7 Field Oriented Control of Induction Motors

The principle of field oriented control is developed in the contextof a squirrel cage induction motor drive. The block diagram of the drive is presented and explained.

7.1. Space Phasors

The conceptual foundation for field oriented control lies in space phasor modelling of **AC** machines. It is therefore necessary to first develop an appreciation of the concept of space phasors. Consider a three phase winding in an **AC** machine, for example, the stator winding of an induction motor. *Figure* 7.1a shows the schematic diagram of the three coils, each of which has N_s turns. The diagram shows the spatial orientation of the three coils, the angles being in electrical radians.

It is assumed that the spatial distribution of *mmf* produced by each coil is sinusoidal in nature and also that the neutral is isolated.

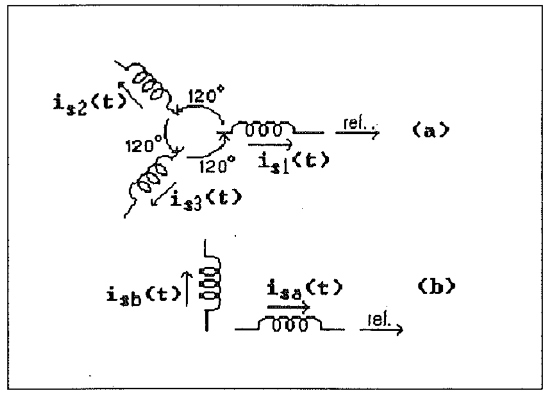

Figure 7.1

So that the condition

$$i_{s1}(t) + i_{s2}(t) + i_{s3}(t) = 0 \qquad \text{...7.1-1}$$

holds at all instants of time. The currents can have any general variation with respect to time. The axis of coil 1 is taken as the reference for spatial orientation. At any given instant of time, the net *mmf* produced by the three coils is given by adding the *mmfs* due to the individual coils, but with appropriate spatial orientation *i.e.*, vectorially. The net *mmf* can, therefore, in general have components along and perpendicular to the reference direction, and these components are denoted by subscripts a and b respectively. The values are given by

$$mmf_a = N_s[i_{s1}(t)+i_{s2}(t) \cos \gamma + i_{s3}(t) \cos 2\gamma] \qquad \text{...7.1-2}$$

$$mmf_b = N_s[i_{s2}(t) \sin \gamma + i_{s3}(t) \sin 2\gamma] \qquad \text{...7.1-3}$$

where $\gamma = 2\pi/3$ electrical radians. The system of three coils can be replaced by a system of two coils a and b as shown in *figure* 7.1b. having the same number of turns N_s as the original coils and carrying currents $i_{sa}(t)$ and $i_{sb}(t)$ given by

$$i_{sa}(t) = i_{s1}(t) - (1/2)\, i_{s2}(t) - (1/2) i_{s3}(t) \qquad \text{...7.1-4}$$

$$i_{sb}(t) = i_{s2}(t)\, (\sqrt{3}/2) - i_{s3}(t)\, (\sqrt{3}/2) \qquad \text{...7.1-5}$$

these can be rewritten as

$i_{sa}(t) = (3/2)\, i_{s1}(t)$ ...7.1-6

$i_{sb}(t) = (\sqrt{3}/2)[i_{s2}(t) - i_{s3}(t)]$ ...7.1-7

The net *mmf* produced by the two systems of coils is identical. The net effect of all the currents is thus obtained by adding $i_{sa}(t)$ and $i_{sb}(t)$ with proper spatial orientation. Using complex notation, this can be expressed by defining a *current space phasor* $\underline{i}_s(t)$ by

$\underline{i}_s(t) = i_{sa}(t) + j\, i_{sb}(t)$ ...7.1-8

The current space phasor is a complex function of time, whose real and imaginary parts give the components of current along two mutually perpendicular directions in space. Pictorially the space phasor $\underline{i}_s(t)$ can be represented by a vector in a two dimensional plane, the real and imaginary components being $i_{sa}(t)$ and $i_{sb}(t)$.

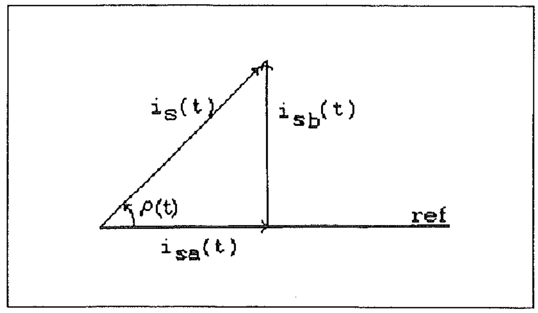

Figure 7.2

The space phasor can also be expressed in polar instead of cartesian form as follows

$\underline{i}_s(t) = i_s(t)\, e^{j\rho(t)}$ ...7.1-9

where $i_s(t)$ - instantaneous amplitude of space phasor and ρ - instantaneous angle that the space phasor makes with the reference direction.

Since the orientations refer to spatial direction in *figure* 7.2, it should not be confused with the usual time phasor diagram of sinusoidal steady state analysis.

