CHAPTER 3

CLASSICAL CONTROL TECHNIQUES
FOR AC DRIVES

3.1 INTRODUCTION

The controllers required for AC drives can be divided into two major types: scalar control and vector control (Bose 1976). In scalar control, which includes v/f control, the magnitudes of the voltage and frequency are kept in proportion. The performance of the v/f control is not satisfactory, because the rate of change of voltage and frequency has to be low. A sudden acceleration or deceleration of the voltage and frequency can cause a transient change in the current, which can result in drastic problems. Some efforts were made to improve v/f control performance, but none of these improvements could yield a v/f torque controlled drive systems and this made DC motors a prominent choice for variable speed applications.

This status began to change when the theory of vector control or field orientation was introduced by Hasse and Blaschke (1972). Field orientation control is considerably more complicated than DC motor control. The most popular class of the successful controllers uses the vector control technique because it controls both the amplitude and phase of AC excitation. This technique results in an orthogonal spatial orientation of the electromagnetic field and torque, and hence commonly known as Field Oriented Control (FOC) (Novotny et al 1986). Vector control (or field oriented control) offers more precise control of AC motors compared to scalar
control. As most of the concepts of scalar control are well known the concept of vector control is discussed in the following sections to facilitate the understanding of the techniques as when applied to SRM. These techniques are in general common to AC machines but differ only in the way of implementation to the respective motors. The forthcoming section explains the concepts as applied to the induction motor.

3.2. VECTOR CONTROL

Scalar control of AC drives produces good steady state performance but poor dynamic response. This manifests itself in the deviation of air gap flux linkages from their set values. This variation occurs in both magnitude and phase. But the vector control has more precise control and hence used in high performance drives where oscillations in air gap flux linkages are intolerable, e.g. robotic actuators, centrifuges, servos. In scalar control there is an inherent coupling effect because both torque and flux are functions of voltage or current and frequency. This results in sluggish response and is prone to instability because of harmonics. Vector control decouples these effects.

The scalar control methods of voltage-fed and current-fed inverters are simple to implement but have the disadvantage of sluggish control response because of the inherent coupling effect in the machine. This problem is eliminated in vector or field oriented control as explained in Figure 3.1. Basically, in vector control (Novotny 1986), an induction motor is controlled like a separately excited DC motor. In a DC motor, the field flux $\psi_f$ and armature flux $\psi_a$ established by the respective field current $I_f$ and armature or torque component of current $I_a$, are orthogonal in space so that when torque is controlled by $I_a$, the field flux is not affected, thus giving fast torque response. Similarly, in induction motor vector control, the synchronous reference frame currents $i_{ds}$ and $i_{qs}$ are analogous to $I_f$ and $I_a$, respectively, and $i_{ds}$ is oriented in
the direction of rotor flux $\psi_r$ (defined as $\psi_r$ orientation). Note that $\psi_r$ is used instead of $\psi_m$ or $\psi_s$ because with $\psi_r$ orientation true decoupling is obtained. However, if leakage inductances are neglected, $\psi_r = \psi_m = \psi_s$. Therefore, when torque is controlled by $i_{qs}$, the rotor flux is not affected thus giving fast DC motor-like torque response. The drive dynamic model also becomes simple like that of a DC machine because of decoupling vector control. Vector control has brought a renaissance to the control of AC drives (both induction and synchronous machines) since its invention at the beginning of the 1970s.

Figure 3.1  Vector Control Analogy with Separately Excited DC Motor Drive

3.2.1  Principle of Vector Control

In a vector-controlled drive (Bose 1981), the machine stator current vector $I_s$ (or $I^s$) has two components: $i_{ds}$ or flux component and $i_{qs}$ or torque
component, as shown in the phasor diagram (Figure 3.2). These current components are to be controlled independently, as in a DC machine, to control the flux and torque, respectively. The $i_{ds}$ is oriented in the direction of $\dot{\psi}_r$ and $i_{qs}$ is oriented orthogonally to it. If $i_{qs}$ is increased to $i'_{qs}$, the stator current $\dot{I}_s$ changes $\dot{I}'_s$ as shown. Similarly, if $i_{ds}$ is decreased to $i'_{ds}$, the corresponding change of $\dot{I}_s$ is also shown. The actual implementation principle of vector control is shown in Figure 3.2.

