CHAPTER 4

SPEED CONTROL TECHNIQUES OF INDUCTION MOTOR DRIVES

4.1 INTRODUCTION

Variable speed induction motor drives have succeeded in replacing dc drives in variable speed applications with the improvement in capabilities and the reduction in the cost of power electronic devices. Speed control techniques of Variable Speed Drives (VSD) are classified into variable voltage constant frequency system and variable voltage variable frequency system. AC-DC-AC converters, cycloconverters and matrix converters are designed to control voltage as well as frequency called as variable voltage variable frequency converters. The following control systems are used in VSD applications.

- Open-loop control.
- Closed-loop control.
- Cascade closed-loop control.

In open loop control systems there is no provision made for the feedback of speed information from the motor to check whether the motor is running at the required speed or not. If the load torque changes, and slip increases or decreases, the converter would not adjust its output to compensate for these changes in the motor. Hence, open-loop control is
adequate only for controlling steady-state conditions and simple applications, which allow a lot of time for speed changes from one level to another and the consequences of the changes in the process are not severe.

In industrial applications, where speed and/or torque must be continuously and accurately controlled, closed-loop control is essential. Standard Variable Voltage Variable Frequency (VVF) AC drives can be used in closed-loop control systems, but in general, these applications are not capable of providing high performance as presented by (Malcolm Barnes 2003).

For the difficult applications, which require very close speed and torque control with a fast response to changes in the process, a single-loop controller may not be adequate to anticipate all the delays in the process. In such cases, cascaded closed loop control is preferred. The outer speed control loop uses the speed error to calculate the desired torque set point to either increase or decrease the speed. The inner torque control loop compares this set torque, the output of the speed controller, with the actual measured value, and calculates the desired output frequency. The measured process variable in this case is the measured motor current, which is proportional to the motor torque. Therefore, this control loop is often called the inner current loop. Vector control drive uses a similar approach. The most important advantage of cascaded controller is that it is possible to impose a current limit on the drive output by placing a limit on the input to the current loop. The current loop can respond quickly, in less than 10ms. The speed loop responds more slowly because motor and load inertia are usually substantial. A response time of about 100 ms is typical for the speed control loop. The simplest type of controller amplifier is one whose output is proportional to the input, called a proportional amplifier or P-control. P-control is not used in speed and current control loops because it does not respond well to the requirements for high
accuracy and a fast dynamic response. It is more common in high performance variable speed drives to use Proportional-Integral control as explained by (Dubey 1989), because it stabilizes the drive and adjusts the damping ratio at the desired value, makes the steady state close to zero by integral action and filters out noise, again due to integral action.

4.2 SCALAR CONTROL TECHNIQUES

The speed control methods of induction motors employing power semiconductor devices and controlling the magnitude of stator voltage and frequency are called as scalar control methods. The following are the scalar control methods applicable to both squirrel cage and wound rotor induction motors.

- Stator voltage control using AC voltage controller.
- Variable frequency control with constant v/f ratio.

In variable stator voltage control method, since the voltage cannot be varied above the rated voltage, the speed control is possible only below the rated speed. Motor torque developed is proportional to the square of supply voltage and rotor current is proportional to the supply voltage in induction motors. Hence, the torque to current ratio is directly proportional to the supply voltage, and while decreasing the terminal voltage to control the speed, the torque developed by the motor will also decreases. The low speed operation without overheating the motor by this method is possible only in specific applications where the load torque decreases with speed.

Any reduction in supply frequency, without a change in the terminal voltage, causes an increase in the air gap flux. Increase in flux will result in saturation and increase the magnetizing current, distort the line current and voltage, increase the core loss and stator copper loss and produce a high pitch
acoustic noise. On the other hand, a decrease in flux will reduce the torque capability of the motor. Hence, it is desired to maintain the flux constant. The variable frequency control below the rated frequency is carried out by reducing the supply voltage along with frequency to maintain flux constant and the operation above the rated frequency is carried out at the rated voltage as the rated voltage cannot be increased.

4.3 VECTOR CONTROL TECHNIQUES

Scalar control techniques control the stator phase current magnitude and frequency but not their phases. This results in deviation of magnitude and phase of air gap flux linkages from their set values. Hence, these methods provide a good steady state response, but the dynamic response is poor. This deviation in set value leads to torque and speed oscillations and sluggishness of control. Scalar control methods cannot be used in high performance applications where high precision, fast positioning and speed control are required. In dc separately excited motor, it needs to be control only the magnitude of armature and field currents and in turn, these two parameters are inherently decoupled and a very good dynamic performance is obtained.

