MOTORS

Outline of Unit

Detail	Duration	Comment
Motors.	2 units	Motors (3 phase and DC inc. starting),

This unit looks at basic characteristics of the plant that will be powered by a range of power electronic systems.

The aim is not to develop a full understanding of these various plants but rather to understand the interactions that occur in practice and those design issues which must be addressed when specifying power electronic systems.

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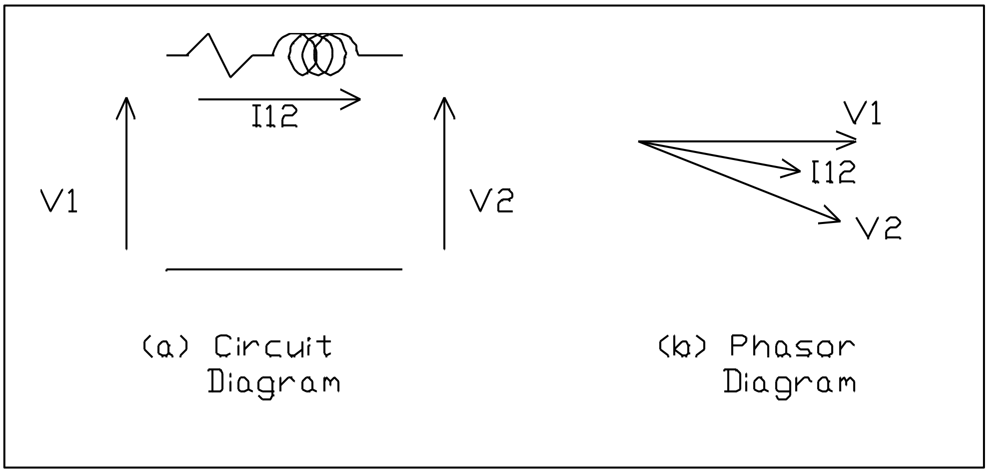
1 Motors

1.1 Basic Concept

All electric machines work on the basis of a driving and a driven vector. In the case of a generator, the generator voltage vector pulls the system vector behind it and in the case of a motor vice versa.



If we neglect the series resistance in the above circuit the power is given by

P12 := {abs(V1) * abs(V2) * sin (arg V1 – argV2) }/ X12

Try it for yourself time : derive the equation for the power and Var at the load (node 2) including the effects of the resistance.

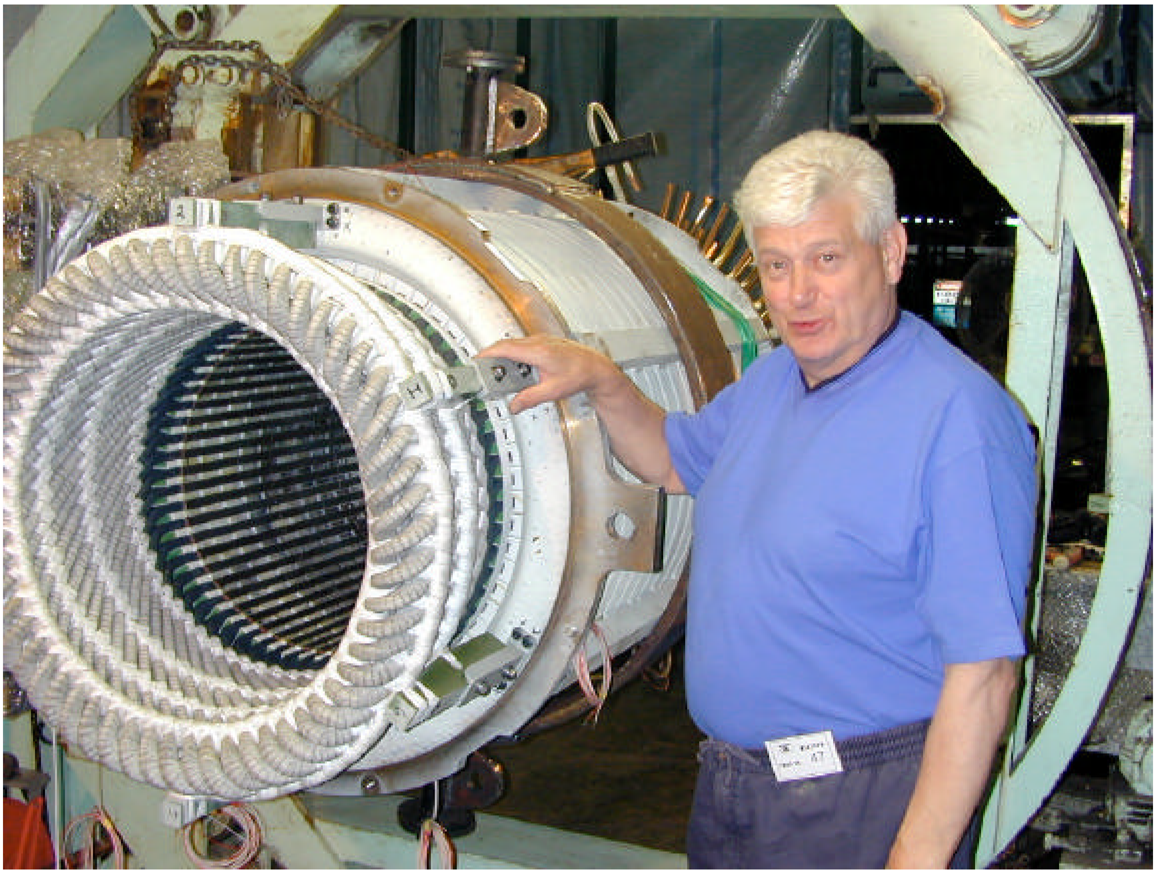
Discussion point : what is the power factor in this circuit ?