![Figure 3.2](image)

**Figure 3.2** (a, b) Vector Control Principle by Phasor Diagram and (c) Vector Control Implementation

The machine model is shown in a synchronous frame at the right, and the two front-end conversions of phase currents in a stationary frame are also shown. The controller should make the two inverse transformations, where the unit vector $\cos \theta_e$ and $\sin \theta_e$ in the controller should ensure correct alignment of $i_{ds}$ in the direction of $\dot{\psi}_r$ and $i_{qs}$ at 90° ahead of it. Obviously, the
unit vector is the key element for vector control. Note that the inverter’s dynamics and its transfer characteristics, if any, have been neglected. There are two methods of vector control depending on the derivation of the unit vector. They are the direct (or feedback) method and indirect (or feedforward) method.

3.2.2 Flux Estimation Methods

In a scalar or vector control method, the machine flux is normally maintained at a predetermined value (as in a DC motor) by feedback control. In vector control, the flux vector signal (magnitude as well as direction) is required. The feedback flux signal (scalar or vector) can be obtained with the help of sensors, or estimated from the machine terminal voltage and current signals. Modern drives invariably use the latter method. The different methods for estimation of flux are flux coils in airgap, hall sensors in airgap, open-loop voltage model, cascaded low-pass filter voltage model, open-loop current model (or blaschke equation), integration of voltage and current models, model referencing adaptive principle and speed adaptive flux observer.

The flux coils and Hall sensors are basically sensor-based methods. In the former method, flux coils are mounted in the airgap direct (d^*) and quadrature (q^*) axes. The induced voltages in these coils (v'_{dm}, v'_{qm}) are then integrated and processed further to obtain the rotor flux vector components (ψ_{dr}^*, ψ_{qr}^*). Apart from the mounting difficulty, at very low frequency, integration of very small signals becomes difficult due to a drift problem. Hall sensors are also mounted in the airgap like flux coils, but here the accuracy becomes difficult due to temperature drift.
These two methods are now practically obsolete. The voltage model depends on machine terminal voltages and currents, whereas the current model depends on the currents and speed signal. In the hybrid model, the voltage and current models are blended. The closed-loop observer methods are more sophisticated. The voltage and current models will be described next.

![Diagram: Voltage Model Feedback Signal Estimation of Induction Motor]

**Figure 3.3 Voltage Model Feedback Signal Estimation of Induction Motor**

The calculation of various feedback signals with the help of DSP is as shown in Figure 3.3. For an isolated neutral machine, only two current sensors are needed. The analog voltage and current signals are filtered and...
converted to two-phase signals by op amps, and then converted to digital signals by A/D converters (Boldea et al. 1988). The block diagram indicates that the vector components of stator flux \((\psi^s_{ds}, \psi^s_{qs})\), airgap flux \((\psi^s_{dm}, \psi^s_{qm})\), rotor flux \((\psi^s_{dr}, \psi^s_{qr})\), torque \((T_e)\), and unit vector \((\cos \theta_e, \sin \theta_e)\) signals can be calculated. Then, using the unit vector, synchronous frame stator currents \((i^s_{ds}, i^s_{qs})\) can be calculated. The accuracy of the estimated signals depends on the machine parameters, which vary during machine operation. At very low speed, ideal integration becomes difficult because the voltage signals are very low at low frequency and sensor DC offsets tend to build up.

The current model signal estimation was first proposed by Blaschke (the inventor of direct vector control) and, therefore, the equation is known as the Blaschke equation. Basically, it uses the stator currents \((i^s_{ds}, i^s_{qs})\) and speed \((\omega_e)\) signals to estimate the rotor flux vector \((\psi^s_{dr}, \psi^s_{qr})\) by solving Equations (3.1) and (3.2) in real time.

\[
\frac{d\psi^s_{dr}}{dt} = \frac{L_m}{T_r} I^s_{ds} - \omega_e \psi^s_{qr} - \frac{1}{T_r} \psi^s_{dr}
\]

(3.1)

\[
\frac{d\psi^s_{qr}}{dt} = \frac{L_m}{T_r} I^s_{qs} + \omega_e \psi^s_{dr} - \frac{1}{T_r} \psi^s_{qr}
\]

(3.2)

These equations are the rotor circuit equations of stationary frame where the rotor time constant \(T_r = L_r / R_r\) and the rotor currents are replaced by the stator currents. The block diagram for solving these equations is shown in the Figure 3.4. Although the flux vector estimation (Casadei et al. 1993) requires the speed signal, the advantage is that ideal integration is not required and the model works well from zero speed.
Figure 3.4 Current Model Feedback Signal Estimation.