Figure 4.1 Vector controlled induction motor fed with matrix converter
Figure 4.1 shows the vector controlled induction motor fed with matrix converter. In AC induction motors, only the stator current produces flux and torque and is not decoupled as in dc separately excited motor. Hence, independent control of flux and torque producing components of stator current is possible only if the stator current is resolved in such a way that the flux producing component oriented along the rotor flux linkages and torque producing component 90° lagging behind it. Induction motor can be operated like a dc separately excited motor, if the control is considered in a rotating reference frame (d-q), where the sinusoidal variables appear as dc quantities in steady state. In Figure 4.1, \(i_{ds}^*\) and \(i_{qs}^*\) are the reference flux and torque producing components of stator current in synchronously rotating reference frame. These two components are analogous to field and armature currents in dc machine. Hence, the torque equation can be written as,

\[
T_e = K_t \dot{\psi}_r i_{qs} \quad \text{or} \quad T_e = K_t \, i_{ds} i_{qs}.
\]

This dc machine like performance is possible in induction motor only if \(i_{ds}\) is oriented in the direction of \(\dot{\psi}_r\) and \(i_{qs}\) is established perpendicular to it. This field orientation is essential under all operating conditions in a vector controlled drive. It needs rotor position sensor and complex calculation for coordinate transformations. This field orientation of flux producing component of stator current along the rotor flux linkages is called as field oriented or vector control technique.

The equivalent circuit of field orientation principle is shown in Figure 4.2, and from the phasor diagram shown in Figure 4.3 it is clear that vector control provides an independent control of flux and torque producing components of stator current without affecting each other.
Figure 4.2 $d^c$-$q^c$ Equivalent circuit of induction motor

Figure 4.3 Phasor diagram for independent torque and flux variation in vector control

Fundamentals of vector control implementation principle with machine $d^c$-$q^c$ model and coordinate transformations used are shown in Figure 4.4. There are two methods in vector control, one is feedback or direct vector control method proposed by (Blaschke 1972), and the other is feed forward or indirect vector control method proposed by (Hasse 1969).
4.3.1 Direct Vector Control Technique

The block diagram of matrix converter fed direct vector control method for induction motor is shown in Figure 4.5. For the operation of induction motor in constant torque region requires flux command to be maintained at its rated value. The operation in constant power region is referred to as field weakening mode where the flux command is reduced.

Desired speed and actual speed measured from the motor are compared and the speed loop generates $i_{qs}^*$. The desired flux and actual flux estimated from voltage model based flux vector estimator are compared in current loop to generate $i_{ds}^*$. Inverse transformations are then carried out to produce required values of stator phase currents. Phasor diagram of correct rotor flux orientation (Bose 2002) is shown in Figure 4.6.
Stator flux vectors $\psi_{ds}^s$ and $\psi_{qs}^s$ are calculated by measuring voltage and current signals from the machine and converting them into two phase stationary reference frame variables using Clarke’s transformation.

$$
\psi_{ds}^s = \int (V_{ds}^s - R_s i_{ds}^s) dt \tag{4.1}
$$

$$
\psi_{qs}^s = \int (V_{qs}^s - R_s i_{qs}^s) dt \tag{4.2}
$$

$$
\psi_{dr}^s = \frac{L_r}{L_m} (\psi_{ds}^s - \sigma L_s i_{ds}^s) \tag{4.3}
$$

$$
\psi_{qr}^s = \frac{L_r}{L_m} (\psi_{qs}^s - \sigma L_s i_{qs}^s) \tag{4.4}
$$

where, $\sigma = 1 - \frac{L_m^2}{L_r L_s} \tag{4.5}$
Figure 4.6 $d^e$-$q^e$ and $d^o$-$q^o$ phasors showing correct rotor flux orientation

From the phasor diagram shown in Figure 4.6, the following equations are derived to estimate $d$ and $q$ axis components of rotor flux using unit vectors $\cos \theta_e$ and $\sin \theta_e$. These unit vectors are calculated from the feedback flux vectors in this method.

\[ \psi_{dr}^s = \psi_r \cos \theta_e \quad (4.6) \]
\[ \psi_{qr}^s = \psi_r \sin \theta_e \quad (4.7) \]
\[ \cos \theta_e = \frac{\psi_{dr}^s}{\psi_r} \quad (4.8) \]
\[ \sin \theta_e = \frac{\psi_{qr}^s}{\psi_r} \quad (4.9) \]
\[ \psi_r = \sqrt{\psi_{dr}^s \psi_{dr}^s + \psi_{qr}^s \psi_{qr}^s} \quad (4.10) \]

4.3.2 Indirect Vector Control Technique

In indirect field orientated control method, the angular position rotor flux vector $\theta_r$ is determined indirectly as (Trzynadlowski 2001),
\( \theta_r = \int_0^1 \omega_r^* \, dt + p \, \theta_m \) \hspace{1cm} (4.11)

where \( \omega_r^* \) denotes the rotor frequency, and \( \theta_m \) is the angular displacement of the rotor measured using rotor position sensor. The desired rotor frequency for the field orientation can be calculated directly from motor equations. In field oriented control method, \( \lambda_{qr} = 0 \) and hence, the total rotor flux is directed along d-axis.