Torque (Newton meters) is the basic performance parameter of a machine; torque can best be visualised as the ability to do work whilst power (NM per second) is the rate of doing work. Torque is achieved in magnetic systems by the interaction of two mmf phase displaced from each other. Thus to make a machine do work in the steady state we have to arrange a fixed (stator) and a moving (rotor) coil system such that a steady displacement exists between the two in the steady state despite the movement of the rotor.

1.2 Rotating Field

The discussion that follows is based on motors; for a generator just swap the relative positions of the voltages.

In order to pull the rotor around it is necessary that we make the magnetic field rotate with respect to the frame of the motor. How this is achieved distinguishes the three types of motor (induction, synchronous and DC).

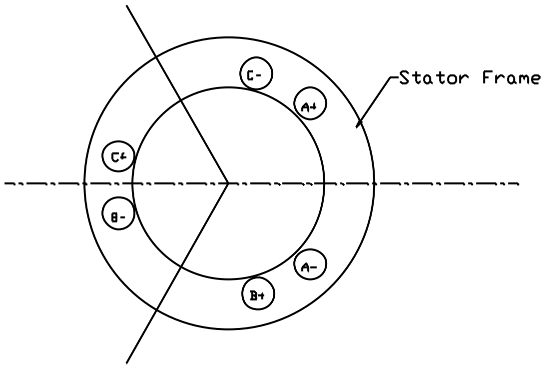


View of a 2.6MW 2pole 11kV motor stator frame and winding after repair.

Consider a stator frame with a round hole for the rotor and a three phase set of stator windings uniformly distributed. Imaging first that we are at the point in time when phase A is at its peak value. Phases B & C are both equal to –0.5 (cos(120deg)) but because of the orientation of the coils the mmf adds to that of phase A and hence a peak flux value is experienced along the axis of the A phase field winding. 1/3rd of a cycle later, the same peak flux appears along the axis of phase B etc. What therefore appears to be happening is that a rotating magnetic field exists so that if a rotor with closed windings is inserted into the rotor bore it.

The above description explains the production of rotating fields in all polyphase ac machines. In a DC machine the same effect is produced by the use of a commutator which switches the current into different rotor coils and thus produces a rotating field on the rotor.

In the case of the single phase AC machine an artifice is required to produce the rotating field. Three types are common



- Shaded pole
- Capacitor start
- Capacitor start & run

In all three cases a second weaker filed is created by phase displacing current (capacitor methods) or mmf (shaded pole).

1.3 Induction Motors

1.3.1 Concept

This is the most important motor of all.