However, one problem of the model is that it is dependent on a rotor time constant ($T_r$) which varies widely primarily due to temperature variations of $R_r$. Note that the voltage model has good accuracy at higher frequencies, whereas the current model is good at low frequencies. These two models can be blended into a hybrid model to cover the whole frequency range.

3.3 Direct Field Oriented Current Control

In direct field oriented current control the rotation angle of the $i^*_{qs}$ vector with respect to the stator flux $\psi^r_{qr}$ is being directly determined (e.g. by measuring air gap flux). The block diagram of Direct Vector Control (DVC) with rotor flux orientation (Casadei et al 1993) is shown in Figure 3.5, where $i^*_{ds}$ is the flux component of stator current and $i^*_{qs}$ is the torque component of stator current. The Vector Rotation (VR) and 2Φ/3Φ transformation in the forward direction, are also indicated. The $i^*_{ds}$ signal is obtained from a flux control loop, whereas the $i^*_{qs}$ signal is obtained from the speed control loop.
An additional torque control loop can be added within the speed loop, if desired.

The unit vector and $\hat{\psi}_r$ signals are calculated from the voltage model estimation (Bonanno et al. 1995). The alignment of $i_{ds}$ in the direction of $\hat{\psi}_r$ and $i_{qs}$ perpendicular to it is explained in the phasor diagram, where the $d^e$-$q^e$ axes rotate counterclockwise at speed $\omega_e$ with respect to the $d^s$-$q^s$ axes. The unit vectors $\cos\theta_e$ and $\sin\theta_e$ remain aligned with the signals $\psi_{ds}^s$ and $\psi_{qs}^s$, respectively. If $i_{qs}^*$ is negative for regeneration or the reverse speed, its direction is reversed as shown. The self-control nature is obtained, where the inverter frequencies as well as the phase for the control are generated by feedback with the help of the unit vector. The current model can also be used to estimate the flux and unit vector.

![Diagram](image)

**Figure 3.5** Direct Vector Control with Rotor Flux Orientation
3.4 INDIRECT VECTOR CONTROL

Indirect field oriented current controlling the rotor angle is being measured indirectly, such as by measuring the slip speed. Indirect Vector Control (IVC) is essentially the same as direct vector control except the unit vector \((\cos \theta_e, \sin \theta_e)\) is generated in feed forward manner as explained in the phasor diagram (Figure 3.6). The rotor \(d'\)-\(q'\) axes fixed on the rotor rotate at speed \(\omega_r\), whereas the synchronously rotating \(d^e\)-\(q^e\) axes are at slip angle \(\omega_{sl}\) ahead of it (+\(\omega_{sl}\)) so that \(\theta_e = \theta_r + \theta_{sl}\), and \(\psi_r\) is oriented at \(d^e\) axis as before. If torque is negative, \(d^e\) axis falls behind \(d'\) because \(\omega_{sl}\) is negative. The rotor circuit equations can be written from \(d^e\)-\(q^e\) circuits. Then, by eliminating the rotor currents, equations (3.3) and (3.4) can be derived relating rotor fluxes with stator currents. Substituting the conditions \(\psi_{qr} = 0\) and \(d\psi_{qr} / dt = 0\) for decoupled control and \(d\psi_{dr} / dt = 0\) for constant flux, equations (3.5) and (3.6) can be derived. Equation (3.5) indicates how the control slip command \(\omega_{sl}\) can be derived in feedforward manner from the control current \(i_{qs}\), whereas equation (3.6) shows that rotor flux is a function of \(i_{ds}\) in the steady-state condition.