Therefore, let \( \lambda_r^* = \lambda_{DR} \),

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

where \( \tau_r \) is the time constant of rotor.

\[
\lambda_{DR} (1 + p \tau_r) = L_m i_{DS}
\] \hspace{1cm} (4.14)

\[
\tau_r \omega_r \lambda_{DR} = L_m i_{QS}
\] \hspace{1cm} (4.15)

Replacing \( \omega_r \) with \( \omega_r^* \), \( \lambda_{DR} \) with \( \lambda_{DR}^* \) and \( i_{QS} \) with \( i_{QS}^* \) in the Equation(4.15),

\[
\omega_r^* = \frac{L_m \, i_{QS}^*}{\tau_r \, \lambda_r^*}
\] \hspace{1cm} (4.16)

In steady state, \( \lambda_r^* = \lambda_{DS}^* = L_m i_{DS} \)

\[
\omega_r^* = \frac{1}{\tau_r} \frac{i_{QS}^*}{i_{DS}^*}
\] \hspace{1cm} (4.17)

Variables \( i_{DS}^* \) and \( i_{QS}^* \) represent the required flux-producing and torque producing components of the stator current vector, \( i_s^* \).
The angle, \( \theta_r \) of the rotor flux vector is determined as

\[
\theta_r = \theta_r^* + \theta_o \tag{4.21}
\]

where \( \theta_r^* \) denotes the time integral of the reference rotor frequency, \( \omega_r^* \) and \( \theta_o = p_r \theta_M \) is the angular displacement of the rotor. The block diagram of indirect vector control technique is shown in Figure 4.7.
4.4 MATRIX CONVERTER FED INDUCTION GENERATOR OPERATION

Blaabjerg et al (2012) presented that the global accumulated installed power capacity is as shown in Figure 4.8. As there exists an interface between the wind turbine generator and power grid, the wind power converter has to satisfy the requirements to both sides. For the generator side: the current flowing in the generator stator should be controlled to adjust torque and as a consequence the rotating speed. This will contribute to the active power balance in normal operation when extracting the maximum power from the wind turbine but also in case grid faults appear as presented by Hansen et al (2004).

![Figure 4.8 Global Accumulated Installed Power Capacity](image-url)
Moreover, the converter should have the ability to handle variable fundamental frequency and voltage amplitude of the generator output to control the speed. For the grid side, the converter must comply with the grid codes regardless of the wind speed. This means it should have the ability to control the inductive/capacitive reactive power $Q$, and perform a fast active power $P$ response. The fundamental frequency as well as voltage amplitude on the grid side should be almost fixed under normal operation, and the Total Harmonic Distortion of the current must be maintained at a low level as per Teodorescu et al (2011). Inherently, the converter needs to satisfy both the generator side and grid side requirements with a cost-effective and easy maintenance solution. This requires a high-power density, reliability and modularity of the entire converter system. Matrix Converter provides high power density because of the absence of bulky energy storage elements. Also in Matrix converter, the harmonics, and hence THD, is very less. Hence, Matrix Converter is found to be suitable for wind energy conversion systems. The demands posed on power electronic converters for wind energy conversion systems are shown in Figure 4.9.

![Figure 4.9 Demands posed on power electronic converters](image-url)
Recently, the Squirrel Cage Induction Generator (SCIG) based wind energy conversion system is increasing because of the advantages of squirrel cage induction motor. The power available from a wind turbine is a function of its shaft speed for a given wind velocity. Using matrix converter, the terminal voltage and frequency of the induction generator are controlled in such a way that the wind turbine is operating at its maximum power point for all wind velocities. The technical advantage of this system is the elimination of capacitor in the dc link which is bulky and costly and reduces the lifetime. The matrix converter provides a large number of control levels that allow for independent control on the output voltage magnitude, frequency, phase angle and input power factor.

The block diagram of the wind energy conversion system using matrix converter fed induction generator is shown in Figure 4.10.