Imagine a motor with the rotor locked and a three phase supply applied to the stator. The net effect is just like a transformer with an airgap in it's core. Thus the rotor windings have 50 Hz (or what ever the stator frequency is) induced in them. A rotor field is then established and it rotates at the same speed as that of the stator & torque is produced. We call this "synchronous speed"

If we now rotate the rotor in the same direction the rotating field and a speed being a fraction of synchronous speed, the current induced in the rotor will have a frequency equal to the difference between synchronous speed and the rotor speed.

Fr = Fsynch * (ns – nr) / ns

At the same time the induced voltage is smaller.

The rotor current produces a rotating field on the rotor but because the rotor is moving, the net speed of the rotor field as viewed from the stator is still synchronous speed.

Because the rotor moves at less than synchronous speed it is usually talked of as "slipping" and hence the idea of defining it's speed as

Slip = (ns – nr) /ns pu

This is a convenient notation because most induction motors run with a slip I the range 0.5% - 1.5% at maximum power.

1.3.2 Induction motor equivalent circuit

The transformer exact equivalent circuit is the starting point.

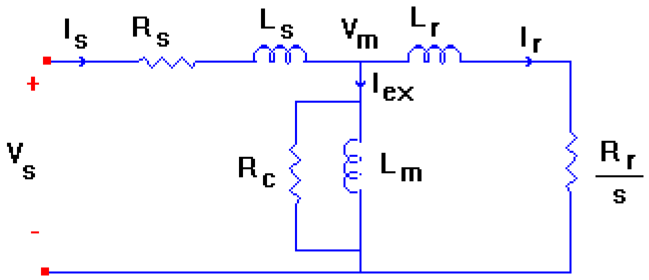
Note that the effect of the variation in speed of the induction motor means that the ideal trf winding is now a variable voltage and frequency device.

Unlike the trf we are not normally interested in the oltage and current in the rotor (this will change when Slip Energy Recovery drives are investigated).

The rotor impedances are "referred" to the primary as follows

Reactance = same numerical value as in the secondary circuit

Resistance = R2' * (1/slip)



The resistance term is then broken into two parts, one being associated with the copper loss term Rr and the other Rr (1-s)/s with the power output.

Power output = $I_r^2 * R_r *(1-s)/s$

If working in real quantities as opposed to per unit remember that the above is per phase.

Sometimes the magnetising branch is put across in input terminals – "approximate equivalent circuit" and sometimes it might be omitted all together. This is not as rough as it might sound – the inductances and resistance values used in the equivalent circuit are difficult to determine and are rarely constant at all values of slip and load.

1.3.3 Induction Motor Torque

The power crossing the airgap is

$$\begin{aligned} P_g &= I_{2'}^2 * R_2 / 2 \\ &= s* P_g + (1-s)*P_g \end{aligned}$$

Hence the torque is

$T(s) = 3^* P_m / w$

$= 3^*P_g^*(1-s)/\{2^*pi^*n_s^*(1-s)\}$

$= Pg * \{3/(2^*pi^* n_s)\}$ Nm (total 3 phase torque)

Induction Motor Example

Motor : 500V 3-phase, 8 pole, star connected
R1=0.13 Ohm, R2=0.32 Ohm, X1=0.6 Ohm, X2=1.48 Ohm
Ymag=0.004 - j0.05 Mho ref primary side
full load slip = 2.5%
rotor / stator turns ratio = 1 / 1.57

1. Convert rotor values to "refered to primary" values

$$R2d := 0.32 \cdot \left(\frac{1}{1.57}\right)^2 \qquad R2d = 0.13 \qquad \text{Ohms}$$

$$X2d := 1.48 \cdot \left(\frac{1}{1.57}\right)^2 \qquad X2d = 0.6 \qquad \text{Ohms}$$

2. Calculate input impedance as function of slip

$$Zin(s) := \left[\left(\frac{0.13}{s + 10^{-6}} + 0.6 j\right)^{-1} + (0.004 - 0.05 j)\right]^{-1} + (0.13 + 0.6 j)$$

$$sfl := 0.025$$

3. Calculate input current, torque and power factor

$$I(s) := \frac{500}{\sqrt{3}} \cdot Zin(s)^{-1} \qquad Iin(s) := |I(s)| \qquad Iin(1.0) = 238.643$$