The space phasor $\underline{i}_s(t)$ can also be expressed in terms of the original three phase currents as follows

$\underline{i}_s(t) = i_{s1}(t) + i_{s2}(t)\, e^{j\gamma} + i_{s3}(t)\, e^{j2\gamma}$ ...7.1-10

where $\gamma = 2.\pi / 3$

Similarly, space phasors can be defined for other quantities such as voltages and flux linkages associated with the three phase system of windings.

From a study of polyphase windings, it is seen that, if the three individual quantities are balanced three phase sinusoids, then the space phasor will have a constant amplitude and will rotate in space with constant angular velocity.

But, the definition of space phasors is not limited to sinusoidal quantities alone. Any general time variation is possible for the three individual variables. The concept of a space phasor is a useful tool in the analysis of the AC motor drives, because the inverters that drive the motor produce non-sinusoidal voltages. The currents produced by a current source inverter, for example, have the waveform shown in *figure* 7.3. The corresponding space phasor will therefore occupy a fixed position in space for one sixth of a cycle and jump in position by 60° at every commutation in the inverter.

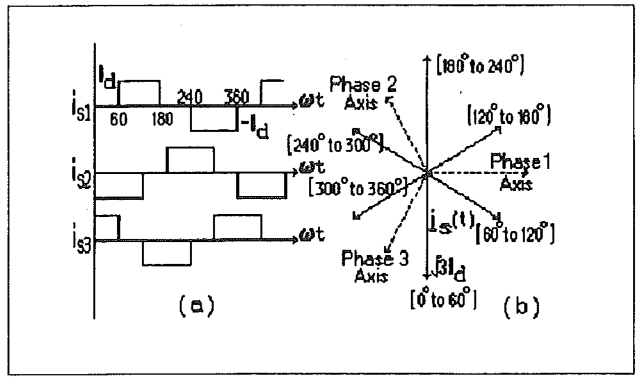

Figure 7.3

This describes the equivalence between three phase and two phase windings, with the important extension that the two real quantities are composed into one complex quatity known as the *space phasor*. The advantage, is that the motion of the space phasor can be visualized.

7.2. Equations in Space Phasor Form

The symmetrical three phase squirrel cage induction motor has a three phase system of coils on the stator and a cage on the rotor which can be considered to be equivalent to a three phase winding. The two sets of windings can be represented by two equivalent two phase coils as shown in *figure* 7.4. The rotor axis makes an angle $\in(t)$ with respect to the stator axis.

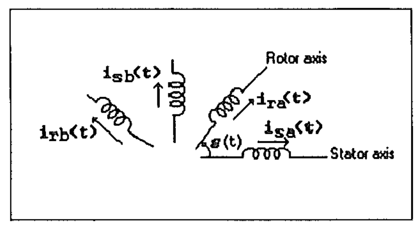

Figure 7.4

The two current space phasors $\underline{i}_s(t)$ and $\underline{i}_r(t)$ can be defined for the stator and rotor current respectively as follows

$$\underline{i}_s(t) = i_{sa}(t) + ji_{sb}(t) \qquad ...7.2\text{-}1$$

$$\underline{i}_r(t) = i_{ra}(t) + ji_{rb}(t) \qquad ...7.2\text{-}2$$

The two space phasors are defined with respect to different coordinates axes, $\underline{i}_s(t)$ with respect to stator coordinates and $\underline{i}_r(t)$ with respect to rotor coordinates.

The flux linkages of the various coils are a first step towards the machine voltage equations

$$\psi_{sa}(t) = L_s\, i_{sa}(t) + Mi_{ra}(t)\cos\in - Mi_{rb}(t)\sin\in \qquad ...7.2\text{-}3$$

$$\psi_{sb}(t) = L_s\, i_{sb}(t) + Mi_{ra}(t)\sin\in + Mi_{rb}(t)\cos\in \qquad ...7.2\text{-}4$$

where L_s is the self inductance and M is maximum value of mutual inductance between stator and rotor coils.

Combining the equations 7.2-3 and 7.2-4 to form the stator flux space phasor.

$$\underline{\psi}_s(t) = \psi_{sa}(t) + j\,\psi_{sb}(t) \\ = L_s\,\underline{i}_s(t) + M\underline{i}_r(t)\,e^{j\epsilon} \qquad ...7.2\text{-}5$$

Similarly, the rotor flux linkage space phasor can be derived as

$$\underline{\psi}_r(t) = \psi_{ra}(t) + j\,\psi_{rb}(t) \\ = L_r\,\underline{i}_r(t) + M\underline{i}_s(t)\,e^{-j\epsilon} \qquad ...7.2\text{-}6$$

where L_r is the self inductance of the rotor coils referred to stator number of turns. The form of these equations 7.2-5 & 7.2-6 resembles an equation for a coil with self and mutual inductance except the expression for the current in the second term. It must be remembered that equation 7.2-5 is with respect to stator coordinates and equation 7.2-6 is with respect to rotor coordinates. Therefore, space phasors defined with respect to another coordinate system have to be transformed to the co-ordinate system of the equation.

Multiplication by $e^{j\epsilon}$ results in a clockwise rotation of the coordinate system by an angle ϵ, while multiplication by $e^{-j\epsilon}$ results in an anticlockwise rotation of the coordinate system by the same angle.