![Figure 4.10 Block diagram of wind energy conversion system using MC](image)

The wind turbine with the gear box arrangement increases the shaft speed of the turbine. The matrix converter interfaces the squirrel cage induction generator with grid and implements shaft speed control to achieve maximum power point tracking at varying wind velocities. It also controls the output power factor to satisfy the reactive power requirements of induction generator. The power handling capacity of the system can be increased by
using multilevel converters. The mechanical power generated by the wind
turbine is given as,

\[ p = \frac{1}{2} \rho C_p A_r V_w^3 \] (4.22)

where \( p \) is the power in watts, \( \rho \) is the air density in g/m\(^3\), \( C_p \) is the power co-
efficient, \( A_r \) is the turbine rotor area in m\(^2\) and \( V_w \) is the wind velocity in m/s.
The power co-efficient is related to the tip speed ratio \( \lambda \) and rotor blade pitch angle \( \theta \) as per the following Equation (4.23).

\[ C_p(\lambda, \theta) = 0.73 \left( \frac{151}{\lambda} - 0.58\theta - 0.002\theta^2 + 13.2 \right)e^{-18.4/\lambda_i} \] (4.23)

where

\[ \lambda_i = \frac{1}{\lambda - 0.002\theta - \frac{0.003}{\theta^3 + 1}} \] (4.24)

and

\[ \lambda_r = \frac{\omega_r R_r}{V_w} \] (4.25)

where \( \omega_r \) is the angular speed of the turbine shaft in rad/s. The theoretical
limit for power co-efficient according to Betz’s Law is 0.59. The typical
characteristic of power co-efficient and tip speed ratio are shown in
Figure 4.11.

From the Equations (4.22 - 4.25) it is clear that the mechanical power
generated by the wind turbine at a given wind velocity is a function of shaft
speed. At any given wind velocity, maximum power can be tracked from the
wind if the shaft speed is adjusted at the value corresponding to the maximum power.

**Figure 4.11** Power co-efficient verses Tip Speed Ratio

**Figure 4.12** Speed-torque characteristics of SCIG
Speed-torque characteristics of Squirrel Cage Induction Generator is shown in Figure 4.12. $T_e$ is the induced torque in the induction machine. The speed-torque convention for four quadrant operation is given below.

- **Quadrant I**: Motor rotates in forward direction of rotation and Motor developed torque $T_e > 0$
- **Quadrant II**: Motor rotates in forward rotation and Motor developed torque $T_e < 0$
- **Quadrant III**: Motor rotates in reverse direction of rotation and Motor developed torque $T_e < 0$
- **Quadrant IV**: Motor rotates in reverse direction of rotation and Motor developed torque $T_e > 0$

The magnitude of the counter torque developed in the induction generator as a result of the load connected at the stator terminals of the machine is then $T_c = -T_e$. The theoretical range of operation in the generator mode is limited between synchronous speed $\omega_s$ and the speed $\omega_r$ corresponding to the pushover torque. The synchronous speed is given as,

$$\omega_s = \frac{4\pi}{p} f_e$$

(4.26)

where $f_e$ is the terminal frequency of the induction generator and $p$ is the number of poles of the induction generator. From the Figure 4.12 it is clear that when the speed of induction motor becomes greater than its synchronous speed, the induction motor will operate as an induction generator.

Figure 4.13 shows the characteristics between power and angular speed of the turbine shaft as well as between torque and angular speed of the
turbine shaft. By varying $f_e$ and hence $\omega_s$, the $T_c - \omega_r$ curve can be shifted to the right or left hand side with respect to the speed-torque curve of the wind turbine to assume a wide range of possible steady state operating points defined by the intersection of the two curves. Obviously, one of the operating points corresponds to maximum power. To move from one operating point to the other, $f_e$ is changed in small steps and the difference between the wind turbine torque and the new counter torque of induction generator at the operating speed will accelerate or decelerate the shaft according to the Equation (4.27) until the new steady state operating point is reached.

$$T_w - T_c = J \frac{d\omega_r}{dt}$$

(4.27)

![Diagram showing power, torque, and angular speed of the turbine shaft](image)

Figure 4.13 Power, torque and angular speed of the turbine shaft
4.5 COMPARISON OF OPEN LOOP AND CLOSED LOOP PERFORMANCES

Simulation was carried out with the following parameters of induction motor using Matlab/Simulink and the simulation diagram is shown in Figure 4.14. The open loop and closed loop performance of induction motor fed through matrix converter with PI controller is evaluated. Steady state and dynamic behavior of the motor is verified. Induction generator operation of motor is also verified through simulation.

