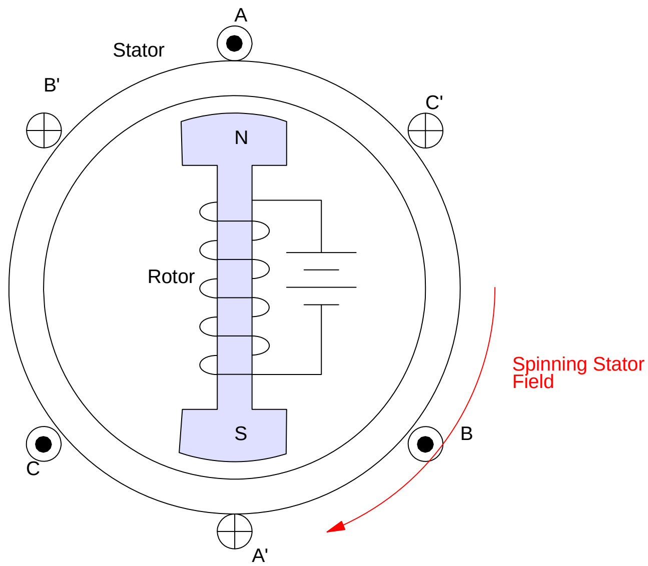
AC Synchronous Motors

The stator is the same as an AC induction motor: 3-phase conections make the magnetic field spin.

The rotor is magnetized, however, with electromagnets. This results in the rotor following the spinning field at synchronous speed:



Synchronous Speed: (P = # of poles in the rotor)

$$n_s = \frac{2\pi \cdot 60Hz}{P/2}$$

If you're not running at synchronous speed, the average torque is zero. Likewise, this causes problems at start-up: the average toruqe is zero.

- Use an external motor to get close to synchronous speed then power up the rotor
- Imbed a squirrel cage in side the motor so it runs like an asynchronous motor on startup. Remove th eload until you get close to synchronous speed (slip is close to zero). Power up the rotor to lock on at synchronous speed.

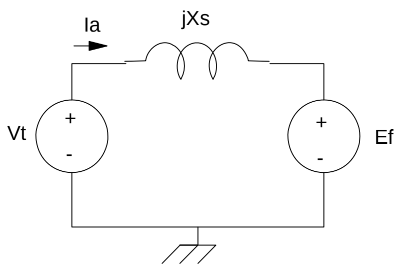
Circuit Equivalent:

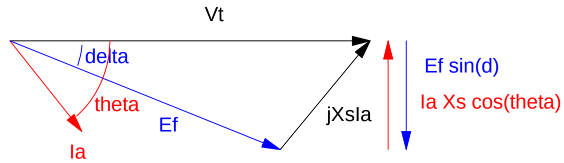
$$V_T = (R_a + jX_s)I_a + E_f$$

- Ra = armature resistance
- Xs = Synchronous Reactance = armatude leakage reactance (Xl) + armature reaction reactance (Xar). The motor acts like a big inductor - Xs is the net inductance (reactance) of the motor.
- Ef = Excitation voltage per phase

Assume Ra = 0:

$$V_T = jX_s \cdot I_a + E_f$$





The excitation voltage can be any amplitude and is set by the voltage you apply at the rotor's electromagnets.

The rotor will be running at synchronous speed, but will lag slightly behind the rotating field by an angle δ. When the power delivered is zero, this lag will be zero as well:

$$-E_f \cdot \sin(\delta) = I_a X_s \cos(\theta) \qquad (8\text{-}11)$$

Multiply by Vt and divide by Xs to get power per phase (times 3 since it's three phase)

$$P = 3 \cdot V_t I_a \cdot \cos(\theta)$$

$$P = 3 \cdot \left(\frac{-V_t E_f}{X_s}\right) \cdot \sin(\delta)$$

Example 8-1: 100hp, 3 phase, 4-pole, 60Hz, $265V_{LN}$, Xs = 2.72 Ohms is delivering 100hp with a power factor of 0.8 leading.

a) Find the developed torque:

Speed: $n_s = (2\pi \cdot 60Hz)\left(\frac{1}{2}\right) = 188.5$ rad/sec

Power: $100hp \cdot \left(\frac{746W}{hp}\right) = 74.6kW$

Torque: $T = \left(\frac{74.6kW}{188.5rad/\sec}\right) = 395.7Nm$

b) Find the input current:

$$3 \cdot V_t I_a \cos(\theta) = 74.6kW$$

$$3(265V)(Ia)(0.8) = 74.6kW$$

$$I_a = 117.29A$$

or

$$I_a = 117.29\angle 36.87^0$$

c) Find the slip (delta): First, find the excitation voltage:

$$V_T = jX_s \cdot I_a + E_f$$

$$265V = (j2.72)(117.29\angle 36.87^0) + E_f$$

$$E_f = 522.9\angle -29.2^0 \text{ Volts}$$

The slip is

$$P = 3 \cdot \left(\frac{-V_t E_f}{X_s}\right) \cdot \sin(\delta)$$

$$74.6kW = 3 \cdot \left(\frac{-265V \cdot 522.9V}{2.72\Omega}\right) \sin(\delta)$$

$$\delta = -29.2^0$$

The rotor is lagging the stator's rotating magnetic field by 29.2 degrees.

The maximum torque is when δ is 90 degrees:

$$P = 3 \cdot \left(\frac{-V_t E_f}{X_s}\right) \cdot \sin(\delta)$$

$$P_{\max} = 3 \cdot \left(\frac{-265V \cdot 522.9V}{2.72\Omega}\right) = 152.8kW$$

$$T_{\max} = \frac{P_{\max}}{188.5} = 810Nm$$

Effect of Changing the Shaft Load:

Example 8-1: 100hp, 3 phase, 4-pole, 60Hz, $265V_{LN}$, Xs = 2.72 Ohms, Ef = 522V. (as per example 8-1)

Find the slip angle, δ, for a load of 100hp: (check I'm doing it right)

$$P = 3 \cdot \left(\frac{-V_t E_f}{X_s}\right) \cdot \sin(\delta)$$

$$(100hp)\left(\frac{746W}{hp}\right) = 3 \cdot \left(\frac{-265V \cdot 522.9V}{2.72\Omega}\right) \cdot \sin(\delta)$$

$$\delta = -29.2^0$$

Find the input current:

$$V_T = jX_s \cdot I_a + E_f$$

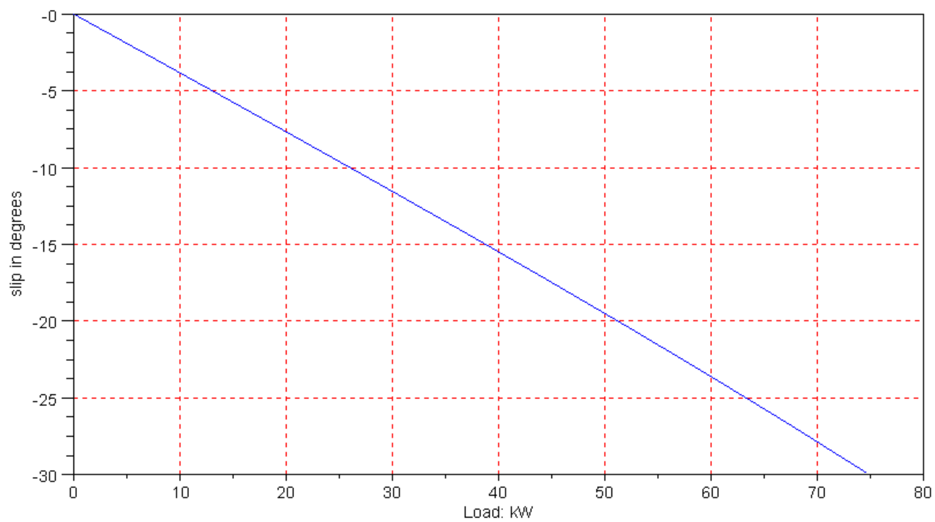
$$265V = (j2.72)(I_a) + (522\angle -29.2^0)V$$

$$I_a = 117.29\angle 36.87^0$$

Plot this for a load from 0hp to 100p:

In SciLab:

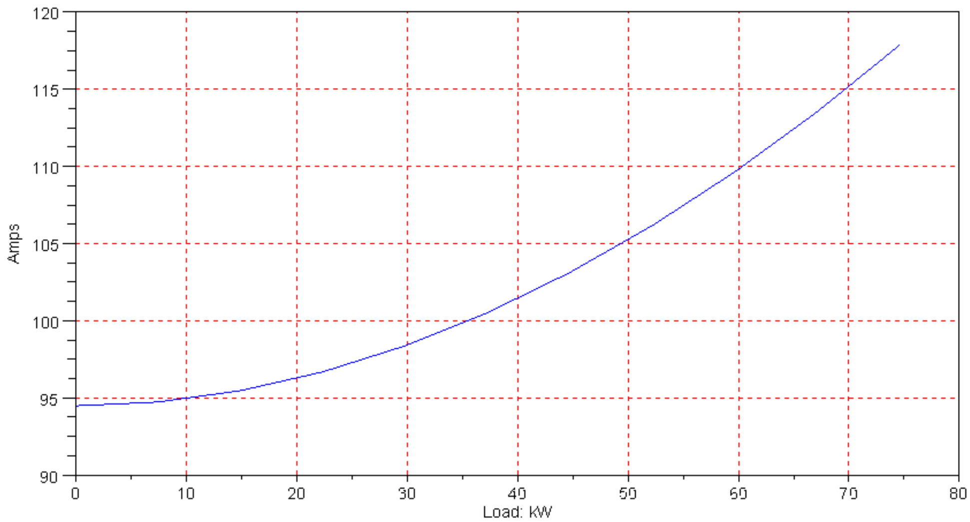
```
-->P = [0:10:100]' * 746
    0.
    7460.
    14920.
    22380.
    29840.
    37300.
    44760.
    52220.
    59680.
    67140.
    74600.

-->delta = asin(-P / 3 / 265 / 522 * 2.77)
-->delta * 180 / %pi    (display the result in degrees)
    0.
  - 2.8541923
  - 5.7154983
  - 8.591193
  - 11.488884
  - 14.416704
  - 17.383544
  - 20.399335
  - 23.475421
  - 26.625057
  - 29.864104
```



Note that as the load increases, the slip angle increases. The speed remains constant, however, at synchronous speed.

```
-->j = sqrt(-1);
-->Ef = 522*exp(j*delta)
-->Ia = (265 - Ef)/(j*2.72)
-->plot(hp,abs(Ia))
-->xlabel('horsepower')
-->ylabel('Amps')
```

```
-->xgrid(5)
```



The current drops as the load decreases. The current, Ia, doesn't go to zero, however.

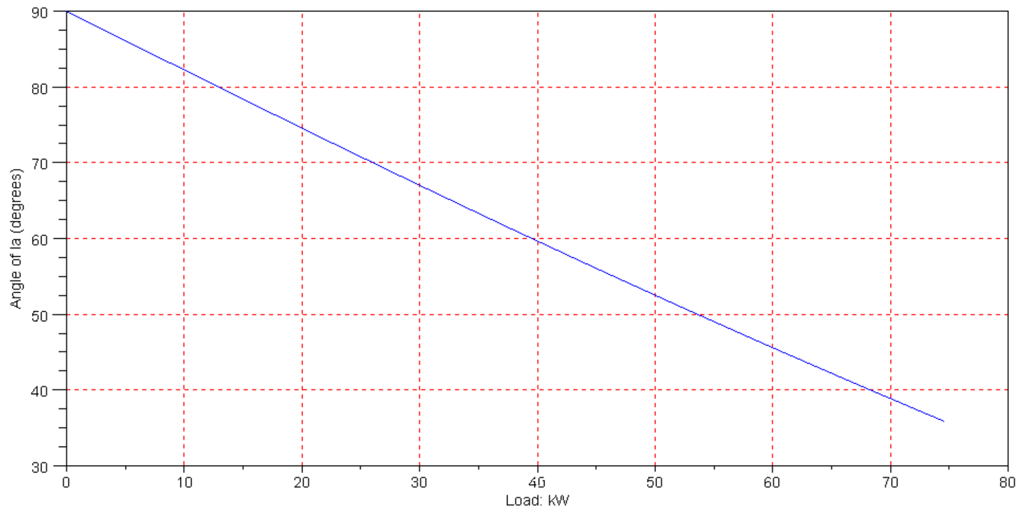
Plotting the phase of Ia vs load:

SciLab Code:

```
->Q = atan(imag(Ia),real(Ia))*180/%pi
 Q  =

    90.
    84.210315
    78.451104
    72.750792
    67.133953
    61.619937
    56.222002
    50.946947
    45.795116
    40.760615
    35.831561

-->plot(P/1000,Q)
```

MATLAB Code:

```
> Q = angle(Ia) * 180/pi;
> plot(P/1000, Q);
```



The phase of Ia increases to +90 degrees (capacitive) as the load is reduced to zero.

Note that this motor behaves like a capacitor with no load. You can use a 3-phase synchronous motor for power factor correction(!).

Effect of Changing the Excitation Voltage (Ef):

With Ef large (522V), the above example resulted in a capacitive load for the 3-phase synchronous motor. What happens if you change Ef?

