8.1 Introduction

Multi-phase machines can be used in variable speed drives. The applications are electric ship propulsion, 'more-electric aircraft' and traction applications, also Electric Vehicles and Hybrid Electric Vehicles. The multi-phase machines enables independent control of a few numbers of machines that are connected in series in a particular manner and the supply is fed from a single voltage source inverter (VSI). The idea was first implemented for a five-phase series-connected two-motor drive system, but is now applicable to any number of phases more than or equal to five-phase. The number of series-connected machines is a function of the phase number of VSI. The theoretical and simulation studies have already been reported for series-connected two five-phase induction motor drive.

Variable speed induction motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. To replace the sensor, information of the rotor speed is extracted from measured stator currents and voltages at motor terminals. Open-loop estimators or closed-loop observers are used for this purpose. They differ with respect to accuracy, robustness, and sensitivity against model parameter variations. This chapter analyses operation of a speed estimator based sensorless control of vector controlled series-connected two-motor five-phase drive system with current control in the stationary reference frame. Results, obtained with fixed-voltage and fixed-frequency supply fed and hysteresis current control is presented for various operating conditions on the basis of simulation results. The purpose of this chapter is to report first time, the simulation results on a sensorless control of a five-phase two-motor series-connected drive system. The operating principle is given first and then description of the sensorless technique.

Idea of multi-phase motor drives is old (1969) but, the interest in multi-phase motor drive applications has uplift during the last few years. The main reason for the development of this research is: large cranes, railway traction application and EV/HEV applications, 'more-electric aircraft' and 'more-electric ship' applications. The application of multi-phase drives
system vary from application to application. The multi-phase machines reduces the inverter (VSI) per-phase rating in high power drives application (ship-propulsion, railway-traction) and also improved the efficiency of the system (low power drives and integrated drives) and also up to some extent improved fault tolerance capacity.

The excellent application of multi-phase machines is independent control of a group of series-connected machines, which is fed through a single voltage source inverter. This concept is explained in, where a five-phase two-motor drive was explained. The concept originated from the theory that any multi-phase machine requires only two currents for independent flux and torque control. Thus, the remaining currents in a multi-phase machine can be used to control other machines connected in series. This implies that there are additional degrees of freedom in a multi-phase machine. An appropriate phase transposition is necessary when connecting the machines in series. This logic is applicable to all machines having phase numbers greater than or equal to five. Generalizations to all possible machines having even and odd phase numbers have been reported in literature where proper machine winding connections and the number of machines connected in series depends on drive phase number were reported. This theory is applying to symmetrically series connected multi-phase machines (angular difference between any two consecutive phases is $2\pi/n$, where $n$ is the number of phases) with sinusoidal flux distribution. However, the idea of series connection can be applied to the asymmetrical machines also, in which machine stator winding consists greater than or equal to two three-phase windings displaced in space with a specific angle. The two-motor drive system of this type, using asymmetrical six-phase machines (with two three-phase windings spatially displaced by 30°) has been reported.

From the industrial applications point of view only the 5-phase or 6-phase two-motor drives has the gravity. The reason behind this is, because in the series connected machines flux and/or torque producing currents of one machine flow through the other machines in the system and so machine stator windings copper loss increases, therefore efficiency of the system reduces. The literature available on series-connected drive systems describes mostly two types of configurations first is five-phase and second two possible six-phase (with symmetrical or asymmetrical six-phase machines). The operating principle of the series-connected two-motor five-phase drive system has been reported in literature, and a $d$-$q$ modeling for this drive system is reported in literature. Inverter current control can be analyzed by using either synchronous current controllers or phase current controller in the stationary reference frame. A comparison of these two controllers has shown that phase
current control in the stationary reference frame is advantageous for series-connected multi-motor drive systems, since the parameter variation sensitivity in the decoupling circuit increases by the application of synchronous current controller. The phase current control technique is utilized in the paper.

The experimental results of a vector-controlled series-connected two-motor six-phase drive, comprising a symmetrical six-phase machine connected in series with a three-phase machine is available in literature. Also the performance of two series-connected asymmetrical six-phase machines under Volt per Hertz control is presented in literature. This chapter therefore presents the simulation results, collected from a sensorless vector-controlled series-connected five-phase two-motor drive system, which illustrate an ultimate proof of the decoupling of the system. A short overview of the operating principles is discussed first. The number of simulation results, for different test conditions are presented. These test results prove that the coupling of control of the two machines is practically negligible even in sensorless mode, although both machines are connected in series and the supply is fed from a single five-phase VSI.

The two-motor drive system presented in this chapter has a good panorama for industrial applications allied to winders. In such an application use of two series-connected five-phase machines is advantageous in two folds, first it save one inverter leg (when compared to an equivalent two-motor three-phase system) and second reduces the inverter rating, thus reducing the capital expense. The best results can be obtained with permanent magnet synchronous machines, since machine de-rating would not be required to compensate for the excess stator winding losses.

Sensorless operation of a vector controlled three-phase induction machine drive is broadly discussed in the literature, but the same is not true for multi-phase induction machine. Only few application of sensorless operation of multi-phase machine is presented in the literature. The difficulties associated with the position sensor in ‘more-electric’ aircraft fuel pump fault tolerant drive is highlighted in literature.

Although several schemes are available for sensorless operation of a vector controlled drive, but the simplest is the open-loop scheme because of ease of their realization. An attempt is made in this chapter to extend the different sensorless techniques of a three-phase machines and five-phase machines to series-connected two-motor five-phase drive system.

The analysis is here limited to Open-Loop, MRAS, ELO and EKF-based sensorless control of a series-connected two-motor five-phase drive system, with current control in the stationary reference frame. Phase currents are controlled using hysteresis current control
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method. A simulation test is performed for speed mode of operation, for a number of operating conditions, and the results are presented in the chapter.


8.2 Sensorless operation of a five-phase series-connected two machines

The developed model of a series-connected two five-phase induction machines suggest that a speed estimator used for five-phase machines can be easily extended to multi-phase, multi-motor machines. For multi-phase machines too any speed estimator requires only $d$ and $q$ components of stator voltages and currents for first machine. From the model of a five-phase induction machine (chapter 3), it has been shown that the stator and rotor $d$ and $q$ axis flux linkages are function of magnetizing inductance $L_m$ and stator and rotor $d$ and $q$ axis currents, where as the $x$ and $y$ axis flux linkages are function of only their respective currents. Therefore in speed estimation for multi-phase multi-motor machine the $x$ and $y$ components of voltages and currents are required for speed estimation of second machine. Therefore speeds can be estimated using $d$-$q$ and $x$-$y$ components of stator voltages and currents. A principal block-diagram of the sensorless control of series-connected five-phase two-motor drive system based on Model Reference Adaptive System (MRAS) is shown in Fig. 8.1.