$$Iin(0) = 14.051$$

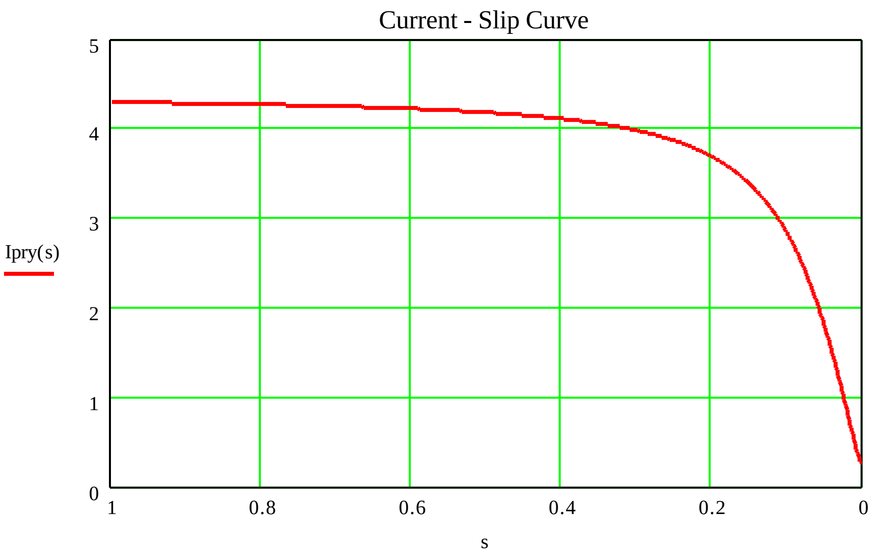
$$PF(s) := \cos(\arg(I(s)))$$

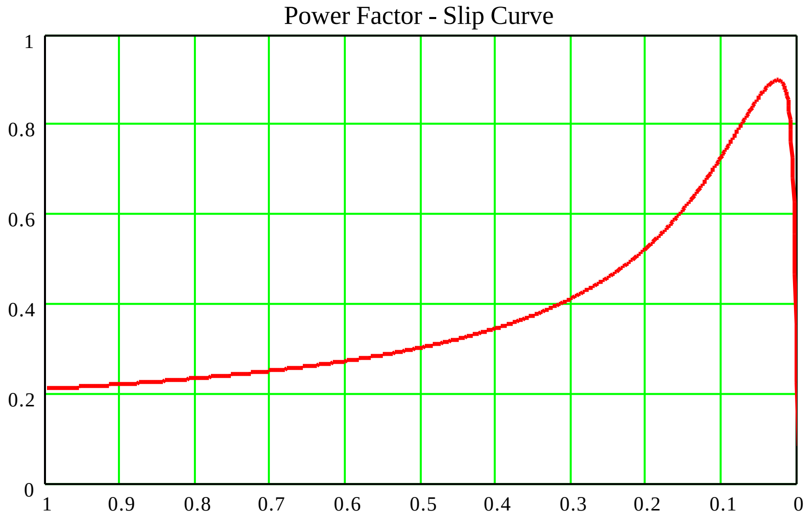
remove mag branch components $\qquad Ird(s) := I(s) - \frac{500}{\sqrt{3}} \cdot (0.004 - 0.05 j)$

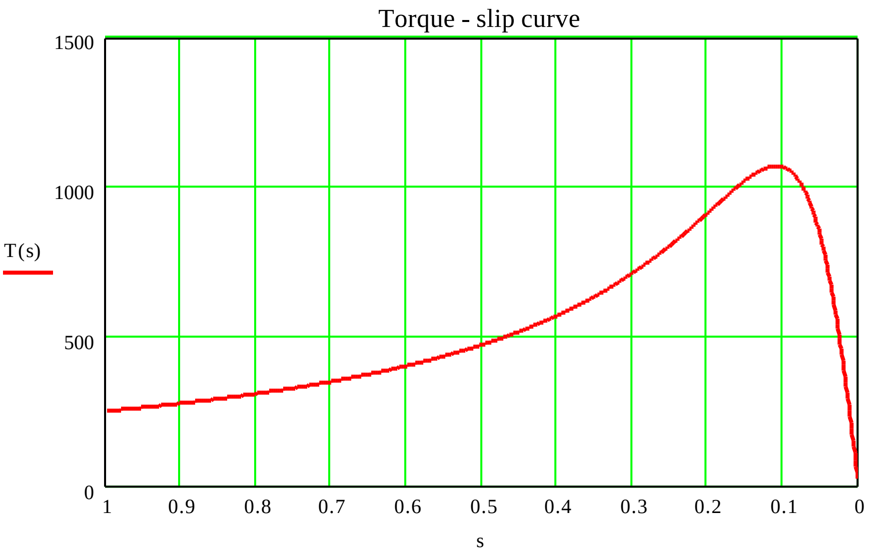
calculate sync speed $\qquad f := 50 \qquad p := 4 \qquad \omega s := 2 \cdot \pi \cdot \frac{f}{p}$

