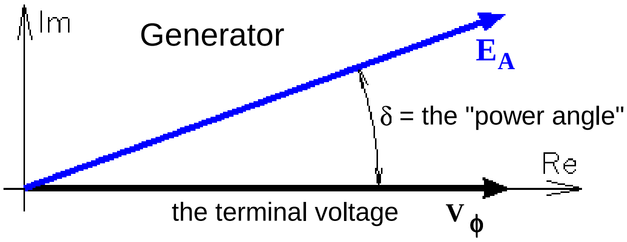
Stator (armature) winding



2-pole, 3-phase synchronous generator

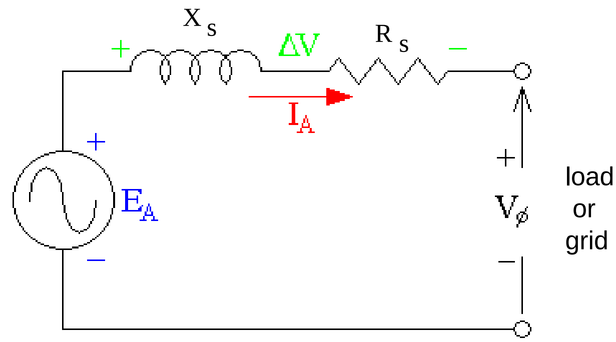
(Brown, Fig.4.1)

Electrical analysis on a per-phase basis



When operated as a generator, the induced armature voltage (E_A) leads the terminal voltage, V_ϕ .

The magnitude E_A depends on the DC field current, I_f .



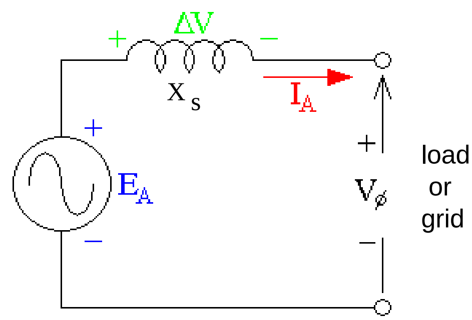
The electrical model of an armature winding

X_s is the armature inductance
(armature windings and leakage)
(magnetization)

R_s is the armature winding resistance

This is almost always simplified to this:
(Especially in our class)

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



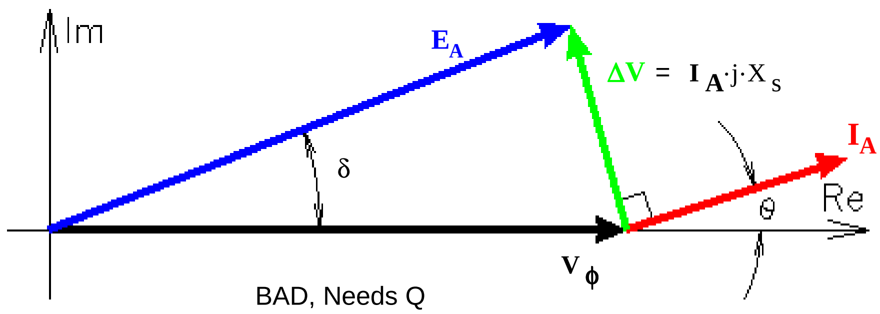
Low, or Under-excited (θ > 0)

Low DC field current

Low E_A

Makes -Q

"Uses" Q like an inductive load



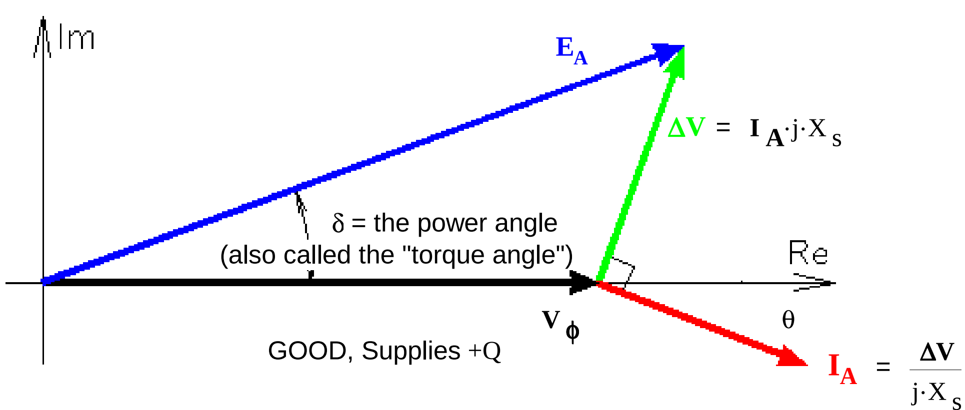
The **under-excited** condition, the current leads the terminal voltage, V_ϕ . The generator supplies -Q (-VARs), that is, it absorbs +Q (+VARs), just like an inductive load. Usually not desirable.