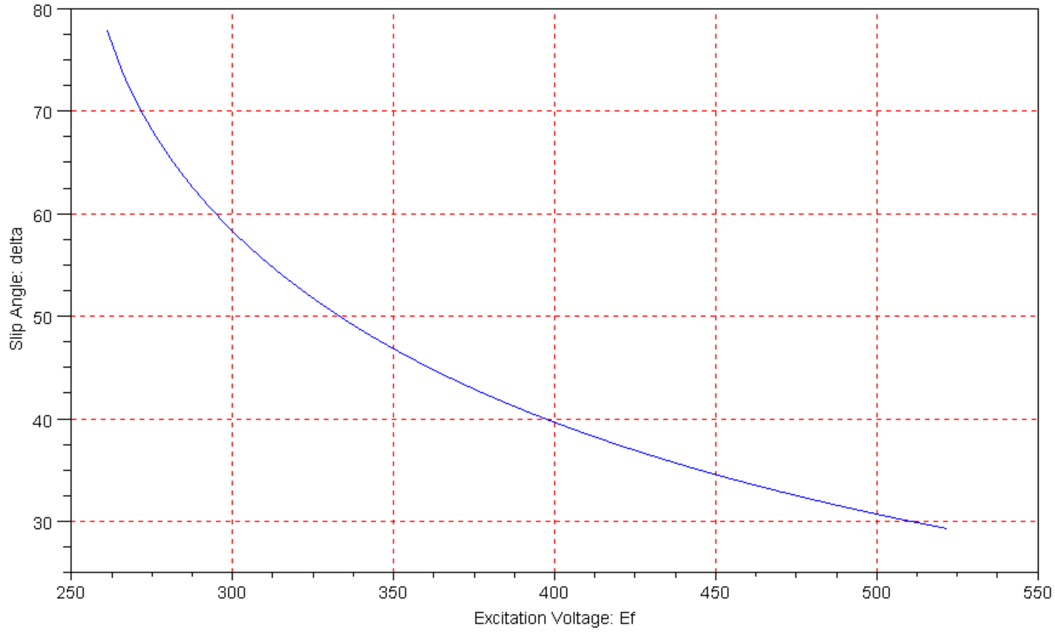
Lets repeat the previous example, assume a 100hp load, and vary Ef:

Example 8-1: 100hp, 3 phase, 4-pole, 60Hz, 265V_{LN}, Xs = 2.72 Ohms, Load = 100hp.

First, find the slip angle:

```
-->Ef = [0.1:0.1:1]' * 522;
-->P = 100*746;
-->Xs = 2.72;
-->Vt = 265;
-->delta = (P * Xs) ./ (3*Vt * Ef)
-->[Ef,delta]
    52.2     4.8895636
    104.4    2.4447818
    156.6    1.6298545
    208.8    1.2223909
    261.     0.9779127
    313.2    0.8149273
    365.4    0.6985091
    417.6    0.6111955
    469.8    0.5432848
    522.     0.4889564
```

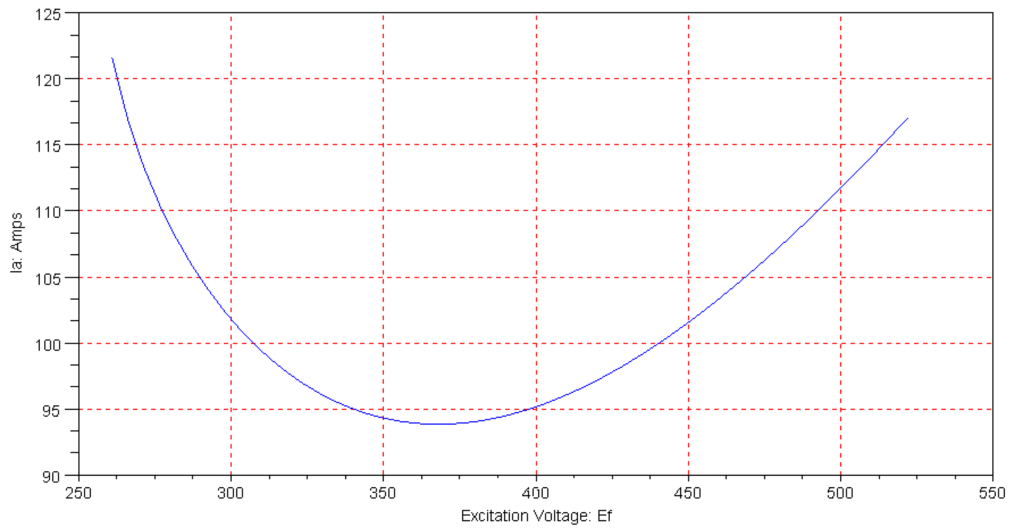
note: you actually need to take the arcsin() of the last column. Numbers bigger than 1.00 are telling you that it won't work. You can't generate 100hp if the excitation voltage is too small. So, let's take Ef from 261V to 522V



The slip increases as you degrease Ef. Once the slip goes past 90 degrees, the motor no longer is able to generate the toque needed to provide 100hp. (note: This also means if you increase Ef, the slip decrases. The magnets get stronger.)