$$T(s) := 3 \cdot (|Ird(s)|)^2 \cdot \frac{R2d}{s} \cdot \frac{1}{\omega s} \qquad \text{Nm}$$

normalise current to full load value $\qquad Ipry(s) := Iin(s) \cdot Iin(sfl)^{-1}$


Current - Slip Curve
Ipry(s)
5
4
3
2
1
0
1
0.8
0.6
0.4
0.2
0
s


Power Factor - Slip Curve
1
0.8
0.6
0.4
0.2
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

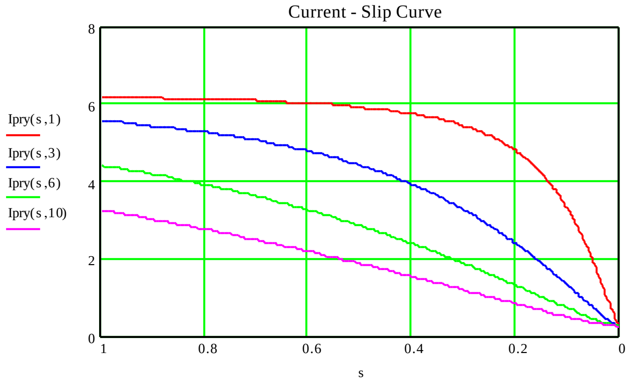

Torque - slip curve
T(s)
1500
1000
500
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
s

Note the very distinctive shape of these characteristics :-

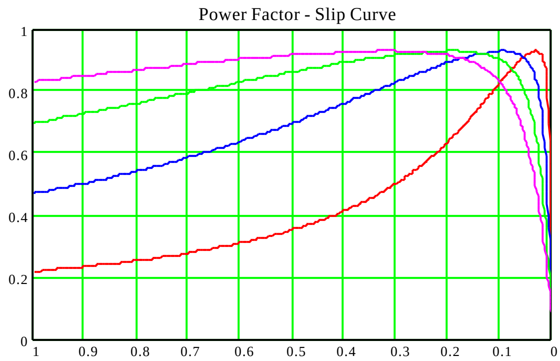
- Starting current is high 4.5 times full load (can be up to 6 times)
- Starting power factor is very low
- Starting torque is commensurate with full load torque (can be lower)

1.3.4 Effect of varying Rotor resistance

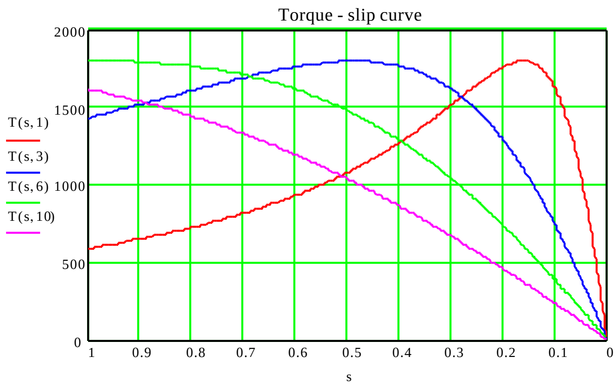
Economic motor design tends (careful with such ideas) to give stator and rotor (referred) ohmic values that are similar. From this point it can be said that :-



High rotor resistance leads to higher starting torque (up to a certain critical value of Rext), lower starting currents, lower running power factors.



Thus the ideal is a rotor with a slip frequency dependent resistance. This is achieved by shaping the rotor bars to be smaller cross-section higher resistivity near surface of rotor and larger CSA lower resistivity below that. Known as “deep bar” or “double cage” construction.



In the equivalent circuit we use parallel rotor referred branches. This type of motor is more expensive than basic motor.