![Figure 8.1. The block diagram for MRAS based sensorless control of series connected two five-phase induction machines.](image-url)
8.3 Open-Loop speed estimator for a five-phase series-connected two motor drive

Although several schemes are available for sensorless operation of a vector controlled drive, but the simplest is the open-loop because of ease of their implementation. An attempt is made in this section to extend the open-loop technique of a three-phase and five-phase machines to five-phase two-motor series-connected drive system.

The analysis in this section is restricted to open-loop sensorless control of a five-phase two-motor series-connected drive system, with current control in the stationary reference frame. Phase currents are controlled using hysteresis current control method. A simulation study is performed for speed mode of operation, for a number of transients, and the results are reported in this chapter.

In the context of speed estimation based on an induction machine model, the term 'open-loop speed estimation' means that the speed estimation purely relies on the equations of an induction machine model. In other words, a corrective action within the speed estimator is not present. If there is certain corrective action within the model based speed estimator, such an estimator is termed 'closed-loop speed estimator'. Note that the meaning of 'open-loop' and 'closed-loop' in this context is not in any way related to the speed control loop of the drive - this loop is always closed and that is precisely the reason why the speed is estimated in the first place. The first attempt to operate the induction machine with closed-loop speed control but without using a speed sensor was based on an analogue slip calculator that computed the slip frequency and dates back to 1975. The slip frequency is the difference between the stator frequency and the electrical frequency corresponding to rotor speed. By calculation of the slip frequency, the speed of the rotor can be determined. The slip information is obtained by measuring the electrical quantities applied to the machine. By performing simple signal processing operations on the measured quantities, an analogue signal proportional to the slip level is derived and used to control the machine. This scheme is applicable only in steady-state, in a limited speed range, and is therefore inappropriate for high performance vector control. During the last couple of years, several open-loop rotor speed estimation methods were developed for sensorless vector control of induction machine. Calculation of the rotor speed is based on the induction machine dynamic model. Rotor speed is calculated as the difference between the machine’s synchronous electrical angular speed and the angular slip frequency.
In this chapter rotor speed and slip frequency estimator is obtained by considering the voltage equations of the induction machine. The scheme explained below use the monitored stator voltages and currents or the monitored stator currents and reconstructed stator voltages. In general, the accuracy of open-loop estimators depends greatly on the accuracy of the machine parameters used. At low rotor speed, the accuracy of the open-loop estimator is reduced, and in particular, parameter deviations from their actual values have great influence on the steady-state and transient performance of the drive system which uses an open-loop estimator. Furthermore, high accuracy is achieved if the stator flux is obtained by a scheme which avoids the use of pure integrators. It is possible to have a rather accurate estimate of the appropriate ‘hot’ stator resistance by using a thermal model of the induction machine.

In some schemes, the rotor flux linkage estimation requires the rotor time constants, which can also vary, since it is the ratio of the rotor self-inductance and the rotor resistance, and the rotor resistance can vary due to temperature effects and skin effects, and the rotor self-inductance can vary due to skin effect and saturation effects. The changes of the rotor resistance due to temperature changes are usually slow changes. Due to main flux saturation, the magnetizing inductance \( L_m \) can change and thus the stator self-inductance \( L_s = L_{sl} + L_m \) and rotor self-inductance \( L_r = L_{rl} + L_m \) can also change even if the leakage inductances \( L_{sl}, L_{rl} \) are constant. The changes of the rotor self-inductance due to saturation can be fast. Due to leakage flux saturation, \( L_{sl}, L_{rl} \) and the stator transient inductance \( L_s' \) can also change. In a vector-controlled drive, where the rotor flux amplitude is constant, the variation of \( L_m \) are small.

Rotor speed is calculated as the difference between the machine’s synchronous electrical angular speed and the angular slip frequency. In other words,

\[
\omega_r = \omega_{mr} - \omega_{sl}
\]

where \( \omega_r \) is the rotor speed, \( \omega_{mr} \) is the speed of rotor flux and \( \omega_{sl} \) is the angular slip frequency. In a rotor flux oriented controlled induction machine, it is possible to obtain the angular slip frequency by using the rotor voltage equation of the machine in the rotor flux oriented reference frame. The angular slip frequency can be calculated from:

\[
\omega_{sl} = \frac{L_m j^{INV}}{T_r^{TM} \psi_r}
\]  

(8.1)

where \( j^{INV} \) can be obtained from the torque equation as:
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\[
 i_{INV}^{lfs} = \frac{2T_e L_r^{TM}}{5P \psi_r} \tag{8.2}
\]

Substitution of equation (8.2) into (8.1), considering that \( \psi_r = \psi_{ar} \) in the rotor flux oriented reference frame and that

\[
 T_e = \frac{5}{2} P \frac{L_r^{TM}}{L_m^{TM}} (\psi_{ar} i_{INV}^{lfs} - \psi_{br} i_{INV}^{lfs}) \tag{8.3}
\]

Yields

\[
 \omega_{sl} = \frac{L_m^{TM}}{T_r^{TM}} \frac{1}{\psi_r^2} (\psi_{ar} i_{INV}^{lfs} - \psi_{br} i_{INV}^{lfs}) \tag{8.4}
\]

The electrical angle \( \phi_r \) of the rotor flux vector is defined as:

\[
 \phi_r = \tan^{-1} \left( \frac{\psi_{br}}{\psi_{ar}} \right) \tag{8.5}
\]

The derivative of the angle equation (8.5) can be used to obtain the electrical angular speed of the rotor flux. Therefore,

\[
 \omega_{mr} = \frac{d\phi_r}{dt} = \frac{\psi_{ar} \frac{d\psi_{br}}{dt} - \psi_{br} \frac{d\psi_{ar}}{dt}}{\psi_{ar}^2 + \psi_{br}^2} \tag{8.6}
\]

If the rotor flux components are known, the electrical angular speed of rotor flux can be calculated by using equation (8.6). It is convenient to estimate the rotor flux components from the stator voltage equations. Derivatives of the rotor flux components can be then given as:

\[
 \frac{d\psi_{ar}}{dt} = \frac{L_r^{TM}}{L_m^{TM}} \left( \psi_{as}^{INV} - R_s^{TM} i_{as}^{INV} - \sigma_{ar}^{TM} L_s^{TM} \frac{dI_{INV}^{lfs}}{dt} \right) \tag{8.7}
\]

\[
 \frac{d\psi_{br}}{dt} = \frac{L_r^{TM}}{L_m^{TM}} \left( \psi_{bs}^{INV} - R_s^{TM} i_{bs}^{INV} - \sigma_{br}^{TM} L_s^{TM} \frac{dI_{INV}^{lfs}}{dt} \right)
\]

