2 Synchronous Machine Operation

2.1. Synchronous Machine With Stationary Field

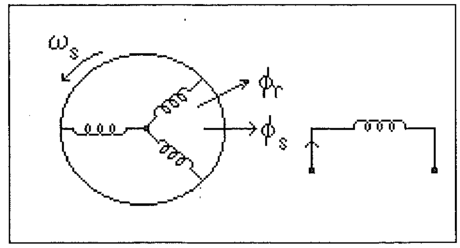

Figure 2.1

The stationary field winding, (*figure* 2.1) carries a direct current and sets up the stator flux ϕ_s stationary in space. The rotor winding carries balanced three phase currents of frequency ω_s, the supply frequency. The three phase balanced currents in the three phase rotor winding results in the rotor flux of constant magnitude and rotating in space at synchronous frequency *with respect to the rotor*. The rotor flux ϕ_r is therefore stationary in space, and at a constant angle with respect to the stator flux. This is a necessary condition for the production of average torque. *If the rotor rotates at any speed other than ω_s, then the stator and rotor fluxes will not be stationary with respect to each other and hence the mean torque is zero.*

2.2. Synchronous Machine With Rotating Field

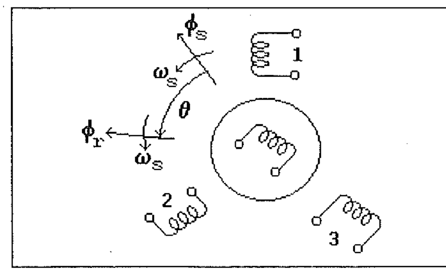

Figure 2.2

The *figure* 2.2 shows the synchronous machine with rotating field. In this case, when the rotor is rotating at synchronous speed, the rotor flux and the stator flux are stationary relative to each other, and there is a net generated torque.

2.3. Calculation Of Torque

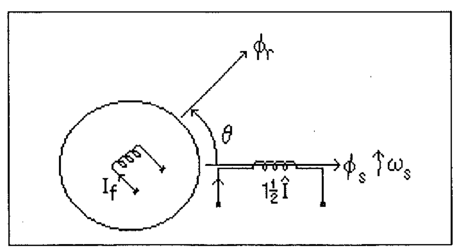

Figure 2.3

The above types of synchronous machines are mathematically similar to each other. Consider the rotating field machine for analysis. When the three phase windings carry balanced three phase currents, it is magnetically equivalent to a single winding carrying a direct current 3/2 times the peak value of the ac phase current and rotating in space at synchronous speed.

The *figure* 2.3 shows this equivalent winding together with the rotor winding.

Let the maximum mutual inductance between the windings be M_o and let the angle between the windings be θ. Further, assume that the rotor and stator are nonsalient.

$m_d = i_1 i_2 \, dM/d\theta$

$i_2 = I_f$ = field current

$i_1 = (3/2)\hat{I}$; $\hat{I}$ = peak ac phase current

$M = M_o \cos \theta$

$M_d = -(3/2)\ I_f\ \hat{I}\ M_o \sin \theta$ ...2.3-1

Torque is **DC** when θ is constant.

If the rotor were to move at a speed ω different from ω_s, then $\theta = (\omega - \omega_s)t$ and torque becomes pure ac with no average value.

Torque is maximum when θ = ±90° and zero when θ = 0°.

When the machine is not loaded (M_L=0), θ is zero. When the machine is loaded as a motor, then the rotor will temporarily slow down allowing θ to reduce to a value necessary to generate the required torque. Then it will continue to run at synchronous speed.

If the machine is loaded as a generator, it will speed up temporarily and θ will increase till the braking torque equals the prime mover torque. As a generator, the rotor flux leads the stator flux.

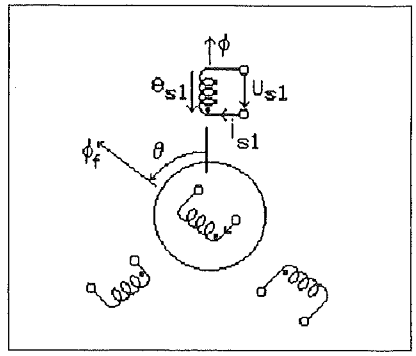

Figure 2.4

2.4. Voltage Equation

Consider the synchronous machine shown in *figure* 2.4 in the open circuited condition (I = 0). Assume the mutual inductance between phase 1 winding and the field is $M = M_o \cos \theta$, where θ is the angle by which the field leads phase 1 winding, in the direction of rotation. Let the value of θ at time t = 0 be δ, so that $\theta = \omega t + \delta$.