The deep bar construction work because the outer cage exhibits a lower inductance than the inner one so that it’s impedance is predominantly resistive and will carry more current at low speeds (= high rotor frequency) than the deeper cage. As the speed rises, the deeper cage takes over most of the conduction.

1.3.5 Starting Induction Motors

The basic induction motor places a great strain on the power system (high starting current at low power factor) = voltage drop.

Solutions :-

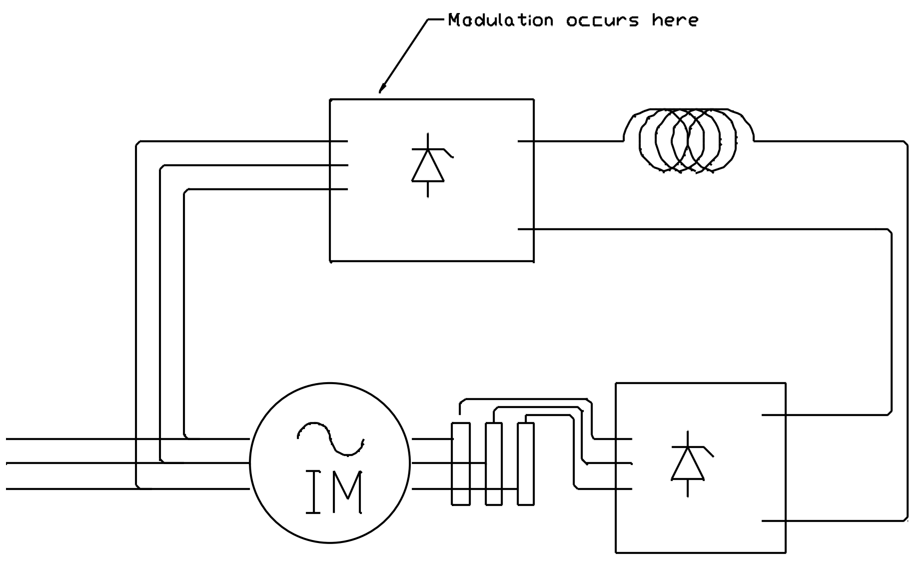
Method	**Cost**	**Pros & Cons**
Star – delta starting	lowest	Open circuit at transition causes large mechanical forces on shaft & load. Not practical with MV motors
Stator reactor	Next lowest	Larger reduction in torque for same reduction in current. Cheapest option for MV motors
autotransformer	Increasing	Similar to Star-Delta starting applied to MV motors.
Korndorfer starter	More expensive	Is the auto-transformer method with extra contactor to avoid the open circuit transition.
Rotor Resistance	Comparable with Korndorfer	Motor is much more expensive due to slip rings. Maintenance required on brushes. Slip Energy Recovery can be used giving speed control over a range of about +/-30% of ns (more possible but gets more & more expensive).
Phase Control	OK with LV motor but not MV	Electronic version of infinitely adjustable autotransformer ratio. Harmonics and sharp wave fronts a problem.
PWM	More expensive the phase control	Ditto (1) above, harmonics not so bad but sharp wavefronts a lot worse (switching frequency). Can get V/F constant so better torque possible.

1.3.6 Slip Energy Recovery

It has already been seen that physically changing the rotor resistance will change the shape of the torque speed curve. Suppose that a resistor could be made to take any of a range of positive and negative values and connect that resistor into the rotor circuit by slip rings.

Increasing the resistance produces the effects already seen whilst reducing it drives the characteristic the other way.

Positive resistance ulls more energy across the airgap (Pg) and thus causes a larger slip. Negative resistance is the same as injecting energy into the rotor. An electronic unit can thus change the magnitude and direction of the airgap power flow and hence vary the induction motor speed over a range above & below synchronous speed.



Slip Energy Recovery Drive System

SERs produce inter-harmonics in the following way.

- The rotor circuit current is rectified in 6 pulse (to expensive to have a 6 phase wound rotor and slip rings)
- 6 pulse harmonics of the slip frequency produced in rotor
- inversion into stator circuit can be 6 or 12 pulse and has normal harmonics
- rotor circuit harmonic voltage causes ripple on the current pulses of the inverter modulation at slip frequency harmonics.
- = a right mess (analytically speaking)

An other drive known as a cyclo-converter (good for very large low speed drives) does similar things.