High, or Over-excited (θ < 0)

Higher DC field current

High E_A

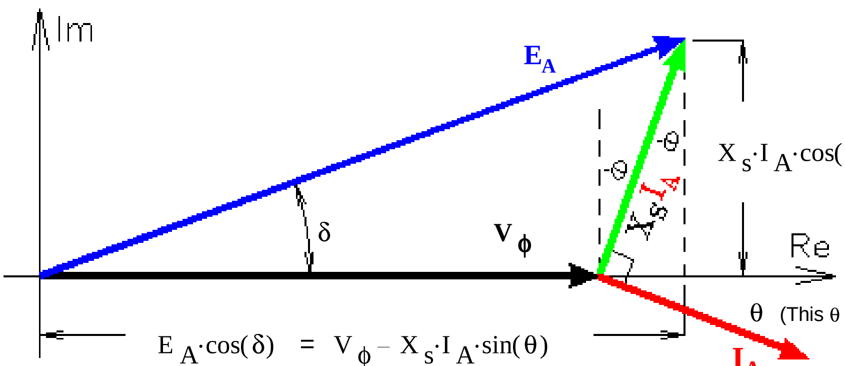
Makes Q



current lags, matching the need of most loads

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.

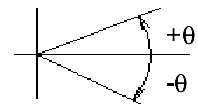
Important relations



Note: Voltages and currents are magnitudes, not complex numbers

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

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



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

(θ is negative)

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

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

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

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

$$P_{1\phi} = V_\phi \cdot I_A \cdot \cos(\theta)$$

Important Equations →

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

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

← Important Equations

→ $$\mathbf{E_A} = \mathbf{V_\phi} + \mathbf{I_A} \cdot j \cdot X_s$$

$$\delta = \operatorname{asin}\left(\frac{P_{1\phi} \cdot X_s}{V_\phi \cdot E_A}\right)$$

$$E_A = \sqrt{\left(V_\phi - X_s \cdot I_A \cdot \sin(\theta)\right)^2 + \left(X_s \cdot I_A \cdot \cos(\theta)\right)^2}$$

Be careful with the sign of θ.

$$\operatorname{asin} = \sin^{-1}$$

Pullout power

If δ reaches 90°, the generator will lose synchronization.
Pullout power is the maximum power a generator can produce for a given excitation, at $\delta := 90 \cdot \text{deg}$

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

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

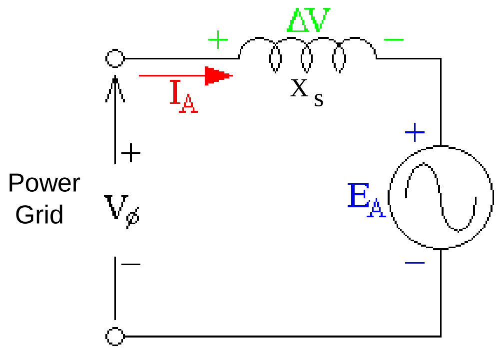
Shaft speed in rad/sec $\qquad \omega_{mech} = \dfrac{4 \cdot \pi \cdot f}{N_{poles}} = \dfrac{2 \cdot \left(377 \cdot \frac{rad}{sec}\right)}{N_{poles}}$ for 60Hz systems

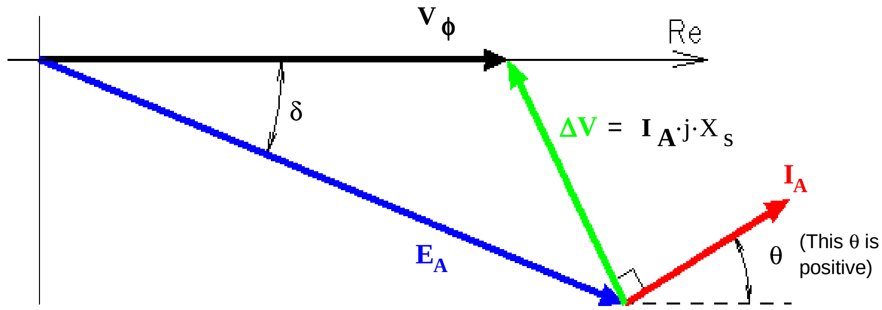
Shaft speed in rev/min $\qquad n = \dfrac{f \cdot \frac{2 \cdot poles}{cyc} \cdot \frac{60 \cdot sec}{min}}{N_{poles}} = \dfrac{7200 \cdot rpm}{poles}$ for 60Hz systems