The voltage-current equations for the stator and the rotor windings are written in the space phasor form. First the individual coil equations are written as:

$$v_{sa}(t) = R_s\,i_{sa}(t) + (d/dt)\psi_{sa}(t) \qquad ...7.2\text{-}7$$
$$v_{sb}(t) = R_s\,i_{sb}(t) + (d/dt)\psi_{sb}(t) \qquad ...7.2\text{-}8$$
$$v_{ra}(t) = R_r\,i_{ra}(t) + (d/dt)\psi_{ra}(t) \qquad ...7.2\text{-}9$$
$$v_{rb}(t) = R_r\,i_{rb}(t) + (d/dt)\psi_{rb}(t) \qquad ...7.2\text{-}10$$

Combining eq. 7.2-7 with 7.2-8 and 7.2-9 with 7.2-10, the resultant complex equations:

$$\underline{v}_s(t) = R_s\,\underline{i}_s(t) + (d/dt)\underline{\psi}_s(t) \qquad ...7.2\text{-}11$$
$$\underline{v}_r(t) = R_r\,\underline{i}_r(t) + (d/dt)\underline{\psi}_r(t) \qquad ...7.2\text{-}12$$

Using equations 7.2-5 and 7.2-6 these can be rewritten as

$$\underline{v}_s(t) = R_s\,i_s(t) + L_s(d/dt)\,\underline{i}_s(t) + M(d/dt)(\underline{i}_r(t)\,e^{j\epsilon}) \qquad ...7.2\text{-}13$$

$$\underline{v}_r(t) = R_r\,i_r(t) + L_r(d/dt)\,\underline{i}_r(t) + M(d/dt)(\underline{i}_s(t)\,e^{-j\epsilon}) \qquad ...7.2\text{-}14$$

eq. 7.2-13 refers to the stator and is in stator coordinates whereas eq. 7.2-14 refers to the rotor and is the rotor coordinates. For the squirrel cage induction motor, of course, $\underline{v}_r(t)$ is zero.

Each of the above equations is actually two equations combined into one. With these two equations the electrical behaviour of the machine is defined.

The torque developed by the machine is given by

$$M_d = (2/3)M\ \mathrm{Im}[\underline{i}_s(t)\{i_r(t)e^{j\epsilon}\}^*] \qquad ...7.2\text{-}15$$

Where Im stands for the imaginary part and * denotes the complex conjugate. Therefore the complete equations that describe the behaviour of the machine are as follows:

$$R_s\,\underline{i}_s(t) + L_s(d/dt)\,\underline{i}_s(t) + M(d/dt)(\underline{i}_r(t)\,e^{j\epsilon}) = \underline{v}_s(t)$$

$R_r \underline{i}_r(t) + L_r(d/dt)\, \underline{i}_r(t) + M(d/dt)(\underline{i}_s(t)\, e^{-j\epsilon}) = 0$

$J(d\omega/dt) = (2/3)M\ \mathrm{Im}[\underline{i}_s(t)\{\underline{i}_r(t)e^{j\epsilon}\}^*] - M_{load}$

$\omega = d\epsilon/dt$ ...7.2-16

The above equations describe the dynamic behaviour of the machine. The steady-state behaviour, pertaining to the sinusoidal steady state operation, can be deduced from the above.

7.3. Sinusoidal Steady State Performance

Under sinusoidal steady state conditions, the applied stator voltages can be expressed as follows:

$v_{s1}(t) = \sqrt{2}\ V_s \cos(\omega_1 t + \tau_1)$
$v_{s2}(t) = \sqrt{2}\ V_s \cos(\omega_1 t - \gamma + \tau_1)$
$v_{s3}(t) = \sqrt{2}\ V_s \cos(\omega_1 t - 2\gamma + \tau_1)$ ...7.3-1

When composed into a space phasor according to eq. 7.1-10, the stator voltage space phasor is expressed as

$\underline{v}_s(t) = (3\sqrt{2}/2)\ \underline{V}_s\ e^{j(\omega 1t + \tau 1)}$ ...7.3-2
ie
$\underline{v}_s(t) = (3\sqrt{2}/2)\ \underline{V}_s\ e^{j\omega 1t}$ ...7.3-3

where $\underline{V}_s$ is a complex constant, with amplitude equal to the rms line to neutral voltage and spatial orientation giving the instantaneous position of the peak of the voltage space wave at the instant t = 0. With the voltage input, the solution to the stator and rotor equation in 7.2-16 can be shown as:

$\underline{i}_s(t) = (3\sqrt{2}/2)\ \underline{I}_s\ e^{j\omega 1t}$ ...7.3-4
$\underline{i}_r(t) = (3\sqrt{2}/2)\ \underline{I}_r\ e^{j\omega 2t}$ ...7.3-5

where $\omega_2 = \omega_1 - \omega = \omega_1 - d\epsilon/dt$ ...7.3-6

The rotor current referred to the stator coordinates is given by

$\underline{i}_r(t)e^{j\epsilon(t)} = (3\sqrt{2}/2)\ \underline{I}_r\ e^{j\omega 1t}$ ...7.3-7