1.4 DC Motors

The DC machine comes in two forms Series and Shunt fields; they are noted for

- high starting torque -- good, and
- commutator & brushes -- bad

The ability to produce very large and easily controlled torque arises from the fact that the torque is produced by the interaction of two magnetic fields. In the case of the separately excited shunt field the torque can easily controlled.

Note a basic problem of DC machines : loss of the field can be very destructive:-

Torque = $k_0 * k_1 * I1 * k_2 * I_2 = P / w$

If one of the currents falls to zero then the speed has to rise very high with the very real danger that the rotor and / or commutator may fragment.

Equally the DC machine, unlike the induction motor, is capable of a wide range of operating speeds

DC machines have been controlled by phase controlled bridges for a long time. Applications such as mine winders and reversing (rolling) mills require the very high torque at zero speed are still a natural load for the DC motor despite the relative lack of knowledge these days about commutator and brush gear selection and maintenance (a black art !).

1.5 Synchronous motors

1.6 Steady State

The normal construction is a field winding with DC current in it on the rotor and the polyphase AC windings in the stator. This means that the synchronous machine is a truly constant speed machine.

DC is fed to the rotor in one of two ways

- Slip rings, or
- AC rotating field with a rotating diode bridge feeding the actual field winding.

These two methods reflect the benefits and drawbacks of slip rings and carbon brushes; the slip ring method allows great control over the magnitude and polarity of the voltage used to regulate the field current whilst the rotating diode method removes the maintenance issues at the expense of slower regulation (there are now two field time constants to overcome) and loss of reversing the field voltage. Some very large synchronous machines have used rotating thyristors in an attempt to overcome limitations of the rotating diode system.

Because the rotor of the synchronous machine is stationary with respect the rotating field, we can write the steady state power and kVAr transfer equation (ignoring resistance) as

P = E * Vbus * sin (?) / X

Q=

Were ? is the angle between the internal emf and X the reactance.

The first derivative of this expression gives the rate of change of power output with pole angle and is also a measure of the amount of reserve power available to pull the machine back into synchronism after a disturbance (sometimes referred to as the synchronising power curve).

The internal EMF of the machine is a function of the excitation current and the load current. These two both produce an MMF and the phasor sum of the two mmfs gives the net excitation. If a synchronous motor is running at virtually no-load its pole angle will be zero degrees and if we then vary the excitation only the kVAr flow will change. At one point this will approach zero (only losses etc require that a finite current flow). This condition is by convention a reference value; higher field current causes over-excitation and lower current under-excitation. By phasor diagrams it can be shown that

- For a synchronous motor, over excitation is required to make the motor draw a leading current, and

- For a synchronous generator, over excitation is required to make the generator supply a lagging current.

These are the two normal (desirable) ways of operating synchronous machinery.

1.7 Transient & Sub-transient Reactance

If the earlier mention of DQ0 theory had been carried on, it would have been seen that there are time dependant reactances in all electrical machines. This same effect can be seen by considering what happens when there is any attempted sudden change of stator current. Stator current produces an mmf which has to link with the rotor coils but these coils all posses a substantial inductance and hence changes in flux linkages cannot occur instantly. Thus whenever there is an attempted change of current in the AC machine, the flux path is confined to the surface of the rotor (so that the current in the rotor bars does not change). These flux paths are result in the stator seeing a low reactance.

As time carries on, the flux gradually links more of the rotor winding and the reactance increases.

Thus the initial reaction to any attempt to change the rotor current, the ac motor impedance initially reduces by a factor of 6 ~ 10 fold; this is known as the sub-transient reactance. After about 1~ 1.5 cycles the reactance has increased to give a factor of 3 ~ 5 times; this is known as the transient reactance. The rate of increase of reactance now slows down. The near steady state reactance is achieved after about a second. Three values of reactance with their associated time constants are traditionally identified because the model used to develop the equations damping windings. Had their been two damper windings plus the field winding, the resultant DQ style equations would have a 4th reactance and associated time constant.

The process described above should not be confused with the speed dependence of current when an induction motor is started but the initial value of stating current in the induction motor

2 Reference List

Hindmarsh – Electrical Machines and their applications (Pergammon press)

Kimbark – Power System Stability vol2.