The generated voltage in the phase 1 winding e_{s1} will be the terminal voltage

$e_{s1} = (d/dt)\ M\ I_f = I_f\ (dM/dt) = I_f\ (dM/d\theta)(d\theta/dt)$

$= -I_f\ \omega\ M_o \sin \theta$

$= -I_f\ \omega\ M_o \sin(\omega t + \delta)$

$e_{s1} = -E \sin(\omega t + \delta)\ ;\ E = \omega\ M_o\ I_f$ ...2.4-1

When the machine is loaded, the phase windings carry balanced three phase currents

$i_{s1} = I \cos \omega t\ ;\ i_{s2} = I \cos(\omega t - 120°);\ i_{s3} = I \cos(\omega t - 240°)$

The field current is I_f. For balanced conditions, the voltage induced in phase 1 winding on account of 2 & 3 phase currents can be accounted for by assuming an effective value for the self inductance of the phase 1 winding equal to 3/2 times the actual value. Zero time is defined as the instant of maximum current in phase 1.

Then,

$v_{s1} = i_{s1}R_s + (d/dt)L_s i_{s1} + (d/dt)\, MI_f$

$= R_s i_{s1} + L_s(di_{s1}/dt) - E\sin(\omega t + \delta)$ ...2.4-2

Substituting for $i_{s1} = I\cos\omega t$, we get

$v_{s1} = R_s I\cos\omega t + L_s(d/dt)\, I\cos\omega t$
$- E\cos(\omega t + \delta + 90^{o})$ ...2.4-3

2.5. Phasor Diagram

The eq. 2.4-3 may be represented in the phasor form, assuming that the machine is operating at a lagging power factor as a motor. The input power is positive. The terminal voltage is taken as the reference phasor. The relationship between V_s and I_s are as shown in *figure* 2.5. The numbers in the phasor diagram give the sequence in which it is constructed. When the resistive (I_sR_s) and reactive (I_sX_s) drops are added to Vs, the induced voltage E is generated. The field *mmf* (Fr) is at a right angle to the generated voltage E. The gap *mmf* is obtained by adding Fs & Fr.

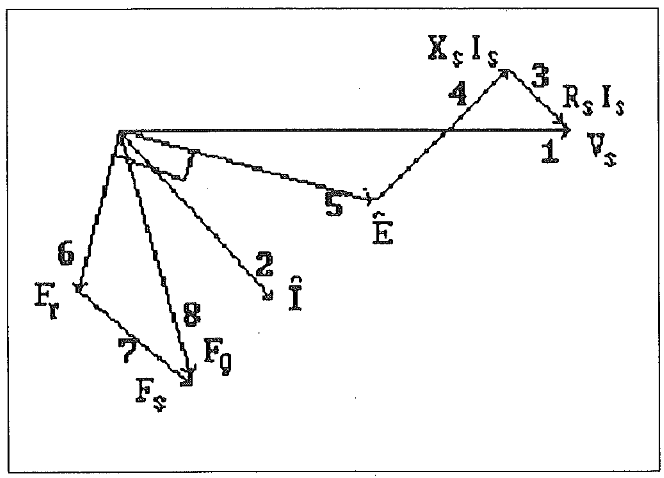

Figure 2.5

The reactance X_s ($=\omega L_s$) of the machine has two components, the magnetising reactance X_m and the leakage reactance X_{ls}. The voltage behind the leakage reactance will be voltage corresponding to the gap flux. The phasor diagram of conventional equivalent circuit is shown in *figure* 2.6.

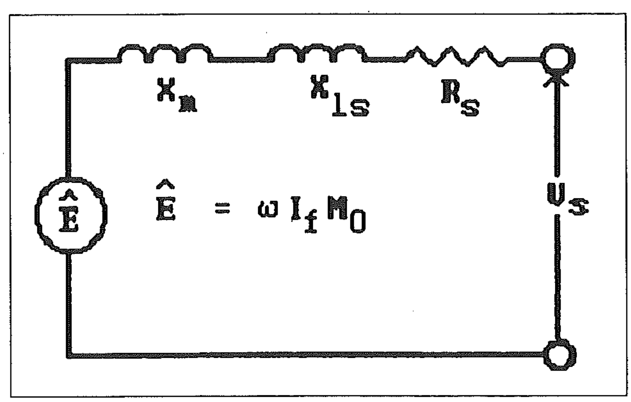

Figure 2.6

NOTES