CHAPTER FIVE

DYNAMIC MODEL OF THE INDUCTION MOTOR

5.1 Space Vectors of Motor Variables:

Space vectors of three-phase variables, such as the voltage, current, or flux, are very convenient for the analysis and control of induction motors. Voltage space vectors of the voltage source inverter have already been formally introduced in Section 3.7. Here, the physical background of the concept of space vectors is illustrated [13][4].

Space vectors of stator MMFs in a two-pole motor have been shown in Chapter 2 in Figures 2.7 through 2.10. The vector of total stator MMF, $\boldsymbol{\mathcal{F}}_S$, is a vectorial sum of phase MMFs, $\boldsymbol{\mathcal{F}}_{as}$, $\boldsymbol{\mathcal{F}}_{bs}$, and $\boldsymbol{\mathcal{F}}_{cs}$, that is[13],

$$\boldsymbol{\mathcal{F}}_s = \boldsymbol{\mathcal{F}}_{as} + \boldsymbol{\mathcal{F}}_{bs} + \boldsymbol{\mathcal{F}}_{cs} = \mathcal{F}_{as} + \mathcal{F}_{bs}\, e^{j\frac{2}{3}\pi} + \mathcal{F}_{cs}\, e^{j\frac{4}{3}\pi} \tag{5.1}$$

where $\mathcal{F}_{as}$, $\mathcal{F}_{bs}$, and $\mathcal{F}_{cs}$, denote magnitudes of $\boldsymbol{\mathcal{F}}_{as}$, $\boldsymbol{\mathcal{F}}_{bs}$, and $\boldsymbol{\mathcal{F}}_{cs}$, respectively. In the stationary set of stator coordinates, dq, the vector of stator MMF can be expressed as a complex variable, $\boldsymbol{\mathcal{F}}_s = \mathcal{F}_{ds} + j\mathcal{F}_{qs} = \mathcal{F}_s e^{j\theta S}$, as depicted in Figure 5.1. Because:

$$e^{j\frac{2}{3}\pi} = -\frac{1}{2} + j\,\frac{\sqrt{3}}{2} \tag{5.2}$$

and

$$e^{j\frac{4}{3}\pi} = -\frac{1}{2} - j\,\frac{\sqrt{3}}{2}, \tag{5.3}$$

then, Eq. (5.1) can be rewritten as :

$$\boldsymbol{\mathcal{F}}_s = \mathcal{F}_{ds} + \mathrm{j}\mathcal{F}_{qs} = \mathcal{F}_{as} - \frac{1}{2}\,\mathcal{F}_{bs} - \frac{1}{2}\,\mathcal{F}_{cs} + j\left(\frac{\sqrt{3}}{2}\,\mathcal{F}_{bs} - \frac{\sqrt{3}}{2}\,\mathcal{F}_{cs}\right), \tag{6.4}$$

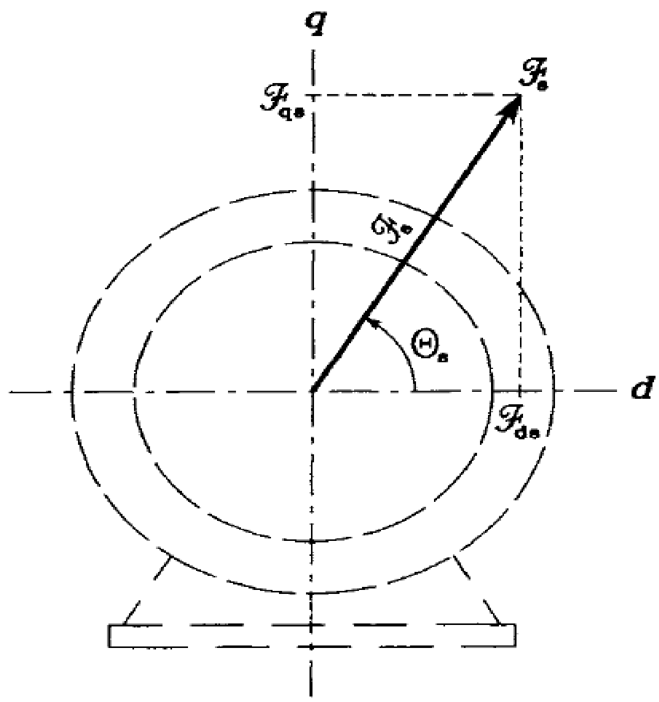

FIGURE 5.1 Space vector of stator MMF.

which explains the abc→dq transformation described by Eq. (3.12). For the stator MMFs,

$$\begin{bmatrix} \mathcal{F}_{ds} \\ \mathcal{F}_{qs} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathcal{F}_{as} \\ \mathcal{F}_{bs} \\ \mathcal{F}_{cs} \end{bmatrix} \tag{5.5}$$

and

$$\begin{bmatrix} \mathcal{F}_{as} \\ \mathcal{F}_{bs} \\ \mathcal{F}_{cs} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} \mathcal{F}_{ds} \\ \mathcal{F}_{qs} \end{bmatrix} \tag{5.6}$$

Transformation equations (5.5) and (5.6) apply to all three-phase variables of the induction motor (generally, of any three-phase system), which add up to zero.

Stator MMFs are true (physical) vectors, because their direction and polarity in the real space of the motor can easily be ascertained. Because an MMF is a product of the current in a coil and the number of turns of the coil, the stator current vector, $\boldsymbol{i}_s$ can be obtained by dividing $\boldsymbol{\mathcal{F}}_s$ by the number of turns in a phase of the stator winding. This is tantamount to applying the abc→dq transformation to currents, i_{as}, i_{bs}, and i_{cs} in individual phase windings of the stator. The stator voltage vector, $\boldsymbol{v}_s$, is obtained using the same transformation to stator phase voltages, v_{as}, v_{bs}, and v_{cs}. It can be argued to which extent $\boldsymbol{i}_s$ and $\mathbf{v}_s$ are true vectors, but from the viewpoint of analysis and control of induction motors this issue is irrelevant.