$\tau_{mech} \cdot \omega_{mech} = P_{3\phi}$ (electrical) neglecting losses

τ_{mech} = mechanical torque

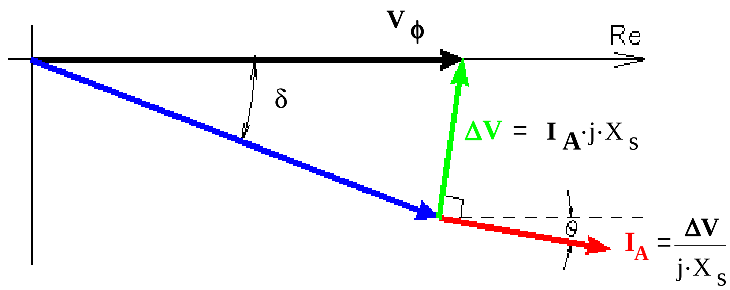
Synchronous Motors





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

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



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

Important relations

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

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

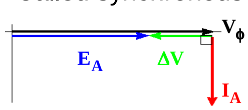
$$Q_{1\phi} = \frac{V_\phi^{\,2} - E_A \cdot V_\phi \cdot \cos(\delta)}{X_s} = V_\phi \cdot I_A \cdot \sin(-\theta)$$

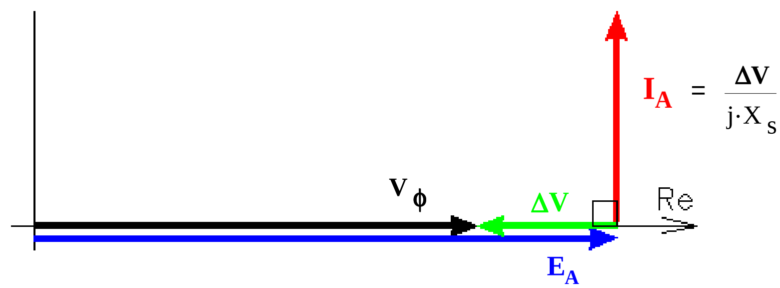
(Bigger E_A makes Q negative (good))

Synchronous Condenser (Capacitor)

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

An under-excited motor with no mechanical load (and neglecting friction) will look like an inductor. Called synchronous reactance.

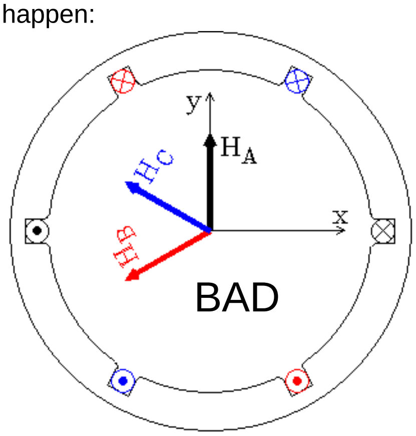


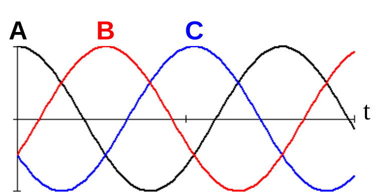


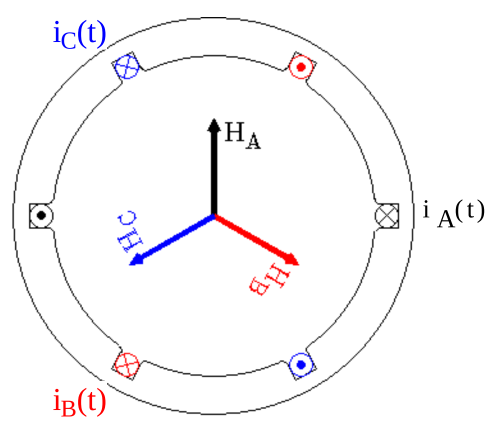
Motor Connections and Changing the Direction of Rotation

DO NOT alter the manufacturer's wiring within the motor, other than to change from Y to Δ or reverse. And then follow directions carefully. Otherwise something like this could happen:

It is OK to change the connections between the power panel and the motor as long as you don't mess with the neutral and/or ground connections. Swapping any two phases from the power panel will reverse the direction of rotation. Works for both Y and Δ connections







The 3 phases create a clockwise rotating magnetic field.