With the definitions $M = L_0$; $L_s = (1+\sigma_s)L_0$; $L_r = (1+\sigma_r)L_0$ the stator and rotor equations in 7.2-16 are rewritten as

$(R_s + j\omega_1\sigma_s L_0)\underline{I}_s + j\omega_1 L_0(\underline{I}_s+\underline{I}_r) = \underline{V}_s$ ...7.3-8
$(R_r + j\omega_2\sigma_r L_0)\underline{I}_r + j\omega_2 L_0(\underline{I}_s+\underline{I}_r) = 0$ ...7.3-9

If the ratio between the rotor frequency ω_2 and the stator frequency ω1 is defined as the slip *i.e.* $s=\omega_2/\omega_1$, equation 7.3-9 can be rewritten as

$(R_r/s + j\omega_1\sigma_r L_0)\underline{I}_r + j\omega_1 L_0(\underline{I}_s+\underline{I}_r) = 0$ ...7.3-10

Equations 7.3-8 and 7.3-10 together yield a steady state equivalent circuit of the induction machine shown in *figure* 7.5.

The complex constants $\underline{V}_s$, $\underline{I}_s$ and $\underline{I}_r$ are proportional to the instantaneous values of the corresponding space phasors $\underline{v}_s$, $\underline{i}_s$, and $\underline{i}_r$ at the instant t = 0.

However, because of the assumption that the winding *mmfs* are sinusoidally distributed in space, there is an one to one correspondence between the above circuit and the usual one based on time phasors.

Hence, the parameters of the above circuit can be determined by the usual *no-load* and *locked rotor* tests.

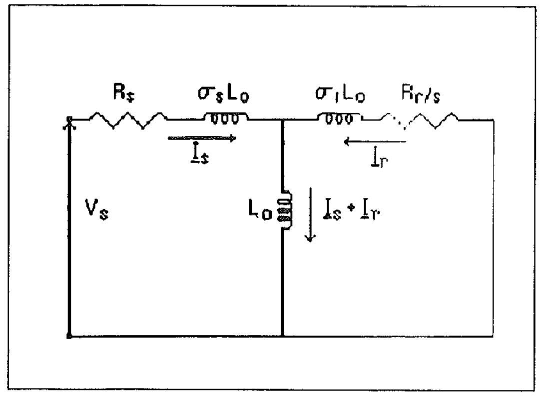

Figure 7.5

All the steady-state characteristics of the machine such as torque-speed characteristics, circle diagram, etc., can therefore be deduced from the equivalent circuit of *figure* 7.5. However, the main interest in the development of the concept of field oriented control is to know the position and magnitude of the different fluxes in the machine. The space phasor diagram of *figure* 7.6 below is drawn to show the spatial orientation of the different fluxes in the machine.

These can be defined as follows:

Mutual or airgap flux $\underline{\psi}_m = L_0[\underline{I}_s+\underline{I}_r] \triangleq L_0\underline{I}_m$

Stator Flux $\underline{\psi}_s = \sigma_s L_0\underline{I}_s + L_0[\underline{I}_s+\underline{I}_r]$
$= L_0[(1+\sigma_s)\underline{I}_s+\underline{I}_r] \triangleq L_0\underline{I}_{ms}$ ...7.3-11

Rotor Flux is $\underline{\psi}_r = \sigma_r L_0\underline{I}_r + L_0[\underline{I}_s+\underline{I}_r]$
$= L_0[(1+\sigma_r)\underline{I}_r+\underline{I}_s] \triangleq L_0\underline{I}_{mr}$ ...7.3-12

In addition to the magnetising current $\underline{I}_m$ responsible for mutual flux, two additional magnetising currents $\underline{I}_{ms}$ and $\underline{I}_{mr}$ have been defined in eq. 7.3-11 and 7.3-12 to account for stator and rotor fluxes also. Even though this has been done in the context of sinusoidal steady-state operation, identical definitions can be given in the general case of transient non-sinusoidal operation also.

All the fluxes rotate at the synchronous speed ω_1 with respect to the stationary stator axis. The torque developed by the machine can be expressed as the vector product of the stator current and any of these fluxes.

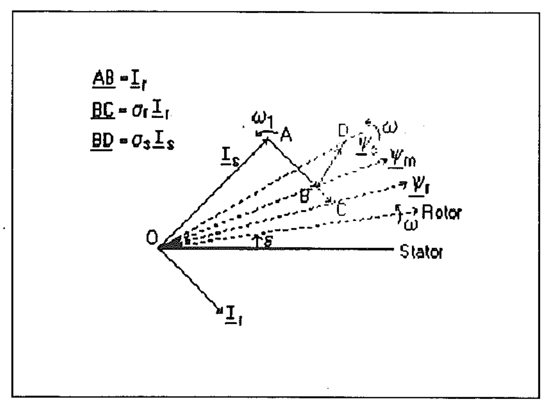

Figure 7.6

In order to establish an analogy between the induction motor and the **DC** machine, with similar decoupling between flux and torque, the stator current I_s should be decomposed into two spatially orthogonal components, along and perpendicular to the flux. But which flux ?