It must be mentioned that the abc→dq and dq→abc transformation matrices in Eqs. (5.5) and (6.6) are not the only ones encountered in the literature. As seen in Figure 2.6, when the stator phase MMFs are balanced, the magnitude. $\mathcal{F}_s$, of the space vector, $\boldsymbol{\mathcal{F}}_s$, of the stator MMF is 1.5 times higher than the magnitude (peak value), $\mathcal{F}_{as}$ of phase MMFs. This coefficient applies to all other space vectors. In some publications, the abc→dq transformation matrix in Eq. (5.5) appears multiplied by 2/3, and the dq→abc transformation matrix in Eq. (5.6), by 3/2. Then, the vector magnitude equals the peak value of the corresponding phase quantities. On the other hand, if the product of magnitudes, $\boldsymbol{V}_s$, and $\boldsymbol{I}_s$, of stator voltage and current vectors, $\boldsymbol{v}_s$ and $\boldsymbol{i}_s$, is to equal the apparent power supplied to the stator, the matrices in Eqs. (5.5) and (5.6) should be multiplied by $\sqrt{(2/3)}$ and $\sqrt{(3/2)}$, respectively.

In practical ASDs, the voltage feedback, if needed, is usually obtained from a voltage sensor, which, placed at the dc input to the inverter, measures the dc-link voltage, v_i. The line-to-line and line-to-neutral stator voltages are determined on the basis of current values, *a, b*, and *c*, of switching variables of the inverter using Eqs. (3.4) and (3.9). Depending on whether the phase windings of the stator are connected in delta or wye, the stator voltages v_{as}, v_{bs}, and v_{cs} constitute the respective line-to-line or. line-toneu.al voltages. Specifically in a delta-connected stator, $v_{as} = v_{AB}$, $v_{bs} = v_{BC}$, and $v_{cs} = v_{CA}$, while in a wye-connected one, $v_{as} = v_{AN}$, $v_{bs} = v_{BN}$, and $v_{cs} = v_{CN}$.

The current feedback is typically provided by two current sensors in the output lines of the inverter. The sensors measure currents i_A and i_C, and if the stator is Connected in wye, its phase currents are easily determined as $i_{as} = i_A$, $i_{bs} = -i_A - i_C$, and $i_{cs} = i_C$. Because of the symmetry of all three phases of the motor and symmetry of control of all phases of the inverter, the phase stator currents in a delta-connected motor can be assumed to add up to zero. Consequently, they can be found as $i_{as} = (2i_A + i_C)/3$, $i_{bs} = (-i_A - 2i_C)/3$, and $i_{cs} = (-i_A + i_C)/3$.Voltages and currents in the wye- and delta-connected stators are shown in Figure 5.2.

In addition to the already-mentioned space vectors of the stator voltage, $\mathbf{v}_s$, and current, i_s, four other three-phase variables of the induction motor will be expressed as space vectors. These are the rotor current vector, $\boldsymbol{i}_r$' and three flux-linkage vectors, commonly, albeit imprecisely, called flux vectors: stator flux vector, $\boldsymbol{\lambda}_s$, air-gap flux vector, $\boldsymbol{\lambda}_m$, and rotor flux vector, $\boldsymbol{\lambda}_r$. The air-gap flux is smaller than the stator flux by only the small amount of leakage flux in the stator and, similarly, the rotor flux is only sight1y reduced with respect to the air-gap flux, due to flux leakage in the rotor.

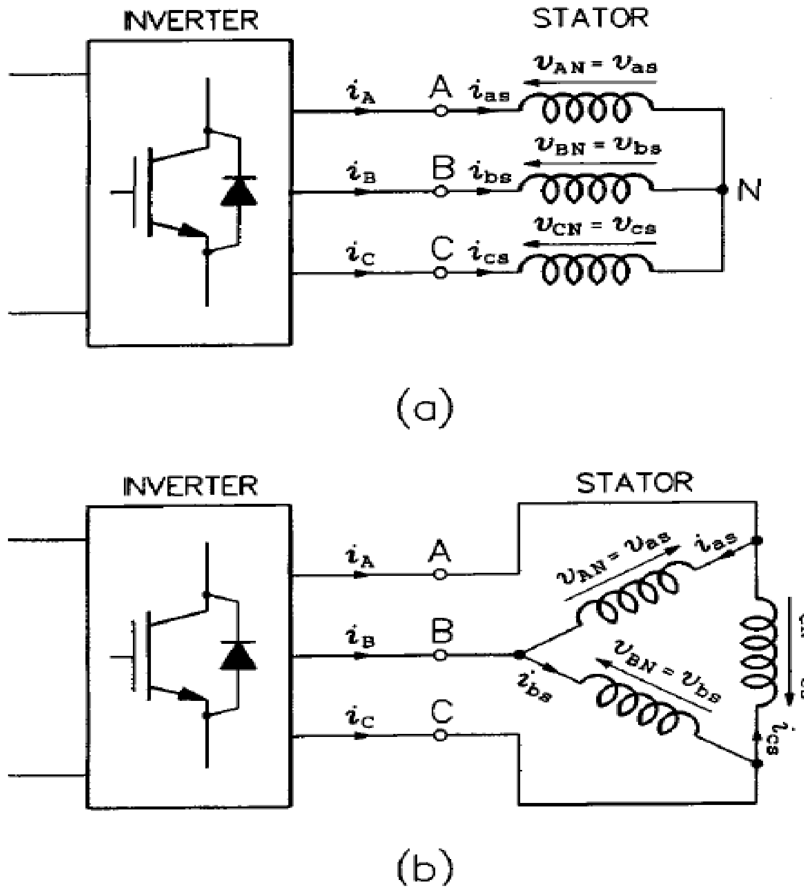

FIGURE 5.2 Stator currents and voltages: (a) wye-connected stator, (b) delta connected stator.

5.2 Dynamic Equations of The Induction Motor:

The dynamic T-model of the induction motor in the stator reference frame, with motor variables expressed in the vector form, is shown in Figure 5.3. Symbol p (not to be confused with the number of pole pairs, p_p denotes the differentiation operator, d/dt, while L_{Is}, L_{Ir}, and Lm are the stator and rotor leakage inductances and the magnetizing inductance, respectively ($L_{Is} = X_{Is}/\omega$, $Lrs = Xrs/\omega$, $Lm = Xm/\omega$). The sum of the stator leakage inductance and magnetizing inductance is called the stator inductance and denoted by Ls. Analogously, the rotor inductance, Lr, is defined as the sum of the rotor leakage inductance and magnetizing inductance. Thus, $L_s = L_{Is} + L_m$, and $L_r = L_{Ir} + L_m$ ($L_s = X_s/\omega$, $L_r = X_r/\omega$).