Electrical angular speed of rotor flux, given with (8.6), and angular slip frequency (8.4) are thus calculated using (8.7) and measured stator voltages and currents. Finally, the rotor speed is estimated from:

\[
 \omega_r = \omega_{mr} - \omega_{sl} = \frac{\psi_{ar} \frac{d\psi_{br}}{dt} - \psi_{br} \frac{d\psi_{ar}}{dt}}{\psi_{ar}^2 + \psi_{br}^2} - \frac{L_m^{TM}}{T_r^{TM}} \frac{1}{\psi_r^2} (\psi_{ar} i_{bs}^{INV} - \psi_{br} i_{as}^{INV}) \tag{8.8}
\]
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The suffix **TM** stands for Two-Motor Model values and **INV** stands for inverter quantity. In the expressions $\alpha = d$ and $\beta = q$ for first machine and $\alpha = x$ and $\beta = y$ for second machine.

A simulink diagram can be implemented using speed estimation scheme based on the equations (8.1)-(8.8). The inputs are stator currents and stator voltages in stationary reference frame. Stator currents can be measured from the machine terminals. Stator voltages can be measured from the machine terminals or reconstructed from the inverter switching states and measured DC link voltage.

The problems encountered in the implementation of open-loop scheme are two-fold. Firstly, since it is model based, accuracy of speed estimation is affected by parameter variation effects. Secondly, the open-loop scheme involves pure integration that fails at very low and zero frequency due to offset and drifts problems. This kind of speed estimator works without failure above 10% of rated synchronous speed.

### 8.3.1 Simulation Results

The simulation results of open-loop based speed estimator are obtained using two identical 4-pole, 50 Hz five-phase induction machines. The indirect vector controller for both machines is the same and is the one shown in Fig. 3.3. Various simulation tests are performed in order to verify the independence of the control of the two machines in sensorless mode i.e. using open-loop speed estimator. The results are reported in this section. Operation in the base speed region only is considered and the stator d-axis current references of both machines are constant at all times. Both machines are running under no-load and load conditions. Both machines can be operated in two ways:

#### 8.3.1.1 Fixed voltage and fixed frequency supply fed five-phase series-connected two motor drive:

Under this condition both machines are connected to two ideal five-phase supply systems. If supply voltages for machine-1 are $v_{a1}, v_{b1}, v_{c1}, v_{d1}, v_{e1}$ and for machine-2 are $v_{a2}, v_{b2}, v_{c2}, v_{d2}, v_{e2}$ then the resultant supply voltages applied to the series-connected two motors are:

$$
\begin{align*}
V_A &= v_{a1} + v_{a2}, \\
V_B &= v_{b1} + v_{b2}, \\
V_C &= v_{c1} + v_{c2}, \\
V_D &= v_{d1} + v_{d2}, \\
V_E &= v_{e1} + v_{e2}
\end{align*}
$$

(8.9)
The simulation time for test is 2 sec. and first machine is loaded at t=1.2s and second machine loaded at t=1.0s. The machines are running under acceleration transient and steady-state at no-load and load conditions. Both the machines are running under different test conditions to verify the decoupling of both machines also. The corresponding test results are shown in Fig. 8.2(a) to (f). Each test results show both reference and estimated speeds for IM1 and IM2.

![Graphs](image)

Figure 8.2. Speed characteristics for fixed voltage and fixed frequency fed series-connected two five-phase induction motors system with open-loop speed estimator.

### 8.3.1.2 Vector controlled five-phase series-connected two motor drive:

In this case both machines are vector controlled. Two vector controllers are used for control of series connected two motors. If the output currents of first controller for IM-1 are $i'_{a1}, i'_{b1}, i'_{c1}, i'_{d1}, i'_{e1}$ and the output currents of second controller for IM-2 are $i'_{a2}, i'_{b2}, i'_{c2}, i'_{d2}, i'_{e2}$ then the resultant supply currents applied to the series-connected two motors are:

$$
\begin{align*}
    i'_a &= i'_{a1} + i'_{a2} \\
    i'_b &= i'_{b1} + i'_{b2} \\
    i'_c &= i'_{c1} + i'_{c2} \\
    i'_d &= i'_{d1} + i'_{d2} \\
    i'_e &= i'_{e1} + i'_{e2}
\end{align*}
$$

The simulation time for test is 2 sec. and both machines are loaded simultaneously at t=1s. The machines are running under acceleration transient from t=0.3s and 0.4s and steady-state at no-load and load conditions. Both the machines are reversing from t=1.2s and 1.3s. Both the machines are running under different test condition to verify the decoupling of both
machines. The corresponding test results are shown in Fig. 8.3(a) to (f). Each test results show both reference and estimated speeds for IM1 and IM2.

![Image of speed characteristics](image.jpg)

Figure 8.3. Speed characteristics for vector-controlled series connected two five-phase induction motors system with open-loop speed estimator.

### 8.3.2 Discussion of results

Fig. 8.2(a) to (f) shows the test results for fixed voltage and fixed frequency supply fed series connected two five-phase induction motors system with open-loop speed estimator. In first test (a), IM1 is running at 1500 rpm and IM2 at 1200 rpm and first machine is loaded at \( t=1.2s \) and second machine is loaded at \( t=1.0s \). In (b), IM1 is running at 1200 rpm and IM2 at 900 rpm. In (c), IM1 is running at 1200 rpm and IM2 at 0 rpm. In (d), IM1 is running at 1200 rpm and IM2 at -900 rpm. In (e), IM1 and IM2 both are running at 1200 rpm but in opposite direction. In (f), IM1 and IM2 both are running at 1500 rpm but in opposite direction.

These test results shows that the estimated speeds are very close to the measured speeds. Only ripples are present in starting due to the presence of integrators in the estimators. The ripples in the responses are so small that can be eliminated. This discussion is true for both conditions i.e. when machine is running in forward direction or in reverse direction. These test results also shows that both machines IM1 and IM2 are independently controlled even in sensorless mode (open-loop).