To decide this question, the machine equations 7.2-16 have to be recast using the stator current components oriented along the different fluxes. It has been established that to obtain decoupling between flux and torque, the equations should be viewed from a frame of reference fixed to the rotor flux $\underline{\psi}_r$ (t).

7.4. Dynamics in Rotor Flux Frame of Reference

It is assumed here that the machine is operated from a current source which impresses on the machine windings a given stator current space phasor $\underline{i}_s(t)$. This can be realised in practice with a pulse width modulated inverter operating at a switching frequency of a few kilohertz in the current regulated **PWM** mode. The first of the machine equations 7.2-16, therefore serves only to determine the stator voltage $\underline{v}_s(t)$ and need not be considered in determining the dynamic response of the machine. It is the second equation, corresponding to the rotor, that determines the machine behavior.

This equation is repeated here, with $M = L_o$ and $L_r = (1+\sigma_r)L_o$

$$R_r\underline{i}_r(t) + (1+\sigma_r)L_0(d/dt)\underline{i}_r(t) + L_0(d/dt)\{(\underline{i}_s(t)e^{-j\epsilon})\} = 0$$

The rotor flux space phasor is given by

$$\underline{\psi}_r(t) = L_0(1+\sigma_r)\underline{i}_r(t) + L_0\underline{i}_s(t)e^{-j\epsilon} \qquad ...7.4\text{-}1$$

in rotor co-ordinates. The representation in terms of stator coordinates can be obtained by multiplying by $e^{j\epsilon}$, giving

$$\underline{\psi}_r(t)e^{j\epsilon} = L_0[\underline{i}_s(t) + (1+\sigma_r)\underline{i}_r(t)e^{j\epsilon} = L_0\underline{i}_{mr} \qquad ...7.4\text{-}2$$

Therefore $\underline{i}_{mr}(t) = \underline{i}_s(t) + (1+\sigma_r)\underline{i}_r(t)e^{j\epsilon}$ ...7.4-3

The rotor equation then becomes

$$[R_r/(1+\sigma_r)]\{\underline{i}_{mr}(t) - \underline{i}_s(t)\}\, e^{-j\epsilon} + L_0(d/dt)\{[\underline{i}_{mr}(t)-\underline{i}_s(t)e^{-j\epsilon}]\} + L_0(d/dt)(\underline{i}_s(t)e^{-j\epsilon}) = 0 \qquad ...7.4\text{-}4$$

It must be observed that 7.4-4 is still in terms of the rotor coordinate system. After simplification

$$[R_r/(1+\sigma_r)]\{\underline{i}_{mr}(t) - \underline{i}_s(t)\}e^{-j\epsilon} + L_0\{(d/dt)\underline{i}_{mr}(t) - j(d\epsilon/dt)\,\underline{i}_{mr}(t)\}e^{-j\epsilon}] = 0 \qquad ...7.4\text{-}5$$

If equation 7.4-5 is multiplied by $e^{j\epsilon}$, the resulting equation will be in terms of stator coordinates. $d\epsilon/dt = \omega$, the speed of the machine,

$$L_0(d/dt)\underline{i}_{mr}(t) + [R_r(1+\sigma_r)]\underline{i}_{mr}(t) - j\omega L_0\underline{i}_{mr}(t) - (R_r/(1+\sigma_r))\underline{i}_s(t) = 0 \qquad ...7.4\text{-}6$$

This equation can now be expressed in terms of a coordinate system fixed to the rotor flux $\underline{\psi}_r(t)$ or equivalently to the current $\underline{i}_{mr}(t)$. To do this, $\underline{i}_{mr}(t)$ is first expressed in polar form with respect to the stator coordinates as

$$\underline{i}_{mr}(t) = i_{mr}(t)e^{j\rho(t)} \qquad ...7.4\text{-}7$$

where $i_{mr}(t)$ is the instantaneous magnitude of the current space phasor $\underline{i}_{mr}(t)$ and ρ is its instantaneous position with respect to the stator real axis. Now eq. 7.4-6 can therefore be written as:

$$L_0(d/dt)i_{mr}(t)e^{j\rho(t)} + [R_r/(1+\sigma_r)]i_{mr}(t)e^{j\rho(t)} - j\omega L_0 i_{mr}(t)e^{j\rho(t)} - (R_r/(1+\sigma_r))\underline{i}_s(t) = 0 \qquad ...7.4\text{-}8$$

ie

$$L_0(d/dt)i_{mr}(t)e^{j\epsilon(t)} + [R_r/(1+\sigma_r)]i_{mr}(t)e^{j\rho(t)} + jL_0(d\rho/dt)i_{mr}(t)e^{j\rho(t)} - j\omega L_0 i_{mr}(t)e^{j\rho(t)} = (R_r/(1+\sigma_r))\underline{i}_s(t) \qquad ...7.4\text{-}9$$

Eq. 7.4-9, which is still in the stator coordinates, can now be transformed into rotor flux coordinates by multiplying by $e^{-j\rho(t)}$, giving

$$L_0(d/dt)i_{mr}(t) + [R_r/(1+\sigma_r)]i_{mr}(t) - j(\omega_{mr}-\omega)\, L_0 i_{mr}(t) = (R_r/(1+\sigma_r))\underline{i}_s(t)e^{-j\rho(t)} \qquad ...7.4\text{-}10$$

where $d\rho/dt = \omega_{mr}$ is the instantaneous angular speed of the rotor flux. The right hand side of eq. 7.4-10 contains the transformation of the stator current space phasor to the rotor flux coordinate system.