\[ R_s = 1.8 \, \Omega, \quad R_r = 1.3 \, \Omega, \quad X_{ls} = 5.2 \, \Omega, \]

\[ X_{lr} = 4.6 \, \Omega, \quad X_m = 140 \, \Omega, \quad J = 0.025 \, \text{Kgm}^2, \quad p = 4, \quad f = 60 \text{Hz}, \quad V = 460 \text{V}. \]

![Figure 4.14 Simulation diagram for indirect vector control technique](image-url)
Simulation result of Figures 4.15 to 4.16 show the speed-torque performance of open loop control of Induction motor fed with matrix converter. Simulation results of Figures 4.17 to 4.18 show the speed-torque performance of closed loop vector controlled induction motor fed with matrix converter. From the simulation results it is clear that the torque ripple is less and the dynamic response is faster in vector controlled induction motor drive fed with matrix converter.

![Figure 4.15 Speed response of open loop for $f_o=60Hz$ and $\frac{1}{4}T_L$ applied at 0.4 s](image)

![Figure 4.16 Torque response of open loop for $f_o=60Hz$ and $\frac{1}{4}T_L$ applied at 0.4 s](image)
Figure 4.17 Speed response of vector control for $f_o = 60$Hz and $\frac{1}{4} T_L$ applied at 0.5 s

Figure 4.18 Torque (N-m) response of vector control for $f_o=60$Hz and $\frac{1}{4}$ $T_L$ applied at 0.5sec
Simulation result of Figure 4.19 to 4.20 shows speed and torque response of Matrix converter fed Induction motor drive. From t=1.5 s to t= 2.5 s, the speed is less than synchronous speed and the torque is positive and hence the Induction motor operation in first quadrant is verified. Synchronous speed is applied at t = 2.5s and the torque becomes zero. From t=3 s to t=5 s, the speed is greater than synchronous speed and the torque is negative and hence the Induction Generator operation in second quadrant is verified. From t= 0 s to t=1.5 s, the speed is negative and the torque is positive and hence the braking operation in fourth quadrant is verified. Table 4.1 gives the values of torque and speed values of induction machine and it is clear that with speed greater than synchronous speed, the machines develops negative torque and operates as generator in second quadrant.

![Figure 4.19 Torque in N-m for Induction generator operation of matrix converter](image-url)
Table 4.1 Torque – Speed of induction machine during different time periods

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Speed (rpm)</th>
<th>Torque (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.5</td>
<td>-2798</td>
<td>4.8</td>
</tr>
<tr>
<td>0.5 – 1.5</td>
<td>-1845</td>
<td>6</td>
</tr>
<tr>
<td>1.5 – 2.5</td>
<td>68</td>
<td>11.2</td>
</tr>
<tr>
<td>2.5 – 3</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>3-3.5</td>
<td>2000</td>
<td>-31</td>
</tr>
<tr>
<td>3.5 – 4</td>
<td>2500</td>
<td>-24</td>
</tr>
<tr>
<td>4 – 4.5</td>
<td>2930</td>
<td>-18</td>
</tr>
<tr>
<td>4.5 - 5</td>
<td>3885</td>
<td>-10.5</td>
</tr>
</tbody>
</table>

Figure 4.21 shows the four quadrant operation of matrix converter fed vector control of Induction motor drive. When the speed is 1000 rpm, the motor operates in first quadrant. When the speed is -1000 rpm, the motor operates in third quadrant. During the transition from 1000 rpm to -1000 rpm...
and from -1000 rpm to 1000 rpm, the motor operates in fourth and second quadrants of operation with maximum torque. The result shows that transient time was reduced much with vector control technique.

![Figure 4.21 Motor speed and torque for four quadrant operation](image)

**Figure 4.21** Motor speed and torque for four quadrant operation

### 4.6 SUMMARY

Control techniques, namely open-loop control, closed-loop control and cascade closed-loop control techniques and their merits and demerits are reviewed. Scalar control, direct vector control and indirect vector control techniques for the speed control of induction motor are reviewed. Cascaded closed loop control with inner current control and outer speed control using PI controller for vector control technique is implemented in this chapter. The dynamic performance of open loop and vector controlled Induction motor drive employing matrix converter is compared. The drive operation in all the four quadrants is verified. The Induction Generator operation in second
quadrant is also realized by increasing the speed of Induction motor above synchronous speed in this chapter. From the simulation results it is clear that the torque ripple is less and the dynamic response is faster in vector controlled drive fed with matrix converter. This work is presented in International Journal of Modelling and Simulation. Internal model control based speed and current controllers for perfect set point tracking load disturbance rejection are presented in the next chapter.