Fig. 8.3(a) to (f) shows the test results for vector controlled series connected two motor systems. In all test, IM1 is set at \( \pm 1200 \) rpm and both machines are loaded at \( t=1.0s \). In
first test (a), IM2 is set at ±1000 rpm. In (b), IM2 is set at ±500 rpm. In (c), IM2 is set at 0 rpm. In (d), IM2 is set at ± 500 rpm. In (e), IM2 is set at ± 1000 rpm. In (f), IM2 is set at ± 1200 rpm. In vector controlled results shows that the estimated speeds are also very close to the measured speeds. In vector controlled speed fluctuation is more as compare to fixed voltage and fixed frequency supply fed and is of 5 rpm. These test results again shows that both machines IM1 and IM2 are independently controlled in vector controlled technique in sensorless mode (open-loop).

8.4 MRAS-based speed estimator for series-connected two five-phase induction motor drive

The model reference scheme uses two independent machine models of different configuration to estimate the same state variable on the basis of different inputs. The estimator that does not involve the quantity to be estimated (i.e. rotor speed) is referred as a reference model. The other estimator, which involves the estimated quantity, is referred as an adaptive model. The error between the outputs of the two estimators is minimized by some appropriate adaptive mechanism that produces the estimated rotor speed. The schematic block of a MRAS based speed estimator is presented in Fig. 8.4.

![Schematic block diagram of MRAS estimator used for two series-connected five-phase induction motor drive system.](image)

In this estimator the outputs of the reference and the adaptive models denoted in Fig. 8.4 by $\psi_r^{(1)}$ and $\psi_r^{(2)}$ are two estimates of the rotor flux space vector, that are obtained from the machine model in the stationary reference frame. By letting $\omega_s = 0$ the following two space vector equations are:

$$\begin{align}
\psi_{\text{INV}}^{\text{INV}} &= R_s i_{\text{INV}}^{\text{INV}} + \frac{d\psi_r}{dt} \\
0 &= R_r i_r + \frac{d\psi_r}{dt} - j\omega_r \psi_r
\end{align}$$

(8.11)
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where \( V_{s}^{\text{INV}} \) and \( I_{s}^{\text{INV}} \) are inverter voltage and current fed to both motors.

Elimination of the stator flux vector and rotor current vector enables rotor flux vector to be expressed in the form of:

\[
\frac{d\psi_r}{dt} = \frac{L_r^{\text{TM}}}{L_m^{\text{TM}}} \left[ V_{s}^{\text{INV}} - R_s^{\text{TM}} I_{s}^{\text{INV}} - \sigma L_s^{\text{TM}} \frac{dI_{s}^{\text{INV}}}{dt} \right]
\]
\[
\frac{d\psi_r}{dt} = \left[ -\frac{1}{T_r} + j\omega \right] \psi_r + \frac{L_m^{\text{TM}}}{T_r} I_{s}^{\text{INV}}
\]

where \( L_m^{\text{TM}} = \) two motor system mutual inductance, \( L_s^{\text{TM}} = \) two motor system stator inductance, \( L_r^{\text{TM}} = \) two motor system rotor inductance and \( R_s^{\text{TM}} = \) two motor system resistance.

The first equation of (8.12) can be used to calculate rotor flux space vector on the basis of the measured stator voltages and currents. The equation is independent of rotor speed and it therefore represents the reference model of Fig. 8.4.

On the other hand, calculation of rotor flux from the second equation of (8.12) requires stator currents only and is dependent on the rotor speed. Hence the second equation of (8.12) represents the adaptive model of Fig. 8.4.

By resolving equations (8.12) into two-axis components, the rotor flux components in the stationary reference frame are obtained as:

\[
\begin{bmatrix}
    \psi_{ar} \\
    \psi_{pr}
\end{bmatrix} = \frac{L_m^{\text{TM}}}{L_m^{\text{TM}}} \begin{bmatrix}
    V_{cs}^{\text{INV}} \\
    V_{ps}^{\text{INV}}
\end{bmatrix} - \begin{bmatrix}
    A + Bp & 0 \\
    0 & (A + Bp)
\end{bmatrix} \begin{bmatrix}
    I_{cs}^{\text{INV}} \\
    I_{ps}^{\text{INV}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    \psi_{ar} \\
    \psi_{pr}
\end{bmatrix} = \begin{bmatrix}
    -C - \omega_r & \psi_{ar} \\
    \omega_r - C & \psi_{pr}
\end{bmatrix} + \frac{L_m^{\text{TM}}}{T_r^{\text{TM}}} \begin{bmatrix}
    I_{cs}^{\text{INV}} \\
    I_{ps}^{\text{INV}}
\end{bmatrix}
\]

where \( A = R_s^{1} + R_s^{2}, B = \sigma (L_{is1} + L_{is2} + L_{m1}), C = \frac{1}{T_r}, \) and \( p = \frac{d}{dt} \)

The angular difference between the two rotor flux space vector positions is used as the speed tuning signal (error signal). The speed tuning signal actuates the rotor speed estimation algorithm, which makes the error signal converge to zero. The adaptation mechanism of MRAS based speed estimation method is a simple PI controller algorithm.

\[
\omega^{\text{est}} = K_p e + K_i \int_0^t e\,dt
\]

where the input of the PI controller is

\[
e = \psi_{pr}^{(2)} - \psi_{pr}^{(1)}, \psi_{pr}^{(1)}, \psi_{pr}^{(2)}
\]

and \( K_p \) and \( K_i \) are any positive constants and \( e \) is error signal. In the expressions \( \alpha = d \) and \( \beta = q \) for first machine and \( \alpha = x \) and \( \beta = y \) for second machine.
8.4.1 Simulation Results

The drive configuration is same as discussed in section 8.3. Different simulation tests are performed in order to proof the independence of the control of the two machines even in sensorless mode (MRAS). The results obtained are presented in this section. Motor operation under base speed region is considered and the stator d-axis current references of both machines are constant at all times. Both machines are running under no-load and load conditions. Both machines can be operated in two ways:

8.4.1.1 Fixed voltage and fixed frequency supply fed five-phase series-connected two motor drive:

The drive configuration is same as discussed in section 8.3.1.1. The simulation time for test is 2 sec. and first machine is loaded at \( t=1.2s \) and second machine loaded at \( t=1.0s \). The machines are running under acceleration transient and steady-state at no-load and load conditions. Both the machines are running under different test conditions to verify the decoupling of both machines even in sensorless mode. The corresponding test results are shown in figure 8.5(a) to (c). Each test results show both reference and estimated speeds for IM1 and IM2.
8.4.1.2 Vector controlled five-phase series-connected two motor drive

The drive configuration is same as discussed in section 8.3.1.2. The simulation time for test is 2 sec. and both machines are loaded simultaneously at t=1s. The machines are running under acceleration transient from t=0.3s and 0.4s and steady-state at no-load and load conditions. Both the machines are reversing from t=1.2s and 1.3s. Both the machines are running under different test condition to verify the decoupling of both machines. The corresponding test results are shown in Fig. 8.6(a) to (c).