The motor equation in the d-q reference frame can be obtained in the form of [4] :

$$v_{s\_\alpha\beta} = v_{s\_dq} e^{j\theta_s}$$

$$i_{s\_\alpha\beta} = i_{s\_dq} e^{j\theta_s} \tag{5.7}$$

$$\lambda_{s\_\alpha\beta} = \lambda_{s\_dq} e^{j\theta_s}$$

The substitution of equations (5.7) into the below voltage equation of induction motor :

$$v(t) = Ri(t) + \frac{d}{dt}\lambda(t) \tag{5.8}$$

Results in the following equations :

$$v_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_s \lambda_{sq}$$

$$v_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} + \omega_s \lambda_{sd} \tag{5.9}$$

The same method can be applied to obtain the rotor voltage equations:

$$v_{rd} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{sl} \lambda_{rq}$$

$$v_{rq} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} + \omega_{sl} \lambda_{rd} \tag{5.10}$$

Hence,

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd}$$

$$\lambda_{sq} = L_s i_{sq} + L_m i_{rq}$$

$$\lambda_{rd} = L_r i_{rd} + L_m i_{sd}$$

$$\lambda_{rq} = L_r i_{rq} + L_m i_{sq} \tag{5.11}$$

The mathematical model of the induction motor in term of d-q reference can be obtained by substituting equations (5.11) into (5.9)-(5.10) :

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ v_{rd} \\ v_{rq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -\omega_s L_s & pL_m & -\omega_s L_m \\ -\omega_s L_s & R_s + pL_s & -\omega_s L_m & pL_m \\ pL_m & -\omega_{sl} L_m & R_r + pL_r & -\omega_{sl} L_r \\ -\omega_{sl} L_m & pL_m & -\omega_{sl} L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \tag{5.12}$$

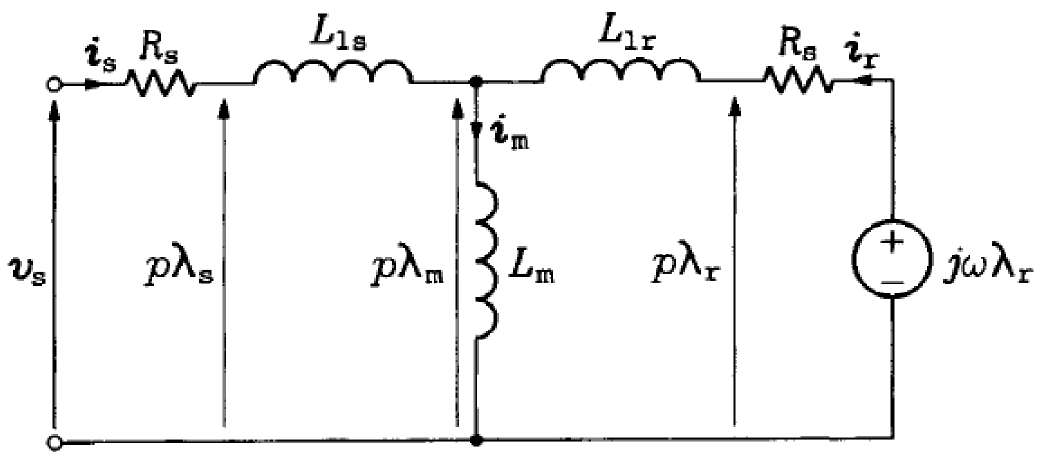

FIGURE 5.3 Dynamic T-model of the induction motor.

In the squirrel-cage motor, the corresponding components, v_{dr} and v_{qr}. of the rotor voltage vector, $\boldsymbol{v}_r$ are both zero because the rotor windings are shorted.

The stator and rotor fluxes are related to the stator and rotor current, as:

$$\begin{bmatrix} \boldsymbol{\lambda}_s \\ \boldsymbol{\lambda}_r \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} \boldsymbol{i}_s \\ \boldsymbol{i}_r \end{bmatrix} \tag{5.13}$$

The stator flux can also be obtained from the stator voltage and current as

$$\frac{d\boldsymbol{\lambda}_s}{dt} = \boldsymbol{v}_s - R_s \boldsymbol{i}_s \tag{5.14}$$

or

$$\boldsymbol{\lambda}_s = \int_0^t (\boldsymbol{v}_s - R_s \boldsymbol{i}_s) dt + \boldsymbol{\lambda}_s(0) \tag{5.15}$$

while the rotor flux in the squirrel-cage motor satisfies the equation

$$\frac{d\boldsymbol{\lambda}_r}{dt} = j\omega_0\boldsymbol{\lambda}_r - R_r\boldsymbol{i}_r \quad (5.16)$$

Finally, the developed torque can be expressed in several forms, such as

$$\boldsymbol{T}_M = \frac{2}{3}p_p Im\{\boldsymbol{i}_s\boldsymbol{\lambda}_s^*\} = \frac{2}{3}p_p\left(i_{qs}\lambda_{\mathrm{ds}} - i_{ds}\lambda_{qs}\right), \quad (5.17)$$

$$\boldsymbol{T}_M = \frac{2}{3}p_p\frac{L_m}{L_r}Im\{\boldsymbol{i}_s\boldsymbol{\lambda}_r^*\} = \frac{2}{3}p_p\frac{L_m}{L_r}\left(i_{qs}\lambda_{\mathrm{dr}} - i_{ds}\lambda_{qr}\right), \quad (5.18)$$

or

$$T_M = \frac{2}{3}p_p L_m Im\{i_s i_r^*\} = \frac{2}{3}p_p L_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right), \quad (5.19)$$

where the star denotes a conjugate vector.

The rather abstract term $Im(i_s\boldsymbol{\lambda}_s^*)$ in Eq. (5.17) and the analogous terms in Eqs. (5.18) and (5.19) represent a vector product of the involved space vectors. For instance,

$$Im(i_s\boldsymbol{\lambda}_s^*) = i_s\lambda_s\sin[\angle(i_s, \boldsymbol{\lambda}_s)]. \quad (5.20)$$

Eq. (5.20) implies that the torque developed in an induction motor is proportional to the product of magnitudes of space vectors of two selected motor variables (two currents, or a current and a flux) and the sine of angle between these two vectors. It can be seen that all the torque equations are nonlinear, as each of them includes a difference of products of two motor variables.