\[
\frac{d\psi_{qr}}{dt} + \frac{R_r}{L_r} \psi_{qr} - \frac{L_m}{L_r} R_r i_{qs} + \omega_{sl} \psi_{dr} = 0. \tag{3.3}
\]

\[
\frac{d\psi_{dr}}{dt} + \frac{R_r}{L_r} \psi_{dr} - \frac{L_m}{L_r} R_r i_{qs} - \omega_{sl} \psi_{qr} = 0. \tag{3.4}
\]

\[\omega_{sl} = \frac{L_m}{\psi_r} \frac{R_r}{L_r} i_{qs} \tag{3.5}\]

\[\hat{\psi}_r = L_m i_{ds} \tag{3.6}\]
In indirect vector control (Ohtani 1992), the slip command signal $\omega_s^*$ is derived from the command $i_{qs}^*$ through the slip gain ($K_s$). This signal is then added to the speed signal, integrated, and then the unit vector components are derived as shown in the Figure 3.7. Thus, the rotor pole and the corresponding current $i_{ds}$ are held ahead of the rotor $d'$ axis at correct angle. The speed signal is obtained from an incremental encoder. In the constant torque region, the rated flux is generated by constant $i_{ds}$ command.

![Indirect Vector Control Phasor Diagram](image)

**Figure 3.6 Indirect Vector Control Phasor Diagram**

For closed-loop flux control in both constant-torque and field weakening regions, $i_{ds}$ can be controlled within the programmed flux control loop so that the inverter always operates in Pulse Width Modulation (PWM) mode. The loss of flux in the field-weakening region causes some loss of torque from that of the square-wave mode, but fast vector control response is retained. The Figure 3.7 shows a position servo, where speed command is generated from the position loop. For simplicity, a hysteresis-band current control is shown, although other types of PWM are entirely possible. The control operates smoothly from zero speed. The IVC is used widely in industry. However, one disadvantage is that the slip gain parameters, particularly $R_s$, vary widely with temperature, causing a coupling effect that
deteriorates transient response and affects the flux and torque transfer characteristics.

Figure 3.7  Indirect or Feed Forward Vector Control with Rotor Flux Orientation

3.5  THE SALIENT FEATURES OF VECTOR CONTROL

- The frequency $\omega_e$ of the drive is not controlled (as in scalar control). The motor is “self-controlled” by using the unit vector to help control the frequency and phase.

- There is no concern about instability because limiting within the safe limit automatically limits operation to the stable region.

- Transient response will be fast because torque control by $i_{qs}$ does not affect flux.

- Vector control allows for speed control in all four quadrants (without additional control elements) as negative torque is directly taken care of in vector control.
3.6 **DIRECT TORQUE CONTROL**

An advanced scalar control technique based on Direct Torque and Flux Control (known as DTFC or DTC) was introduced in 1985, and was recently developed as a product by a large company. The strategy of DTC control (Tiitinen 1995) is shown in this Figure 3.8, and its control principle will be explained in the Figure 3.9. Basically, it uses torque and stator flux control loops, where the feedback signals are estimated from the machine terminal voltages and currents. The torque command can be generated by the speed loop as shown. The loop errors are processed through hysteresis bands and fed to a voltage vector look-up table.

![Figure 3.8 Direct Torque Control (DTC)](image)

The flux loop has outputs +1 and −1, whereas the torque loop has three outputs, +1, 0, and −1 as shown. The inverter voltage vector table also
gets the information about the location of the stator flux vector $\psi_s$. From the three inputs, the voltage vector table selects an appropriate voltage vector to control the PWM inverter switches. The control strategy is based on the torque equation

$$T_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{L_m}{L_r r_m} \psi_s \psi_s \sin \gamma$$

(3.7)

where $\psi_s$ and $\psi_r$ are the stator and rotor fluxes, respectively, and $\gamma$ is the angle between them.

Figure 3.9 Stator Flux Vector Trajectories in DTC Control

Note that the control neither uses any PWM algorithm nor any feedback current signal. It can be used for wide speed ranges including the field-weakening region but excludes the region close to zero speed. DTC control has been used widely, for example, in pump and compressor drives as an improvement of open-loop volts/Hz control.

The stator flux vector $\psi_s$ rotates in a circular orbit within a hysteresis band covering the six sectors as shown in Figure 3.9. The six active
voltage vectors and the two zero vectors of the inverter controlled by the look-up table are shown in Table 3.1. If a voltage vector is applied to the inverter for time $\Delta t$, the corresponding flux change is given by the relation $\Delta \psi_s = V_s \Delta t$. The flux increment vector for each voltage vector is indicated in Figure 3.10.