Each test results show both reference and estimated speeds for IM1 and IM2.
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Figure 8.6. Speed characteristics for vector-controlled series connected two motors system with MRAS speed estimator.

(a) Inverter currents  (b) Motor speeds  (c) Motor torques
8.4.2 Discussion of results

Fig. 8.5(a) to (c) shows the test results for fixed voltage and fixed frequency supply fed series connected two motor systems. The machines operates at six different test conditions which are (i) IM1 is running at 1500 rpm and IM2 at 1200 rpm and first machine is loaded at t=1.2s and second machine is loaded at t=1.0s, (ii) IM1 is running at 1500 rpm and IM2 at 900 rpm, (iii) IM1 is running at 1500 rpm and IM2 at 10 rpm, (iv) IM1 is running at 1500 rpm and IM2 at -900 rpm, (v) IM1 is running at 1500 rpm and IM2 at -1200 rpm (vi) IM1 and IM2 both are running at 1500 rpm but in opposite direction.

When both machines are running at different test conditions, the corresponding currents supplied by inverter, their speeds and torques are shown in Fig. 8.5(a)-(c) respectively. Each speed response shows four different characteristics, two reference speeds and two estimated speeds for each machine. These test results shows that the estimated speeds are very close to the measured speeds. There is a little deviation in speed in acceleration transient period for higher speed (1500 rpm), This discussion is true for both conditions i.e. when machine is running in forward direction or in reverse direction. These test results also shows that both machines IM1 and IM2 are independently controlled even in sensorless mode.

A surprising behavior has been seen when one machine is running at higher speed and second machine is stalled (very low speed) then the current supplied by inverter is of oscillating nature. The current fluctuation is from +23 amp to -18 amp. This behaviour can also be seen in case of vector controlled series connected two motor drive systems when load is applied on machines.

Fig. 8.6(a) to (c) shows the test results for vector controlled series connected two motor systems. In all test, IM1 is set at ±1200 rpm and both machines are loaded at t=1.0s. In first test (i) IM2 is set at ±1000 rpm, (ii) IM2 is set at ±500 rpm, (iii) IM2 is set at 0 rpm, (iv) IM2 is set at ± 500 rpm (v) IM2 is set at ± 1000 rpm, and (vi) IM2 is set at ± 1200 rpm. In vector controlled results shows that the estimated speeds are also very close to the measured speeds. These test results again shows that both machines IM1 and IM2 are independently controlled in vector controlled technique in sensorless mode.

8.5 Extended Luenberger Observer speed estimator for series-connected two five-phase induction motor drive

An observer can be classified according to the type of representation used for the plant to be observed. If the plant is considered to be deterministic, then the observer is a
deterministic observer; otherwise it is a stochastic observer. The most commonly used observers are Luenberger and Kalman types. The Luenberger observer (LO) is of the deterministic type and the Kalman filter (KF) is of the stochastic type. The basic Kalman filter is only applicable to linear stochastic systems, and for non-linear systems the extended Kalman filter (EKF) can be used, which can provide estimates of the states of a system or of both the states and parameters (joint state and parameter estimation). The EKF is a recursive filter, which can be applied to a non-linear time-varying stochastic system. The basic Luenberger observer is only applicable to a linear, time-invariant deterministic system. The extended Luenberger observer (ELO) is applicable to a non-linear, time-varying deterministic system.

In summary it can be seen that both the EKF and ELO are non-linear estimators and the EKF is applicable to stochastic systems and the ELO to deterministic systems. The extended Luenberger observer (ELO) is an alternative solution for real-time implementation in industrial drive systems. The simple algorithm and the ease of tuning of the ELO may give some advantages over the conventional EKF.

A full-order (fourth-order) adaptive state observer (Luenberger observer) which is constructed by using the equations of the induction machine in the stationary reference frame by adding an error compensator is used for speed estimation. In the full-order adaptive state observer the rotor speed is considered as a parameter, but in the EKF and ELO the rotor speed is considered as a state variable. It is shown that when the appropriate observers are used in high-performance speed sensorless torque controlled induction motor drive (vector controlled drives, direct controlled drives), stable operation can be obtained over a wide speed range, including very low speeds.

A simulation study is performed for speed mode of operation, for a number of transients, and the results are presented in this section. A state observer is a model-based state estimator which can be used for the state and/or parameter estimation of a non-linear dynamic system in real time. In the calculations, the states are predicted by using a mathematical model, but the predicted states are continuously corrected by using a feedback correction scheme. The actual measured states are denoted by $x$ and the estimated states by $\hat{x}$. The correction term contains the weighted difference of some of the measured and estimated outputs signals (the difference is multiplied by the observer feedback gain, $G$). The accuracy of the state observer also depends on the model parameters used. The state observer is simpler than the Kalman observer, since no attempt is made to minimize a stochastic cost criterion.
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To obtain the full-order non-linear speed observer, first the model of the induction machine is considered in the stationary reference frame, which can be described as follows:

\[
\frac{dx}{dt} = Ax + Bv \tag{8.16}
\]

and the output vector is

\[
i_s = Cx \tag{8.17}
\]

By using the derived mathematical model of the induction machine, e.g. if the component form of the equations (8.16), is used, since this is required in an actual implementation and adding the correction term, which contains the difference of actual and estimated states, a full-order state observer, which estimates the stator currents and rotor flux linkages, can be described as follows:

\[
\frac{d\hat{x}}{dt} = A\hat{x} + Bv + G(i_e - \hat{i}_s) \tag{8.18}
\]

and the output vector is

\[
\hat{i}_s = C\hat{x} \tag{8.19}
\]

where \(A\) is a state matrix, \(B\) is the input matrix, \(G\) is the observer gain matrix, \(C\) is the output matrix, \(x\) is the state vector, \(v\) is the input vector, \(i_s\) stator current vector.