5.3 Revolving Reference Frame:

In the steady state, space vectors of motor variables revolve in the stator reference frame with the angular velocity, ω, imposed by the supply source (inverter). It must be stressed that this velocity does not depend on the number of poles of stator, which indicates the somewhat abstract quality of the vectors (the speed of the actual stator MMF, a “real” space vector, equals ω/p_p). Under transient operating conditions, instantaneous speeds of the space vectors vary, and they are not necessarily the same for all vectors, but the vectors keep revolving nevertheless. Consequently, their d and q components are ac variables, which are less convenient to analyze and utilize in a control system than the dc signals commonly used in control theory. Therefore, in addition to the static, abc → dq and dq → abc, transformations, the dynamic, dq → DQ and DQ → dq, transformations from the stator reference frame to a revolving frame and vice versa are often employed. Usually, the revolving reference frame is so selected that it moves in synchronism with a selected space vector [13].

The revolving reference frame, DQ, rotating with the frequency ω_e (the subscript. “e” comes from the commonly used term “excitation frame”), is shown in Figure 5.4 with the stator reference frame in the background. The stator voltage vector, $\boldsymbol{v}_s$, revolves in the stator frame with the angular velocity of ω, remaining stationary in the revolving frame if $\omega_e = \omega$. Consequently, the v_{DS} and v_{QS} components of that vector in the latter frame are dc signals, constant in the steady state and varying in transient states. Considering the same stator voltage vector, its dq → DQ transformation is given by [13]:

$$\begin{bmatrix} v_{DS} \\ v_{QS} \end{bmatrix} = \begin{bmatrix} cos\,(\omega_e t) & sin\,(\omega_e t) \\ -\,sin(\omega_e t) & cos\,(\omega_e t) \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \tag{5.21}$$

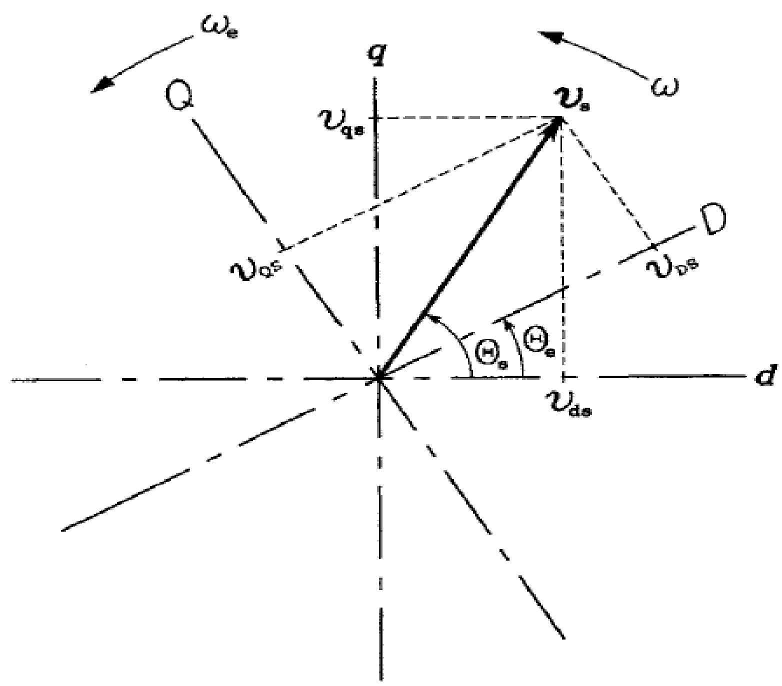

FIGURE 5.4 Space vector of stator voltage in the stationary and revolving reference frames.

and the inverse, DQ → dq, transformation by :

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} cos\ (\omega_e t) & -sin\ (\omega_e t) \\ sin\ (\omega_e t) & cos\ (\omega_e t) \end{bmatrix} \begin{bmatrix} v_{DS} \\ v_{QS} \end{bmatrix} \tag{5.22}$$

To indicate the reference frame of a space vector, appropriate superscripts are used. For instance the stator Voltage vector in the stator reference frame can be expressed as

$$\boldsymbol{v}_s^s = v_{ds} + jv_{qs} = v_s e^{j\Theta_s} \tag{5.23}$$

and the same vector in the revolving frame as :

$$\boldsymbol{v}_s^e = v_{DS} + jv_{QS} = v_s e^{(\Theta s - \Theta e)}, \quad (5.24)$$

where Θ_e. denotes the angle between the frames. Angles Θ_s and Θ_e are given by

$$\Theta_s = \int_0^t \omega dt + \Theta_s(0) \quad (5.25)$$

and

$$\Theta_e = \int_0^t \omega_e dt + \Theta_e(0) \quad (5.26)$$

Motor equations in a reference frame revolving with the angular velocity of ω_e can be obtained from those in the stator frame by replacing the differentiation operator p with $p + j\omega_e$. In particular,

$$\frac{d\boldsymbol{\lambda}_s^e}{dt} = v_s^e - R_s i_s^e - j\omega_e \boldsymbol{\lambda}_s^e \quad (5.27)$$

and

$$\frac{d\boldsymbol{\lambda}_r^e}{dt} = - R_r i_r^e - j(\omega_e - \omega_0)\boldsymbol{\lambda}_r^e \quad (5.28)$$

Equations that do not involve differentiation or integration, such as the torque equations, are the same in both frames.

5.4 Field Orientation:

5.4.1Torque Production and Control In The DC Motor:

The concept of field orientation, proposed by Hasse in 1969 and Blaschke in 1972[13],constitutes, arguably, the most important paradigm in the theory and practice of control of induction motors. In essence, the objective of field orientation is to make the induction motor emulate the separately excited dc machine as a source of adjustable torque. Therefore, we will first review fundamentals of torque production and control in the dc motor.

A simplified representation of the dc motor is shown in Figure 5.5. The pair of magnetic poles, N and S, represents the magnetic circuit of stator, that is, the field part of the machine. Therefore, the space Vector, $\boldsymbol{\lambda}_f$, of flux (flux linkage) generated by the field winding, is stationary and aligned with the d axis of the stator. Thanks to the action of commutator (not shown) and properly positioned brushes, the distribution of armature current in the rotor winding is such that the space vector, $\boldsymbol{i}_a$, of this current is always aligned with the q axis, even though the rotor is revolving [13].