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.

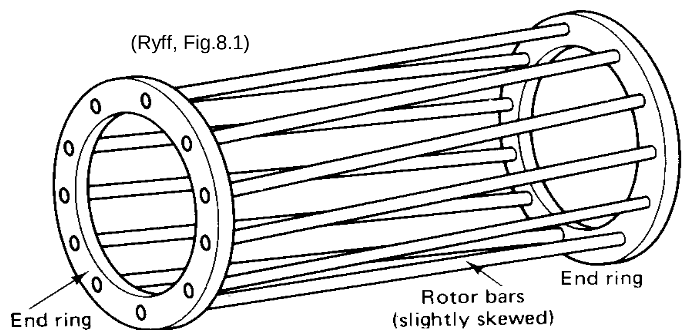
Effect on the network (grid)

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.

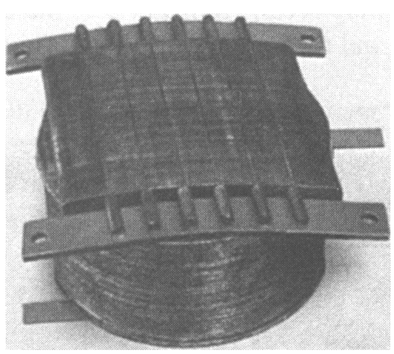
(Ryff, Fig.8.1)



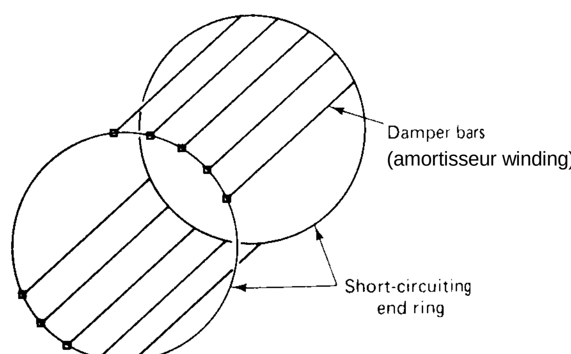
Synchronous machines usually have very similar bars in their rotors. In steady-state synchronous operation, they have no affect. The purpose of these bars is to resist, or dampen, transients. Currents will be induced in these windings when the stator current magnitudes change or when the input rotational 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

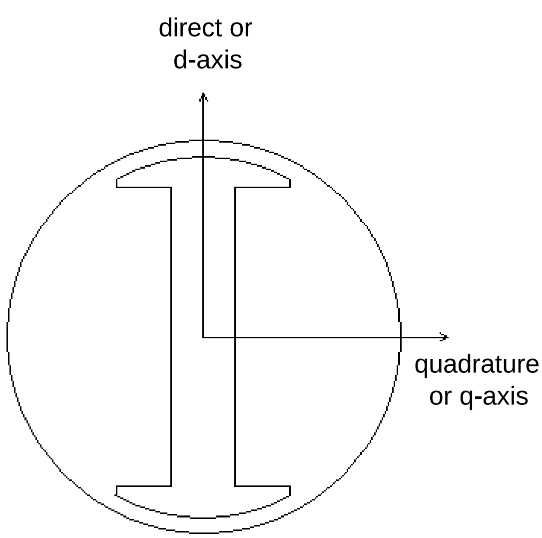
$= \frac{X_s}{10}$ to $\frac{X_s}{4}$

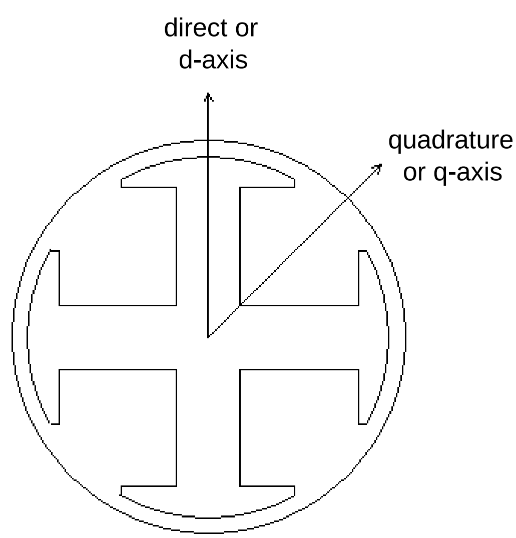
X'_s = transient synchronous reactance, some additional flux goes through rotor after first few cycles until new steady-state.

$\simeq 2 \cdot X''_s$

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. This is beyond the scope of our class.

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