![Figure 3.10 Voltage Vectors to Control Flux Trajectory](image)

The flux is initially established at zero frequency in the radial trajectory $aA$. With the rated flux, a command torque is applied and the flux vector starts rotating in the counterclockwise direction within the hysteresis band depending on the selected voltage vector. The flux is altered in the radial direction due to flux loop error, whereas the torque is altered by tangential movement of the flux vector. Note that $\psi_s$ moves in a jerky manner at $\gamma$ angle ahead for $(+\pi_e)$ of rotor flux $\psi_r$, which has smooth rotation. The jerky variation of stator flux and $\gamma$ angle introduces the torque ripple. Note that the lowest speed is restricted because of the difficulty of voltage model flux estimation at low frequency.

The voltage vector look-up table for DTC control is shown in Table 3.1 for the three inputs [$H_\psi$, $H_{Tc}$, and $S(K)$]. The flux trajectory segments AB, BC, CD, and DE affected by the respective voltage vectors $V_3$, $V_4$, $V_3$, and $V_4$ are shown in Figure 3.9. For example, if $H_\psi = -1$, $H_{Tc} = 1$, and
S(K) = S(2), vector \( V_4 \) will be selected to describe the BC trajectory because at point B, the flux is too high and torque is too low. At point C, \( H_\psi = +1 \) and \( H_{Te} = +1 \), and this will generate \( V_3 \) vector from the Table 3.1(a). The Table 3.1(b) summarizes the flux and torque sensitivity and direction for applying a voltage vector (Casadei et al 1994) for the flux location shown in Figure 3.10. The flux can be increased by \( V_1, V_2, \) and \( V_6 \), whereas it can be decreased by \( V_3, V_4, \) and \( V_5 \). The zero vectors short circuits the machine terminal and keeps the flux and torque essentially unchanged.

**Table 3.1(a) Switching Table of Voltage Vectors and (B) Flux and Torque Sensitivity by Voltage Vectors**

<table>
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<th>( H_\psi )</th>
<th>( HT_e )</th>
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<th>S(2)</th>
<th>S(31)</th>
<th>S(4)</th>
<th>S(5)</th>
<th>S(6)</th>
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<td>( V_2 )</td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_1 )</td>
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<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
<td>( V_0 )</td>
<td>( V_7 )</td>
</tr>
<tr>
<td></td>
<td>-1</td>
<td>( V_6 )</td>
<td>( V_1 )</td>
<td>( V_2 )</td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
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<tr>
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<td>( V_6 )</td>
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<td>( V_3 )</td>
<td>( V_4 )</td>
</tr>
</tbody>
</table>

(a)

<table>
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<th>( V_2 )</th>
<th>( V_3 )</th>
<th>( V_4 )</th>
<th>( V_5 )</th>
<th>( V_6 ) or ( V_7 )</th>
</tr>
</thead>
<tbody>
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<td>( \uparrow )</td>
<td>( \downarrow )</td>
<td>( \downarrow )</td>
<td>( \uparrow )</td>
<td>0</td>
</tr>
<tr>
<td>( T_e )</td>
<td>( \downarrow )</td>
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<td>( \uparrow )</td>
<td>( \downarrow )</td>
<td>( \downarrow )</td>
<td>( \downarrow )</td>
</tr>
</tbody>
</table>

(b)
3.6.1 Essential Features of DTC Control

Basically, the DTC control is accomplished by simple but advanced scalar control of torque and stator flux by hysteresis-band feedback loops. There is no feedback current control although current sensors are essential for protection. Note that no traditional SVM technique is used as in other drives. The indirect PWM control is due to voltage vector selection from the look-up table to constrain the flux within the hysteresis band. Similar to Hysteresis Band (HB) current control, there will be ripple in current, flux, and torque. The current ripple will give additional harmonic loss, and torque ripple will try to induce speed ripple in a low inertia system. In the recent years, the simple HB-based DTC control has been modified by fuzzy and neuro-fuzzy control in inner loops with SVM control of the inverter. Multiple inverter vector selection in SVM, within a sample time smoothen the current, flux, and torque. However, with the added complexity, the simplicity of DTC control is lost. DTC control can be applied to PM synchronous motor drives also.

3.7 SUMMARY

This chapter dealt with the direct and indirect vector control techniques for AC drives. It also describes the basic concept of DTC as applied to Induction motor. The next chapter clearly states the different control techniques for SRM.