Practical dc motors are equipped with auxiliary windings designated to neutralize the so-called armature reaction that is, weakening of the main magnetic field by the MMF produced by the armature current. Then, the developed torque, $\boldsymbol{T}_M$, is proportional to the vector product of $\boldsymbol{i}_a$ and $\boldsymbol{\lambda}_f$, that is, to the sine of angle between these vectors. As seen in Figure 5.5, this is always a right angle, which ensures the highest torque-per ampere ratio. Thus, the torque is produced under optimal conditions, the minimum possible armature current causing minimum losses in the motor and supply system.

In the separately excited dc machine, the field current, $\boldsymbol{i}_f$, producing $\boldsymbol{\lambda}_f$ and the armature current, $\boldsymbol{i}_a$, flow in separate windings therefore, they can be controlled independently. Usually, particularly under high-load operating conditions the flux is kept constant at the rated level within the speed range of zero to the rated value. Field weakening, that is, flux reduction in inverse proportion to the speed, is used at speeds higher than rated. With low loads, the motor efficiency can be improved by reducing the flux to such a trade-off value that the resultant decrease in core losses offsets the simultaneous increase in copper losses.

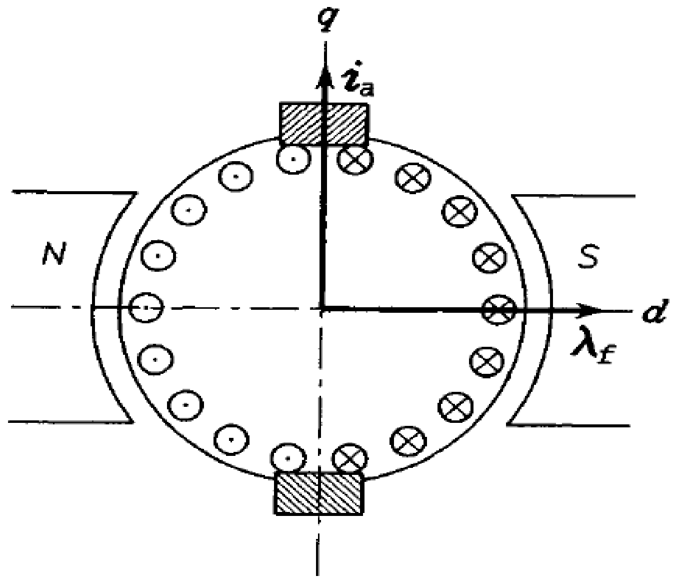

FIGURE 5.5 Simplified representation of the dc motor.

In drives that most of the time run well under the full load, such efficiency optimization schemes can bring significant energy savings.

Presented considerations explain why the separately excited dc motors were for many decades the favorite actuator in motion control systems. The dc motor not only generates the torque under the optimal condition of orthogonality of the flux and current vectors, but it also allows fully independent ("decoupled") control of the torque and the magnetic field. The torque equation, to be used as a reference for the field-oriented induction motor, can be written as

$$\boldsymbol{T}_m = k_T \boldsymbol{\lambda}_f \boldsymbol{i}_a, \tag{5.29}$$

where k_T is a constant dependent on the construction and size of the motor.

5.4.2 Principles of Field Orientation:

All three torque equations, (5.17) through (5.19), of the induction motor in the stator reference frame include the difference-of-products terms. Notice that if, for example, in Eq. (5.18), λ_{qr} were made to equal zero, the resultant formula would be similar to that, (5.29), for the dc motor. Unfortunately, this is not possible, because λ_{qr} constitutes the quadrature component of the revolving vector, $\boldsymbol{\lambda}_r$, of rotor flux. Thus, $\lambda_{qr} = 0$ is possible only if $\boldsymbol{\lambda}_r = 0$, which is absurd.

However, if torque equations in a revolving frame are considered, the manipulation described above becomes feasible. If

$$\boldsymbol{T}_M = \frac{2}{3} p_p \frac{L_m}{L_r} \left(i_{QS} \lambda_{DR} - i_{DS} \lambda_{QR} \right) \tag{5.30}$$

and $\lambda_{QR} = 0$, then

$$\boldsymbol{T}_M = k_T \lambda_{DR} i_{QS}, \tag{5.31}$$

where $k_T = 2p_p L_m/(3L_r)$,and the induction motor, as desired, emulates the dc machine. The described condition is realized by aligning the D axis of the revolving reference frame with the rotor flux vector, $\boldsymbol{\lambda}_r$, as illustrated in Figure 5.6. Similar results can be obtained aligning the D axis with another flux vector, that is, the stator or air-gap flux vector. For instance, the stator field orientation, according to Eq. (5.17), yields

$$\boldsymbol{T}_M = k'_T \lambda_{DS} i_{QS} \tag{5.32}$$

Where: $k'_T = 2p_p/3$

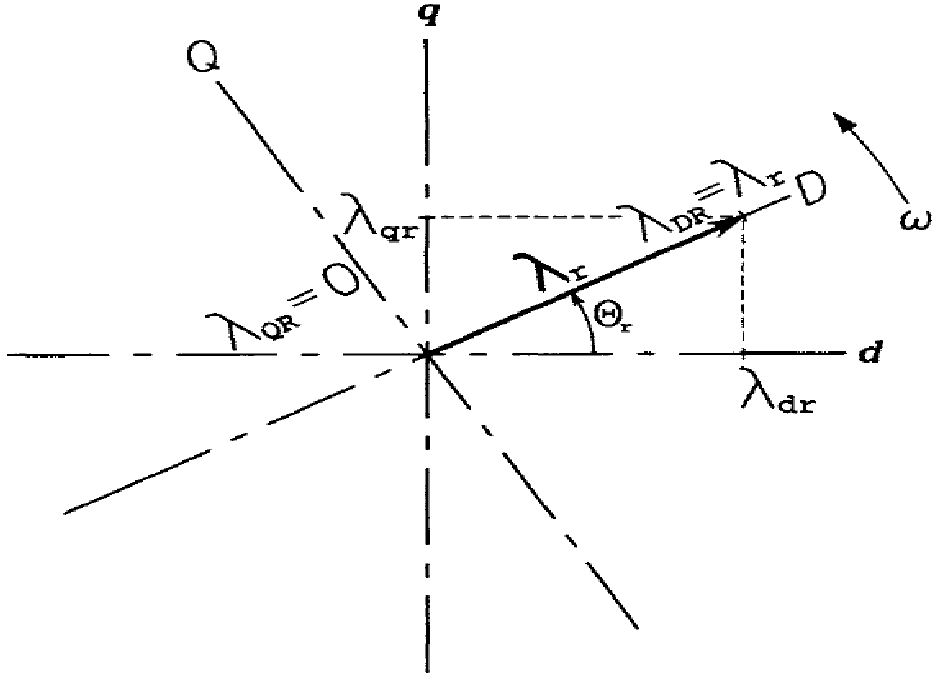

FIGURE 5.6: Alignment of the revolving reference frame with the rotor flux vector.