Plot the current vs. Excitor Voltage:

```
-1->Ia = (265 - Ef.*exp(j*delta))/(j*2.72);
-1->plot(Ef,abs(Ia))
```

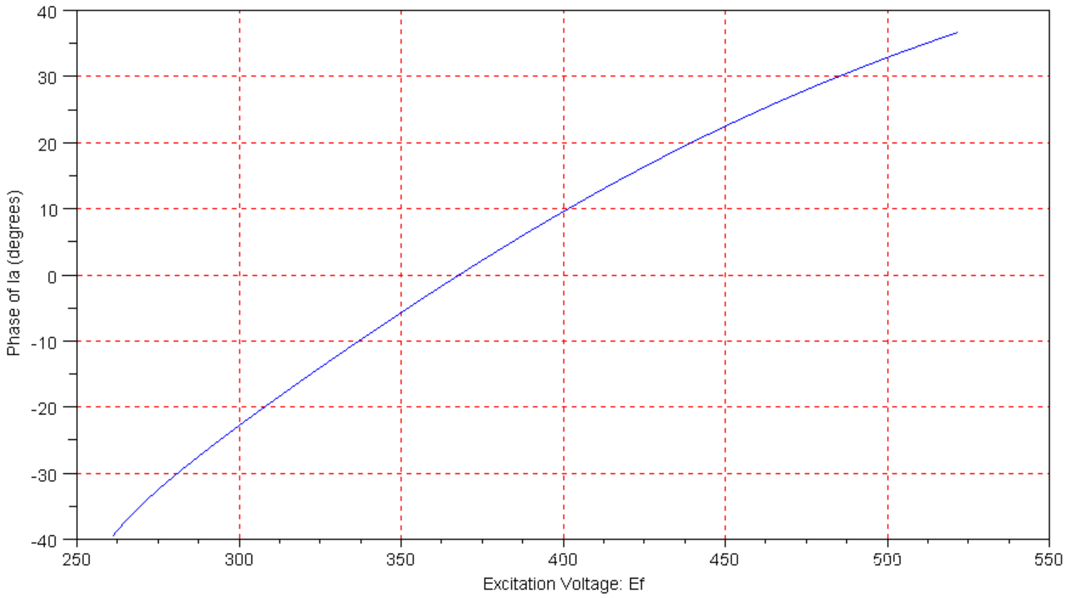


Note there is an 'optimal' excitation voltage that minimizes the stator current.

Plot the angle if Ia (power factor) vs. Excitation Voltage:

```
-->Q = -atan(imag(-Ia),real(-Ia))*180/%pi;
-->plot(Ef,Q)
```

(the minus signe are an error somewhere in my code. At 522V, the phase of Ia should be 36.87 degrees from before.)



Note:

- For large excitation voltages, the motor has a leading power factor (capacitive load). This is called being over-excited.
- For small excitation voltages, the motor has a lagging power factor (inductive load). This is called being under excited.
- You can make the power factor 1.00. This happens at Ef = 368V (found numerically) and

$$V_t = E_f \cdot \cos(\delta)$$

Synchronous Motors Used as a Synchronous Capacitor:

If you remove the load from the motor, the synchronous motor acts like a capacitor with Ia having a phase shift of +90 degrees. You can vary the reactance of the motor by varying the excitation voltage, Ef:

Example: Assume V_{LN} = 1327V, 3 phase, 2600kW machine with a power factor of 0.87 lagging. Add a synchronous capacitor (i.e. 3-phase maching with no load) to bring the power factor to 1.00. Assume Xs = 1.6 Ohms.

Solution: First, find the line current

$$|I_{line}| = \frac{2600kW}{3 \cdot (1327V)(0.87)} = 750.7A$$

The total (real and complex) current is then:

$$I_{line} = 750.7\angle -29.54^0 = (653 - j370)A$$

We need to add +j370A to bring the power factor to 1.00.

b) The kVA rating for the synchronous capacitor needs to be:

$$(1327V)(370A) = 490kVA$$ (line-to-neutral connection assumed.)

c) The excitation voltage is

$$V_T = jX_s \cdot I_a + E_f$$

$$(1327V) = (j1.6\Omega)(j370A) + E_f$$

$$E_f = 1919V$$