If the coordinates of the stator currents in this system are denoted by $i_{ds}(t)$ and $i_{qs}(t)$, then

$$\underline{i}_s(t)e^{-j\rho(t)} = i_{ds}(t) + ji_{qs}(t) \qquad ...7.4\text{-}11$$

Eq. 7.4-10 can now be seperated into real and imaginary parts as follows:

$$L_0(d/dt)i_{mr}(t) + [R_r/(1+\sigma_r)]i_{mr}(t) = (R_r/(1+\sigma_r))i_{ds}(t)$$

$$(\omega_{mr}-\omega)\, L_0 i_{mr}(t) = [R_r/(1+\sigma_r)]i_{qs}(t) \qquad ...7.4\text{-}12$$

Defining the rotor time constant as

$$T_r = L_r/R_r = L_0(1+\sigma_r)/R_r \qquad ...7.4\text{-}13$$

Eq. 7.4-12 can be rewritten as

$$T_r(d/dt)i_{mr}(t) + i_{mr}(t) = i_{ds}(t) \qquad ...7.4\text{-}14$$

$$\omega_{mr}(t) = (d\rho/dt) = \omega + (i_{qs}(t)/T_r i_{mr}(t)) \qquad ...7.4\text{-}15$$

The above equations now describe the dynamics of the current fed induction motor in the *rotor flux oriented reference frame*, referred to as field oriented frame of reference. $i_{ds}(t)$ and $i_{qs}(t)$ are the inputs to the machine. $i_{mr}(t)$, $d\rho/dt$ and ω are the outputs or the response of the machine. To make the equations complete, the torque equation should also be written in terms of field coordinates.

From eq. 7.4-15, the torque developed is given by

$$M_d(t) = (2/3)\{L_0\, \mathrm{Im}\{\underline{i}_s(t)[\underline{i}_r(t)e^{j\epsilon}]^*\}$$
$$M_d(t) = (2/3)\{L_0/(1+\sigma_r)\}\, \mathrm{Im}\{\underline{i}_s(t)[\underline{i}_{mr}(t) - \underline{i}_s(t)]^*\}$$
$$= (2/3)\{L_0/(1+\sigma_r)\}\, \mathrm{Im}\{\underline{i}_s(t)[\underline{i}_{mr}(t)]^*\}$$

$$M_d(t) = (2/3)\{L_0/(1+\sigma_r)\}\, \mathrm{Im}\{\underline{i}_s(t)[i_{mr}(t)e^{j\rho(t)}]^*\}$$
$$= (2/3)\{L_0/(1+\sigma_r)\}\, \mathrm{Im}\{\underline{i}_{mr}(t)[\underline{i}_s(t)e^{j\rho(t)}]\}$$
$$= (2/3)\{L_0/(1+\sigma_r)\}\, \mathrm{Im}\{i_{mr}(t)\{i_{ds}(t)+ji_{qs}(t)\}\}$$
$$= (2/3)\{L_0/(1+\sigma_r)\}\, i_{mr}(t)i_{qs}(t) \qquad ...7.4\text{-}16$$

Therefore the complete machine equations can be given as:

$T_r(d/dt)\, i_{mr}(t) + i_{mr}(t) = i_{ds}(t)$ ...7.4-17
$w_{mr} = (d\rho(t)/dt) = \omega(t) + \{i_{qs}(t)/[T_r i_{mr}(t)]\}$ ...7.4-18
$J(d\omega/dt) = (2/3)(L_0/(1+\sigma_r))i_{mr}(t)i_{qs}(t) - M_{load}$ ...7.4-19
$d\epsilon/dt = \omega$ ...7.4-20

The decoupling between flux and torque control is now clear. If it is desired to change the flux, the input $i_{ds}(t)$ to the machine should be controlled. The response of $i_{mr}(t)$ is slow, limited by a large rotor time constant T_r as seen from eq. 7.4-17.

However, if it is desired to control the torque, this is done by controlling the input $i_{qs}(t)$ appropriately, without disturbing $i_{mr}(t)$ by changing $i_{ds}(t)$. The torque response does not have any limiting time constants under this type of control and torque response is instantaneous.

Thus the stator current is now decomposed into two spatially orthogonal components $i_{ds}(t)$ and $i_{qs}(t)$, resembling the field and armature currents of the dc machine, which control the flux and the torque independently. This is the basis of field oriented control of the induction motor. Pictorially the process of control can be represented as shown in *figure* 7.7

Assume that initially the stator current space phasor is OA. If it is there is a need to increase the developed torque, the correct way to achieve fast decoupled response is to move the stator current to position OB, thereby keeping i_{ds} constant and changing only i_{qs}. If an attempt is made to move the current space phasor to a location such as OC then i_{ds} and consequently i_{mr} have to change. This will result in a slow oscillatory response of the machine.