Also the state matrix of the observer (\(\hat{A}\)) is a function of the rotor speed, and in a speed-sensorless drive, the rotor speed must be estimated. The estimated rotor speed is denoted by \(\hat{\omega}_r\), and in general \(\hat{A}\) is a function of \(\hat{\omega}_r\). The estimated speed is considered as a parameter in \(\hat{A}\), however in extended Kalman filter considered as a state variable. In eqns (8.16) and (8.17) the different terms are explained as follows:

\[
\hat{A} = \begin{bmatrix}
-L_p & \frac{1}{T_s} & L_p \frac{1}{L_r} \\
L_p & \frac{1}{T_s} & L_p \\
0 & 0 & \frac{1}{T_s} \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
I_2 \\
I_2 \\
I_2 \\
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
I_2 \\
I_2 \\
I_2 \\
\end{bmatrix}
\]

\[
v^{\text{INV}} = \begin{bmatrix}
v_s^{\text{INV}} \\
v_s^{\text{INV}} \\
0 \\
\end{bmatrix}
\]

\[
\hat{x} = \begin{bmatrix}
\hat{i}_s \\
\hat{\psi}_r \\
\end{bmatrix}
\]

\[
i_s^{\text{INV}} = \begin{bmatrix}
i_s^{\text{INV}} \\
i_r^{\text{INV}} \\
\end{bmatrix}
\]

\[
J = \begin{bmatrix}
0 & -1 \\
1 & 0 \\
\end{bmatrix}
\]
\( l_2 = \text{diag}(1,1) \) is a second order identity matrix.

\( O_2 \), is a 2x2 zero matrix.

In state matrix \( \hat{A} \), the different terms are as follows:

\( L^TM_m \) and \( L^TM_r \) are the magnetising inductance and rotor self-inductance respectively, \( L^s \) is the stator transient inductance, \( T^s = L^s IR^s \) and \( T^r = L^r IR^r \) are the stator and rotor transient time constants respectively, and \( \sigma = 1 - (L^TM_m)^2 / (L^TM_s L^TM_r) \) is the leakage factor.

The observer gain matrix is defined as

\[
G = \begin{bmatrix} g_1 l_2 + g_2 J \\ g_3 l_2 + g_4 J \end{bmatrix}
\]

which yields a 2x4 matrix. The four gains in \( G \) can be obtained from the eigen-values of the induction motor as follows:

\[
g_1 = - (k - 1) \left( \frac{1}{T^s} + \frac{1}{T^r} \right)
\]

\[
g_2 = (k - 1) \hat{\omega}_r
\]

\[
g_3 = (k^2 - 1) \left( \frac{1}{T^s} + \frac{(1 - \sigma)}{T^r} \right) \left( \frac{L^s L^TM_m}{L^TM_r} + \frac{L^TM_m}{T^r} \right) + \frac{L^s L^TM_m}{L^TM_r} (k - 1) \left( \frac{1}{T^s} + \frac{1}{T^r} \right)
\]

\[
g_4 = - (k - 1) \hat{\omega}_r \frac{L^s L^TM_m}{L^TM_r}
\]

It follows that the four gains depend on the estimated speed, \( \hat{\omega}_r \). By using eqn. (8.16) and (8.17) it is possible to implement a speed estimator which estimates the rotor speed of an induction machine by using the adaptive state observer shown in Fig. 8.7.

![Figure 8.7. Adaptive speed observer (speed-adaptive flux observer) used for series connected two five-phase induction motor drive.](image-url)
In Fig. 8.7 the estimated rotor flux-linkage components and the stator current error components are used to obtain the error speed tuning signal and given by equations:
\[ \dot{\psi}_r = \hat{\psi}_{arr} + j\hat{\psi}_{apr} \quad \text{and} \quad e = e_{ar} + je_{bs}. \]
The estimated speed is obtained from the speed tuning signal by using a PI controller thus,
\[ \dot{\omega}_r = K_p (\hat{\psi}_{pr} e_{as} - \hat{\psi}_{ar} e_{bs}) + K_i \int (\hat{\psi}_{pr} e_{as} - \hat{\psi}_{ar} e_{bs}) dt \quad (8.22) \]
where \( K_p \) and \( K_i \) are proportional and integral gain constants respectively, \( e_{as} = i_{as}^{\text{INV}} - \hat{i}_{as} \) and \( e_{bs} = i_{bs}^{\text{INV}} - \hat{i}_{bs} \) are the stator current errors respectively. The adaptation mechanism is similar to that as used in the MRAS-based speed estimators, where the speed adaptation has been obtained by using the state-error equations of the system considered.

In the expressions \( \alpha = d \) and \( \beta = q \) for first machine and \( \alpha = x \) and \( \beta = y \) for second machine.

**8.5.1 Simulation Results**

The configuration of drive is same as discussed in section 5.3.1. Various simulation tests are performed in order to verify the independence of the control of the two machines. The results are reported in this section. Operation in the base speed region only is considered and the stator d-axis current references of both machines are constant at all times. Both machines are running under load conditions. Both machines can be operated in two ways:

**8.5.1.1 Fixed voltage and fixed frequency supply fed five-phase series-connected two motor drive:**

The test condition is same as before discussed in section 8.3.1.1. The simulation time for test is 2 sec. and both machines are loaded simultaneously at \( t=1.2s \). The machines are running under acceleration transient and steady-state at no-load and load conditions. Both the machines are running under different test conditions to verify the decoupling of both machines. The corresponding test results are shown in figure 8.8(a) to (f). Each test result shows both reference and estimated speeds for IM1 and IM2.
8.5.1.2 Vector controlled five-phase series-connected two motor drive

Again the test conditions are same as explained in section 8.3.1.2. The simulation time for test is 2 sec. and both machines are loaded simultaneously at t=1s. The machines are running under acceleration transient from t=0.3s and 0.4s and steady-state at no-load and load conditions.

Both the machines are reversing from t=1.2s and 1.3s. Both the machines are running under different test condition to verify the decoupling of both machines. The corresponding test results are shown in Fig. 8.9(a) to (f). Each test results show both reference and estimated speeds for IM1 and IM2.

Figure 8.9. Speed characteristics for vector-controlled series connected two motors system with ELO based speed estimator.
8.5.2 Discussion of results

Fig. 8.8(a) to (f) shows the test results for fixed voltage and fixed frequency supply fed series connected two motor systems. In first test (a), IM1 is running at 1500 rpm and IM2 at 1200 rpm and both machines are loaded at t=1s. In (b), IM1 is running at 1200 rpm and IM2 at 600 rpm. In (c), IM1 is running at 900 rpm and IM2 at 0 rpm. In (d), IM1 is running at 1500 rpm and IM2 at -900 rpm. In (e), IM1 and IM2 both are running at 1500 rpm but in opposite direction. In (f), IM1 and IM2 both are running at 900 rpm but in opposite direction.