Principles of field orientation along a selected flux vector, $\boldsymbol{\lambda}_f$ ($\boldsymbol{\lambda}_r$, $\boldsymbol{\lambda}_s$, or $\boldsymbol{\lambda}_m$), can be summarized as follows:

1. Given the reference values, $\boldsymbol{T}_M^*$ and λ_f^*, of the developed torque and selected flux, find the corresponding reference components, i_{DS}^* and i_{QS}^*, of the stator current vector in the revolving reference frame.
2. Determine the angular position, Θ_f, of the flux vector in question, to be used in the DQ → dq conversion from i_{DS}^* to i_{ds}^* and from i_{QS}^* to i_{qs}^*
3. Given the reference components, i_{ds}^* and i_{qs}^*, of the stator vector in the stator reference frame, use the dq → abc transformation to obtain reference stator currents, i_{as}^*, i_{bs}^* and i_{cs}^*, for a current- controlled inverter feeding the motor.

Based on the dynamic equations of the induction motor, a block diagram of the field-oriented motor in a revolving reference frame aligned with the rotor flux vector is shown in Figure 5.7. According to the theory of linear dynamic systems, the integrator block with negative feedback can be replaced with a first-order block, as shown in Figure 5.8. It can be seen that the torque in a field-oriented motor reacts instantly to changes in the i_{QS} component of the stator current, while the reaction of rotor flux to changes in the other component, i_{DS}, is inertial.

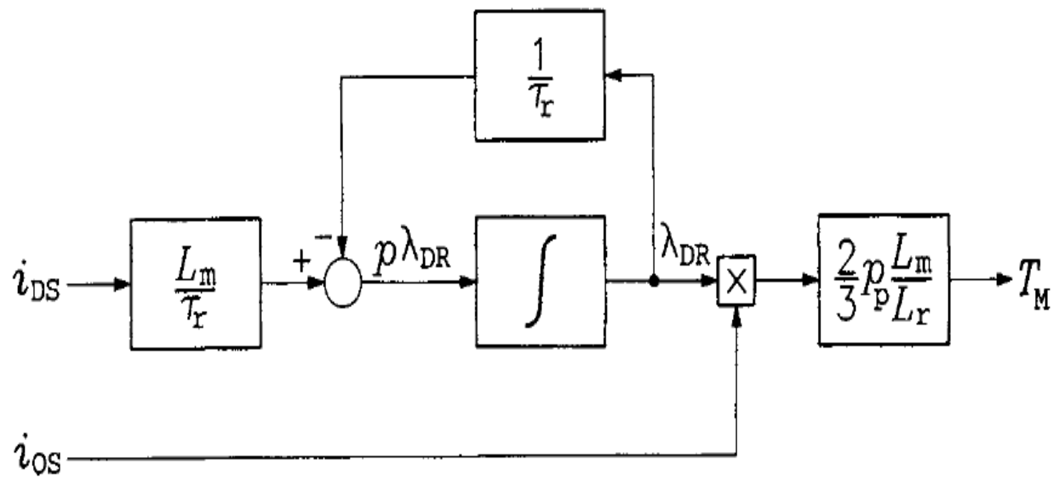

FIG U RE 5.7 Block diagram of the field-oriented motor in a revolving reference frame aligned with the rotor flux vector.

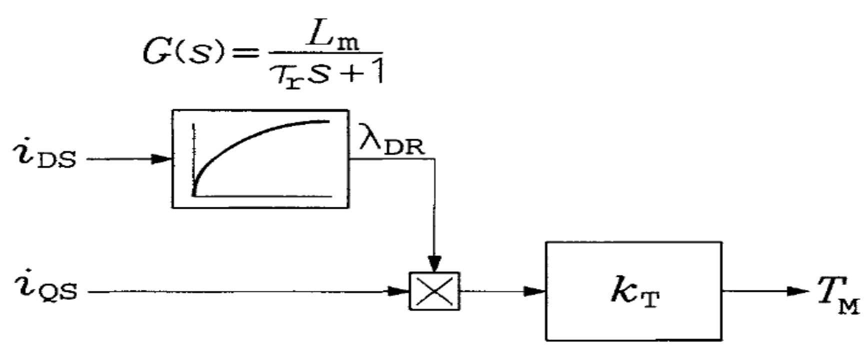

FIGURE 4.8: Reduced block diagram of the field-oriented motor in a revolving reference frame aligned with the rotor flux vector.

Because $\omega_e = \omega$ and $\omega_e - \omega_0 = \omega_r$, then the real part of Eq. (5.28) may be written as :

$$i_{DR} = \frac{1}{R_r}\left(\omega_r \lambda_{QR} - \frac{d\lambda_{DR}}{dt}\right). \tag{5.33}$$

Under the field orientation condition, $\lambda_{QR} = 0$ and, with λ_{DR} = const, $d\lambda_{DR}/dt = 0$, too. Hence, $i_{DR}= 0$ and $i_r^e= i_{QR}$ which, because $\boldsymbol{\lambda}_r^e = \lambda_{DR}$, indicates orthogonality of the rotor current and flux vectors. This is the condition of optimal torque production, that is, the maximum torque per ampere ratio, typical for the dc motor. Thus, the field orientation makes operating characteristics of the induction motor similar to those of that machine.