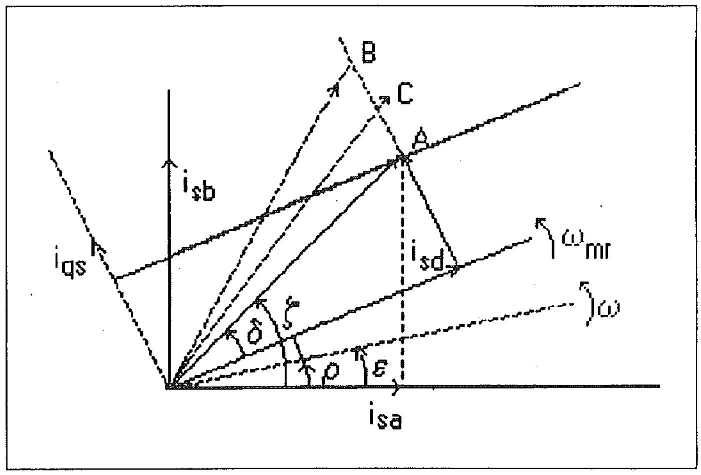

Figure 7.7

The dynamic behaviour of the induction motor in the rotor flux reference frame can be represented by the block diagram shown in *figure* 7.8.

The motor block diagram consists of three sections. In the first section the three phase currents in the stator windings *viz.* i_{s1}, i_{s2} and i_{s3} are converted into equivalent two phase stator currents i_{sa} and i_{sb}.

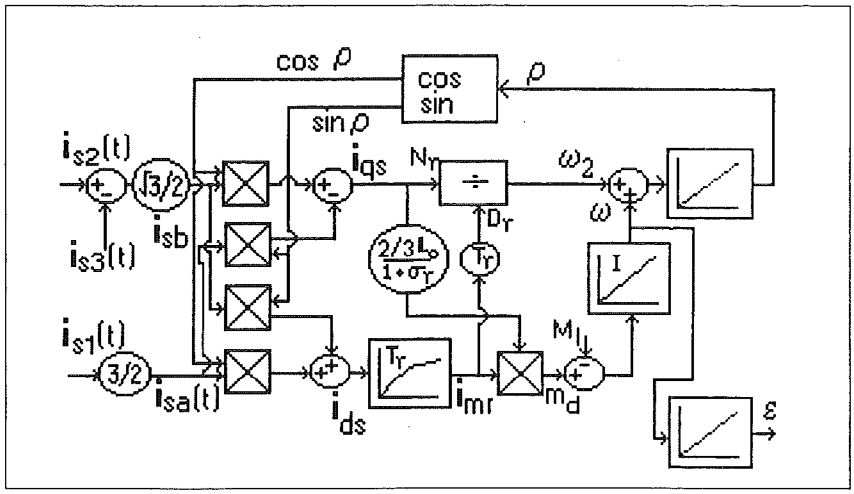

Figure 7.8

In the second section, these two phase currents are transformed onto the rotor flux oriented components i_{ds} and i_{qs} by the relationship:

$$i_{ds}(t) = i_{sa}(t) \cos \rho(t) + i_{sb}(t) \sin \rho(t) \qquad ...7.4\text{-}21$$

$$i_{qs}(t) = i_{sb}(t) \cos \rho(t) - i_{sa}(t) \sin \rho(t) \qquad ...7.4\text{-}22$$

ρ being the instantaneous position of the rotor flux with respect to the stator axis. The third section incorporates the dynamics described by equations.