These test results shows that when machine is running at higher speed then there is settling time delay of around 0.1 sec. Also under loading condition, a 10 rpm difference can be seen. As the speed decreases the settling time delay decreases but ripples in response increases in both conditions i.e. no-load and load conditions. This discussion is true for both conditions i.e. when machine is running in forward direction or in reverse direction. These test results also shows that both machines IM1 and IM2 are independently controlled even in sensorless mode.

Fig. 8.9(a) to (f) shows the test results for vector controlled series connected two motor systems. In all test, IM1 is set at ±1200 rpm and both machines are loaded at t=1.0s. In first test (a), IM2 is set at ±1000 rpm. In (b), IM2 is set at ±500 rpm. In (c), IM2 is set at 0 rpm. In (d), IM2 is set at ±500 rpm. In (e), IM2 is set at ±1000 rpm. In (f), IM2 is set at ±1200 rpm. In vector controlled the settling time error is very small as compare to ideal supply fed machine. Also in vector controlled there is no speed error in loading condition. But when speed decreases then ripples in speed response increases under both forward and reversing conditions. These test results again shows that both machines IM1 and IM2 are independently controlled in vector controlled technique in sensorless mode (ELO).

8.6 Extended Kalman Filter speed estimator for series-connected two five-phase induction motor drive

An adaptive state observer (EKF observer) which is constructed by using the equations of the induction machine in the stationary reference frame by adding an error compensator is used for speed estimation. In the adaptive state observer EKF and ELO, the rotor speed is considered as a state variable. It is shown that when the appropriate observers are used in high-performance speed sensorless torque controlled induction motor drive (vector controlled drives, direct controlled drives), stable operation can be obtained over a wide speed range, including very low speeds.
The Kalman filter takes care of the effects of the disturbance noise of a control system and the errors in the parameters of the system are considered as noise. The Kalman filter can be expressed as a state model:

\[
\dot{x} = Ax + Bu + U(t)w(t) \quad \text{(System equation)} \tag{8.23}
\]

\[
y = Cx + v(t) \quad \text{(Measurement equation)} \tag{8.24}
\]

where

\[
U(t) = \text{weight matrix of noise}
\]

\[
v(t) = \text{noise matrix of output model (measurement noise)}
\]

\[
w(t) = \text{noise matrix of state model (system noise)}
\]

\[U(t), v(t), \text{ and } w(t)\] are assumed to be stationary, white, and Gaussian noise, and their expectation values are zero. The covariance matrices \(Q\) and \(R\) of these noises are defined as:

\[
Q = \text{covariance}(w) = E\{ww'\} \tag{8.25}
\]

\[
R = \text{covariance}(v) = E\{vv'\} \tag{8.26}
\]

where \(E\{\cdot\}\) denotes the expected value.

The basic configuration of the Kalman filter is shown in Fig. 8.10.

![Figure 8.10. The basic configuration of the Kalman filter observer used for two series connected five-phase induction motor drive.](image)

The state equations of the Kalman filter can be made as follows:

\[
\dot{x} = (A - KC)\dot{x} + Bu + Ky \tag{8.27}
\]

The Kalman filter matrix is based on the covariance of the noise and denoted by \(K\). The measure of quality of the observation is expressed as follows:

\[
L_x = \sum E\{[x(k) - \hat{x}(k)]' [x(k) - \hat{x}(k)]\} = \min \tag{8.28}
\]
The value of $K$ should be such that as to minimize $L_x$. The result of $K$ is a recursive algorithm for the discrete time case. The discrete form of Kalman filter may be written by the following equations, in which all symbols denote matrices or vectors:

(i) System state estimation:

$$x(k+1) = x(k) + K(k)(y(k) - \hat{y}(k))$$  \hspace{1cm} (8.29)

(ii) Renew of the error covariance matrix:

$$P(k+1) = P(k) - K(k)h^T(k+1)P(k)$$  \hspace{1cm} (8.30)

(iii) Calculation of Kalman filter gain matrix:

$$K(k+1) = P^*(k+1)h^T(k+1)[h(k+1)P^*(k+1)h^T(k+1)+R]^{-1}$$ \hspace{1cm} (8.31)

(iv) Prediction of state matrix:

$$f(k+1) = \frac{\partial}{\partial x}(A_d x + B_d v)|_{x=x(k+1)}$$ \hspace{1cm} (8.32)

(v) Estimation of error covariance matrix:

$$P^*(k+1) = f(k+1)\hat{P}(k)f^T(k+1) + Q$$ \hspace{1cm} (8.33)

Discretization of (8.23) and (8.24) yields:

$$x(k+1) = A_d(k)x(k) + B_d(k)u(k)$$ \hspace{1cm} (8.34)

$$y(k) = C_d(k)x(k)$$ \hspace{1cm} (8.35)

where $K(k)$ is the feedback matrix of the Kalman filter. $K(k)$ gain matrix calculates how the state vector of the Kalman filter is updated when the output of the model is compared with the actual output of the system. The Kalman filter algorithm can also be used for nonlinear systems (e.g. induction motor). However, the optimal performance may not be obtained and it is impractical to verify the convergence of the model. To realize the recursive algorithm of the extended Kalman filter, a state model of the induction motor is required. After knowing the matrices $A_d$, $B_d$, and $C_d$, the matrices $x(k)$ (state prediction) and $y(k)$ (output prediction) can be calculated.

When rotor speed is considered as a state variable in the induction motor model, then an extended induction motor model is obtained and the rotor speed is considered as an extended state. The discrete induction motor model defined in equations (8.23) and (8.24) can be implemented in the extended Kalman filter algorithm.
If the system matrix, the input and output matrices of the discrete system are denoted by \( A_d, B_d, \) and \( C_d \), while the state and the output of the discrete system are denoted by \( x(k) \) and \( y(k) \), then

\[
A_d = \begin{bmatrix}
1 - \frac{T}{T_s} & 0 & T_{L_m}^{T_m} (L'_{s, T_r}^m) & \omega_r & T_{L_m}^{T_m} (L'_{s, T_r}^m) & 0 \\
0 & 1 - \frac{T}{T_s} & -\omega_r & T_{L_m}^{T_m} (L'_{s, T_r}^m) & T_{L_m}^{T_m} (L'_{s, T_r}^m) & 0 \\
0 & 0 & 1 - \frac{T}{T_r} & -T\omega_r & 0 & 0 \\
0 & 0 & T_{L_m}^{T_m} & T\omega_r & 1 - \frac{T}{T_r} & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

\( B_d = \begin{bmatrix}
\frac{T}{L_s'} \\
0 \\
\frac{T}{L_s'} \\
0 \\
0 \\
0
\end{bmatrix}
\]

\( C_d = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0
\end{bmatrix}
\)

\( x(k) = [i_d(k) i_q(k) \psi_{dr}(k) \psi_{qr}(k) \omega_r(k)]^T \)

\( u(k) = [u_d(k) u_q(k)]^T, \ y(k) = [i_d(k) i_q(k)]^T \)

where \( L'_s = \sigma L_s = (1 - \frac{L_{T_m}^2}{L_{s, T_r}^m})L_s \), \( T'_s = \frac{L'_s}{R_s + R_r (L_{T_m}^{T_m}/L_{T_r}^{T_m})^2} \) and \( T \) is the sampling time.