5.4.3 Direct Field Orientation:

Knowledge of the instantaneous position (angle) of the flux vector, with which the revolving reference frame is aligned, constitutes the necessary requirement for proper field orientation. Usually, the magnitude of the flux vector in question is identified as well, for comparison with the reference value in a closed-loop control scheme. Identification of the flux vector can be based on direct measurements or estimation from other measured variables. Such an approach is specific for schemes with the so-called direct field orientation (DFO), which will be explained for the rotor flux vector, $\boldsymbol{\lambda}_r$, as the orienting vector.

Only the air-gap flux can be measured directly. A simple scheme for estimation of the rotor flux vector, based on measurements of the airgap flux and stator currents, is depicted in Figure 5.9. Two Hall sensors of magnetic field are placed in the motor gap, measuring the direct and quadrature components, λ_{dm} and λ_{qm}, of the air-gap flux vector, $\boldsymbol{\lambda}_m$. Stator currents are measured too. The rotor flux vector, in the rectangular or polar form, is calculated as

$$\boldsymbol{\lambda}_r = \frac{L_r}{L_m}\boldsymbol{\lambda}_m - L_{Is}i_s \tag{5.34}$$

As an alternative to the fragile Hall sensors, flux sensing coils or taps on the stator winding can be installed in the motor. Voltages induced in the coils or the winding are integrated to provide λ_{dm} and λ_{qm}.

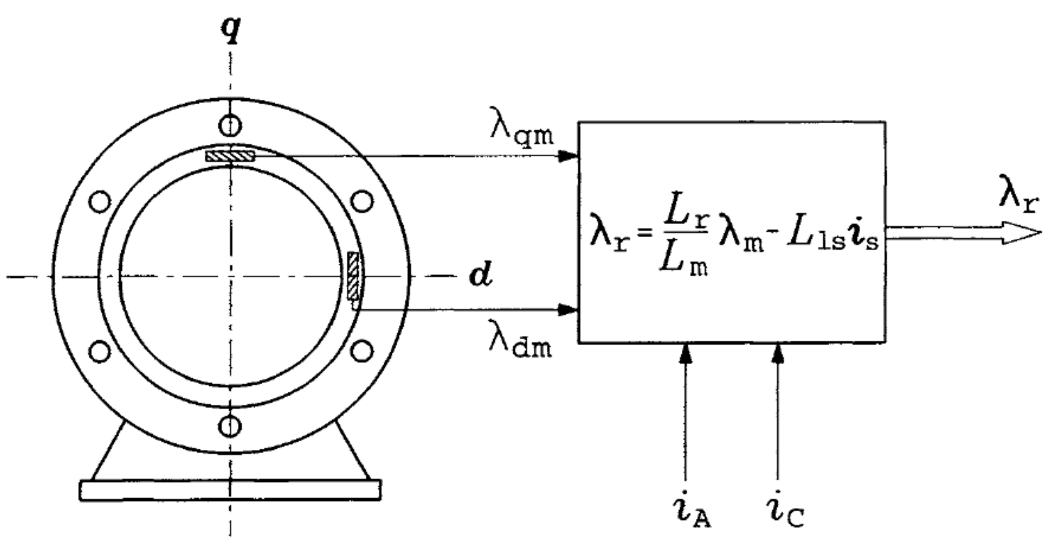

FIGURE 5.9 Estimation of the rotor flux vector based on direct measurements of the air-gap flux.

Sensors of the air-gap flux are inconvenient, and they spoil the ruggedness of the induction motor. Therefore, in practice, the rotor flux vector (or another flux vector used for the field orientation) is usually computed from the stator voltage and current. In particular, the stator flux vector, $\boldsymbol{\lambda}_s$, can be estimated using Eq. (5.15) which, in turn, allows calculation of the air-gap flux vector, $\boldsymbol{\lambda}_m$, as

$$\boldsymbol{\lambda}_m = \boldsymbol{\lambda}_s - L_{ls}i_s \tag{5.35}$$

and estimation of the rotor flux vector, $\boldsymbol{\lambda}_r$, from Eq. (5.34).

For best performance, the torque and flux in induction motors with direct field orientation are closed-loop controlled. The torque, which is difficult to measure directly, can be calculated using an appropriate equation, such as (5.18). A block diagram of the ASD with direct rotor flux orientation using air-gap flux sensors is shown in Figure 5.10. Proportional-Derivative (PD) controllers used in loops of the flux and torque control generate reference components, is i_{DS}^* and i_{QS}^*, of the stator current vector in the revolving reference frame. The DQ → dq dynamic transformation block converts the i_{DS}^* and i_{QS}^* dc signals into i_{ds}^* and i_{qs}^* ac signals representing reference components of the stator current vector in the stator reference frame. Operation of the dynamic transformation block is synchronized by the angle signal, θ_r, from the flux calculator. The i_{ds}^* and i_{qs}^* signals are applied to the dq → abc static transformation block to produce reference currents, i_{as}^*, i_{bs}^* and i_{cs}^*, for individual phases of the current controlled inverter.

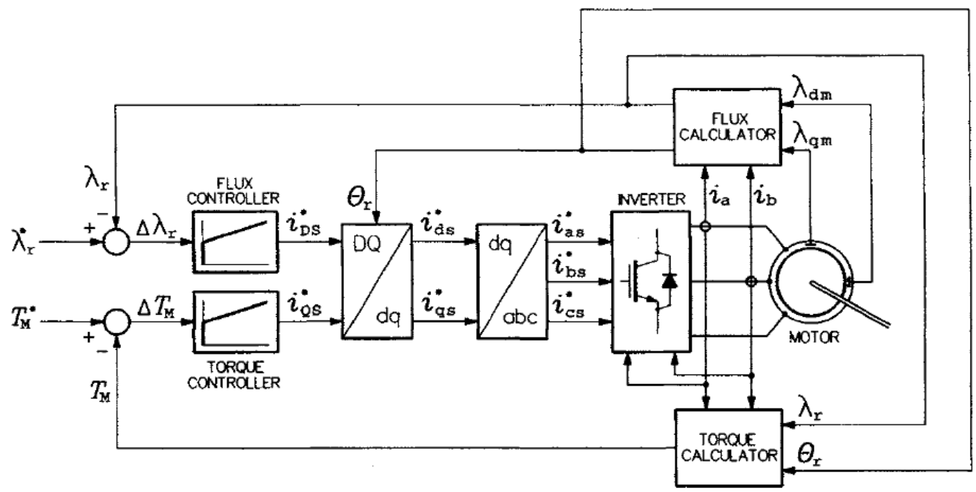

FIGURE 5.10: Block diagram of the ASD with direct rotor flux orientation.