7.5. Field Oriented Control Of Induction Motor

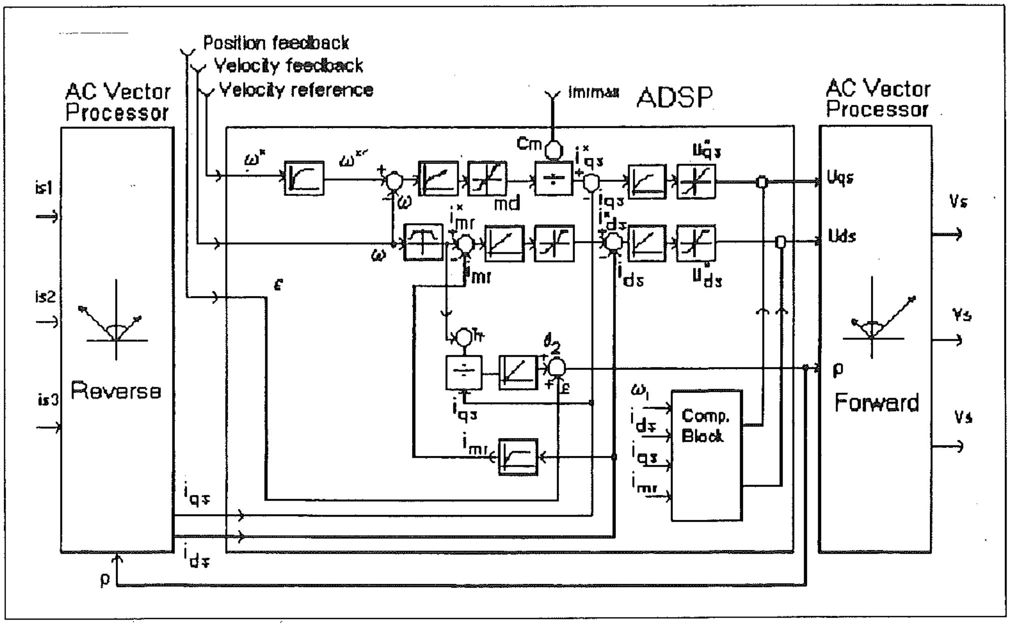

Figure 7.9

It is clear by now that in order to achieve decoupled control of the flux and torque in an induction motor, the components i_{ds} and i_{qs} of the stator current $\underline{i}_s$ have to be controlled. The magnitude of i_{qs} should be controlled to adjust the torque and the magnitude of i_{ds} should be controlled to adjust the rotor flux or equivalently the rotor flux magnetising current i_{mr}. The structure of an induction motor drive based on field orientation is therefore as shown in *figure* 7.9.

The torque loop generates the command value i_{qsref} and the flux loop generates the command i_{dsref}. The speed and position loops are closed around the torque loop. The command values of the field oriented current components have to be translated into command values for the actual stator currents, *i.e.* i_{s1ref}, i_{s2ref} and i_{s3ref}. This is accomplised by a process which is the inverse of that which occurs within the machine. The relevant equations are

$$i_{saref} = i_{dsref} \cos\rho - i_{qsref} \sin \rho \qquad \text{...7.5-1}$$
$$i_{sbref} = i_{qsref} \cos\rho + i_{dsref} \sin \rho \qquad \text{...7.5-2}$$
$$i_{s1ref} = 2/3\, i_{saref} \qquad \text{...7.5-3}$$
$$i_{s2ref} = -(1/3)i_{saref} + (1/\sqrt{3})i_{sbref} \qquad \text{...7.5-4}$$
$$i_{s3ref} = -(1/3)i_{saref} - (1/\sqrt{3})i_{sbref} \qquad \text{...7.5-5}$$

If the command values for the field oriented current components are to be properly translated into command values for the phase currents, it is clear that accurate information regarding the instantaneous position of the rotor flux, given by the angle ρ, is essential. In *figure* 7.9, this is accomplished through the flux acquisition system.

Provided this task can be performed accurately, field oriented control yields significant advantages:

- it allows direct control of flux and torque, making torque limiting and field weakening possible

- with correct information regarding the angle rho, the motor is self controlled and cannot pull out; in the event of overload torque, the motor is stalled with maximum torque.

- decoupling between flux and torque is effective even under dynamic conditions.

- since the controllers process dc quantities in the steady state, the effect of unavoidable phase shifts in the control loops is not present.

- efficient control in field weakening with indirect field oriented control without non linear or adaptive control.

These advantages, however, are based on acquiring the flux signals accurately over the entire speed range down to zero speed, especially for reversing drives. This is a formidable task and had to await the advent of signal processing and vector transform silicon chips. With current trends in signal processing these tasks can be effectively accomplished.

Depending on the method employed to sense the flux, field oriented control can be classified into two major categories, direct and indirect.

In *direct field orientation*, the air gap flux in the machine is directly measured by measuring the induced voltage in Hall sensors or flux sensing coils and integrating it. However, there are several difficulties associated with this approach. The motor has to be specially modified in order to accomodate the sensing device. Moreover, the Hall sensors are fragile. Also, the integrators are subject to drift at low frequencies and this limits the lowest speed at which the technique can be used. The induced voltage in the sensing devices contain harmonics due to rotor slots.

These harmonics are difficult to filter as their frequency changes with the speed of the machine. It is because of these reasons that the direct method is usually very difficult to employ. But it has the merit that the measurements are not dependant on machine parameter values, which change with temparature, saturation etc.

Instead of using the voltages from sensing coils, the machine terminal voltages themselves can be used. However, in this case, the stator resistance drop has to be compensated before integration. Since the resistance changes with temparature, this is difficult to achieve accurately.

A different approach is followed in the *indirect method of field orientation.* This method uses the model equations of the machine with easily measurable quantities as inputs and calculates the magnitudes and position of the rotor flux. The block diagram of *figure* 7.8 which is based on the model of the machine in the field oriented coordinate system, can itself be used to generate the information regarding the actual values of i_{ds}, i_{qs} and i_{mr}, the torque m_d and the angle ρ that the rotor flux makes with the stator axis. The total signal processing tasks to be performed to implement field orientation by this method involves two sets of coordinate transformations.

- the transformation from the actual phase quantities to field oriented coordinates in flux acquisition system.

- the reverse transform from the field coordinates to actual phase coordinates in the control system.

The flux acquisition system accepts as inputs the three (two are sufficient for motors with neutral floating) stator currents and the speed ω and/or the rotor position available from tachometers or position encoders used for speed and position feedback.

Accurate orientation of the stator current space phasor by this method requires a knowledge of machine parameters for performing the computation. For example, the rotor time constant T_r should be known accurately. Since the rotor resistance varies with temparature, T_r is subject to variation. To achieve best results, indirect field orientation requires some kind of adaptation scheme to keep track of parameter variations.