The essential matrices and vectors for the recursive algorithm of the extended Kalman filter can be calculated, with the discrete system model. With the help of Matlab/Simulink program, speed estimation algorithm of the extended Kalman filter can be simulated, as shown in Fig. 8.11. The execution of the S-function block is based on an M-file written as MATLAB code.

![Simulink Based Extended Kalman Filter Speed Estimator](image)

Figure 8.11. Simulink based extended Kalman filter speed estimator used for series connected two five-phase induction motor drive.
8.6.1 Simulation Results

The results of the simulation given in this section are obtained using two identical 4-pole, 50 Hz five-phase induction machines. The indirect vector controller for both machines is the same. Many simulation tests are performed in order to proof the independence of the control of the two machines in sensorless mode (EKF). The results obtained are reported in this section. Motor operation under base speed region is considered and the stator d-axis current references of both machines are constant at all times. Both machines are running under no-load and load conditions. Both machines can be operated in two ways:

8.6.1.1 Fixed voltage and fixed frequency supply fed five-phase series-connected two motor drive:

In this case also both machines are connected to same system as connected for previous cases. The simulation time for test is 2 sec. and both the machines are loaded simultaneously at $t=1.2s$. The machines are running under acceleration transient and steady-state at no-load and load conditions. Both the machines are running under different test conditions to verify the decoupling of both machines even in sensorless mode. The corresponding test results are shown in Fig. 8.12(a) to (c). Each test results show both reference and estimated speeds for IM1 and IM2.
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8.6.1.2 Vector controlled five-phase series-connected two motor drive

In this case also both machines are vector controlled and are connected in same way as was connected for previous case. The simulation time for test is 2 sec. and both machines are loaded simultaneously at t=1s. The machines are running under acceleration transient from t=0.3s and 0.4s and steady-state at no-load and load conditions. Both the machines are reversing from t=1.2s and 1.3s. Both the machines are running under different test condition to verify the decoupling of both machines. The corresponding test results are shown in Fig. 8.13(a) to (c). Each test results show both reference and estimated speeds for IM1 and IM2.
(a) Inverter currents  (b) Machines torques  (c) Machines speeds
Figure 8.13. Current, Torque and Speed responses for vector-controlled series connected two five-phase induction motors system with Kalman filter observer.
8.6.2 Discussion of results

Fig. 8.12(a) to (c) shows the test results for fixed voltage and fixed frequency supply fed series connected two motor systems. The machines operates at six different test conditions which are (i) IM1 is running at 1500 rpm and IM2 at 1200 rpm and both machines are loaded at t=1.2s, (ii) IM1 is running at 1500 rpm and IM2 at 900 rpm, (iii) IM1 is running at 1500 rpm and IM2 at 10 rpm, (iv) IM1 is running at 1500 rpm and IM2 at -900 rpm, (v) IM1 is running at 1500 rpm and IM2 at -1200 rpm (vi) IM1 and IM2 both are running at 1500 rpm but in opposite direction.

When both machines are running at different test conditions, the corresponding currents supplied by inverter, their speeds and torques are shown in Fig. 8.12(a)-(c) respectively. Each speed figure shows four different characteristics, two reference speeds and two estimated speeds for each machine. These test results shows that the estimated speeds are very close to the measured speeds. There is a little deviation in speed in acceleration transient period. This discussion is true for both conditions i.e. when machine is running in forward direction or in reverse direction. These test results also shows that both machines IM1 and IM2 are independently controlled even in sensorless mode.

A surprising behavior has been noticed when one machine is running at higher speed and second machine is stalled (very low speed) then the current supplied by inverter is of oscillating nature. The current fluctuation is from +23 amp to -18 amp. This behaviour can also be noticed in case of vector controlled series connected two motor drive systems when load is applied on machines.

Fig. 8.13(a) to (c) shows the test results for vector controlled series connected two motor systems. In all test, IM1 is set at ±1200 rpm and both machines are loaded at t=1.0s. In first test (i) IM2 is set at ±1000 rpm, (ii) IM2 is set at ±500 rpm, (iii) IM2 is set at 0 rpm, (iv) IM2 is set at ±500 rpm (v) IM2 is set at ±1000 rpm, and (vi) IM2 is set at ±1200 rpm. In vector controlled results shows that the estimated speeds are also very close to the measured speeds. These test results again shows that both machines IM1 and IM2 are independently controlled in vector controlled technique in sensorless mode.

8.7 Summary

This chapter discusses a series-connected five-phase two-motor drive and provides full simulation verification of the possibility of independent fixed voltage and fixed frequency supply fed and vector control of the two machines in sensorless mode. A short review of the operating principles is provided. The emphasis is further placed on presentation of simulation
results for various transients (acceleration, deceleration and speed reversal). By presenting the results of series-connected two-motor five-phase drive it is fully verified that the control of the two series-connected machines is truly decoupled even in sensorless mode.

The analysis in this chapter is limited to Open-Loop, Model Reference Adaptive System (MRAS), Extended Luenberger Observer (ELO) and Extended Kalman Filter (EKF)-based sensorless control of a series-connected two-motor five-phase drive system, with current control in the stationary reference frame. Phase currents are controlled using hysteresis current control method. A simulation test is performed for speed mode of operation, for a number of operating conditions, and the results are presented in this chapter of the thesis.

The investigated drive structure is applicable to all types of five-phase ac machine with sinusoidal flux distribution. It is believed that the best prospect for real-world industrial applications exists in the winder area, where the series-connected two-motor drive could provide a substantial saving on the capital outlay, especially if permanent magnet synchronous machines are used. Although the efficiency of the complete system remains affected by the series connection, there should be no need to de-rate the motors due to the increase in stator winding losses.