5.4.4 Indirect Field Orientation:

In an alternative approach to direct flux orientation, the indirect field orientation (IFO), the angular position, θ_r, of the rotor flux vector is determined indirectly as

$$\theta_r = \int_0^t \omega_r^* dt + p_p \theta_M \tag{5.36}$$

where ω_r^* denotes the rotor frequency required for field orientation and θ_M is the angular displacement of the rotor, measured by a shaft position sensor, typically a digital encoder. The required rotor frequency can be computed directly from motor equations under the field orientation condition. With $\lambda_r^e = \lambda_{DR}$, :

$$i_r^e = \frac{1}{L_r}(\lambda_{DR} - L_m i_s^e), \tag{5.37}$$

which, when substituted in Eq. (5.28), yields

$$\lambda_{DR}[1 + \tau_r(p + j\omega_r)] = L_m i_s^e, \tag{5.38}$$

where τ_r denotes the rotor time constant, L_r/R_r. Splitting Eq. (5.38) into the real and imaginary parts gives

$$\lambda_{DR}(1 + p\tau_r) = L_m i_{DS} \tag{5.39}$$

and

$$\omega_r \tau_r \lambda_{DR} = L_m i_{QS} \tag{5.40}$$

Replacing ω_r with ω_r^*, λ_{DR} with λ_r^*, and i_{QS} with i_{QS}^* in the last equation, and solving for ω_r^*, yields

$$\omega_r^* = \frac{L_m}{\tau_r} \frac{i_{QS}^*}{\lambda_r^*}, \tag{5.41}$$

Indeed, from Eq. (5.39), in the steady state of the motor ($p = 0$),

$$\lambda_r^* = \lambda_{DR}^* = L_m i_{DS}^*, \tag{5.42}$$

which, when substituted in Eq. (5.41), gives:

$$\omega_r^* = \frac{1}{\tau_r} \frac{i_{QS}^*}{i_{DS}^*}, \tag{5.43}$$

Variables i_{DS}^* and i_{QS}^* represent the required flux-producing and torque-producing components of the stator current vector, i_S^*.

The reference current i_{DS}^* corresponding to a given reference flux, λ_r^*, can be found from Eq. (5.39) as :

$$i_{DS}^{*} = \frac{\tau_r p + 1}{L_m}\lambda_r^{*} = \frac{1}{L_m}\left(\tau_r \frac{d\lambda_r^{*}}{dt} + \lambda_r^{*}\right), \qquad (5.44)$$

while the other reference current, i_{QS}^{*}, for a given reference torque, $\boldsymbol{T}_M^{*}$,can be obtained from the torque equation (5.31) of a field-oriented motor as :

$$i_{QS}^{*} = \frac{1}{k_T}\ \frac{\boldsymbol{T}_M^{*}}{\lambda_r^{*}}. \qquad (5.45)$$

A drive system with indirect rotor flux orientation is shown in Figure 5.11. In accordance with Eq. (5.36), the angle, Θ_r, of the rotor flux vector used in the DQ → dq transformation is determined as

$$\Theta_r = \Theta^{*} + \Theta_o, \qquad (5.46)$$

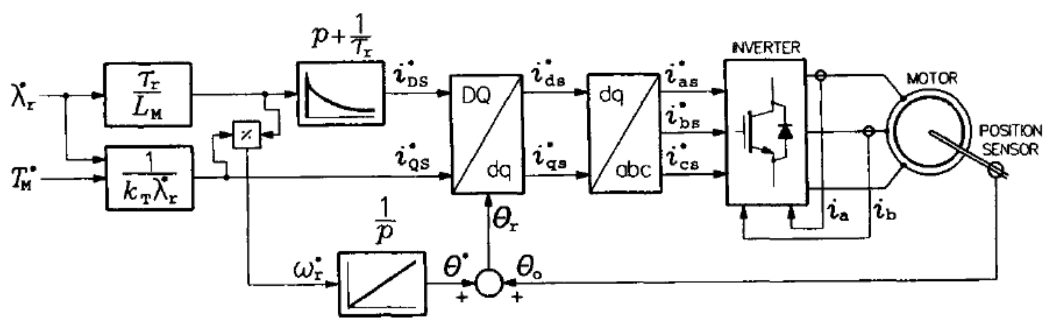

FIGURE 5.11 Block diagram of the ASD with indirect rotor flux orientation.

where Θ^{*} denotes the time integral of the reference rotor frequency, ω_r^{*}, and $\Theta o = p_p\Theta_M$ is the angular displacement of the rotor in an equivalent two-pole motor.

5.5 Summary of The Chapter:

Three-phase variables in the induction motor can be represented by space vectors in the Cartesian coordinate set, dq, affixed to stator (stator reference frame). Space vectors of the stator voltage and current and magnetic fluxes (flux linkages) are commonly employed in the analysis and control of induction motor ASDs. The space vectors are obtained by an invertible, static, abc → dq, transformation of phase variables. The vector notation is used in dynamic equations of the motor.

Space vectors in the stator reference frame are revolving, so that their d and q components are ac signals. A dynamic, dq → DQ, transformation allows conversion of those signals to the dc form. The dq → DQ transformation introduces a revolving frame of reference, in which, in the steady state, space vectors appear as stationary. The revolving frame is usually synchronized with a space vector of certain motor variable. Dynamic equations of the induction motor can easily be adapted to a revolving reference frame by substituting $p + j\omega_e$ for p.

Field orientation, consisting in the alignment of a revolving reference frame with a space vector of selected flux, allows the induction motor to emulate the separately excited dc machine. In this machine, the magnetic field and developed torque can be controlled independently. In addition, the torque is produced under the optimal condition of orthogonality of the flux and current vectors, resulting in the maximum possible torque-per-ampere ratio.

In ASDs with direct field orientation along the rotor flux vector, $\boldsymbol{\lambda}_r$, this vector is determined from direct measurements or estimations of the air-gap flux. The indirect field orientation is based on calculation of the angular position, Θ_r, of $\boldsymbol{\lambda}_r$ as a sum of an integral, Θ^*, of the rotor frequency, ω_r^*, required for the field orientation and the rotor angular displacement, Θ_o, of the equivalent two-pole motor.