MRAS Based Sensorless Control of a Series-Connected Five-Phase Two-Motor Drive System

M. Rizwan Khan† and Atif Iqbal*

Abstract – Multi-phase machines can be used in variable speed drives. Their applications include electric ship propulsion, 'more-electric aircraft' and traction applications, electric vehicles, and hybrid electric vehicles. Multi-phase machines enable independent control of a few numbers of machines that are connected in series in a particular manner with their supply being 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. Theoretical and simulation studies have already been reported for number of multi-phase multi-motor drive configurations of series-connection type. 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 concerning 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 paper analyses operation of an MRAS estimator based sensorless control of a vector controlled series-connected two-motor five-phase drive system with current control in the stationary reference frame. Results, obtained with fixed-voltage, fixed-frequency supply, and hysteresis current control are presented for various operating conditions on the basis of simulation results. The purpose of this paper is to report the first ever simulation results on a sensorless control of a five-phase two-motor series-connected drive system. The operating principle is given followed by a description of the sensorless technique.

Keywords: Five-phase Machine, MRAS-estimator, Multi-phase Multi-motor Drives, Vector Control

1. Introduction

Multi-phase motor drives are not a new invention (1969) but interest in their applications has risen significantly during the last few years. The main reasons for the development of this research are: large cranes, railway traction applications, EV/HEV applications, and 'more-electric aircraft' and 'more-electric ship' applications. The purpose of multi-phase drive systems vary from application to application. The multi-phase machines reduce the inverter (VSI) per-phase rating in high power drive applications (ship-propulsion, railway-traction), improve the efficiency of the system (low power drives and integrated drives) [1], and to some extent improve fault tolerance capacity [2-3].

The best 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 [4], 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 [5-7], where proper machine winding connections and the number of machines connected in series depending on drive phase number were reported. The theory of [4-7] applies 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 also be applied to asymmetrical machines, in which machine stator winding is greater than or equal to two three-phase windings displaced in space with a specific angle. In [8, 9], a two-motor drive system of this type,

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using asymmetrical six-phase machines (with two three-phase windings spatially displaced by 30°) has been reported .

From an industrial applications point of view only the 5-phase or 6-phase two-motor drives has the gravity. The reason behind this is due to the fact that 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, five-phase and 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 [10-12], and a *d-q* modeling for this drive system is reported in [13]. 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 [14] 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 the synchronous current controller. The phase current control technique is utilized in this 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 [9-15]. Furthermore, the performance of two series-connected asymmetrical six-phase machines under Volt per Hertz control is presented in [8].

This paper therefore provides 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 paper has a good panorama for industrial applications allied to winders. In such an application, use of two series-connected five-phase machines is advantageous for two reasons, first it saves one inverter leg (when compared to an equivalent two-motor three-phase system) and second it 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 [16, 17], but the same is not correct for the multi-phase induction machine. Only a few applications of sensorless operation of multi-phase machines are presented in the literature. The difficulties associated with the position sensor in 'more-electric' aircraft fuel pump fault tolerant drive is highlighted in [18]. The drive utilizes a 16 kW, 13000 rpm six-phase permanent magnet motor with six independent single-phase inverter supply. The authors proposed an alternative sensorless drive scheme. The proposed technique makes use of flux-linkage current-angle model to estimate the rotor position (rotor speed).

Although several schemes are available for sensorless operation of a vector controlled drive, the simplest is the open-loop scheme because of ease of its realization. An attempt is made in this paper to extend the MRAS techniques of three-phase machines [19] and five-phase machines [20, 21] to a series-connected two-motor five-phase drive system.

The analysis is here limited to MRAS-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 and for a number of operating conditions. The results are reported in the paper.

2. Five-phase Two-motor Drive System

A primary block-diagram of the series-connected two-motor five-phase drive system is shown in Fig. 1. The stator windings of the two five-phase machines are connected in series, in such a way that flux and/or torque producing currents of one machine emerge as non-flux and/or torque producing currents in the other machines, and vice-versa [4-10]. The connecting machines can be of any type, i.e. induction, synchronous reluctance, or permanent magnet synchronous. It is implicit that the spatial flux distribution in both machines is absolutely sinusoidal. The supply to the machines is a five-phase VSI, whose output terminals are categorized with capital letters A, B, C, D, E, while lower case letters a, b, c, d, e classify phases of the two machines according to the spatial displacement of the stator windings (spatial displacement between any two consecutive phases is $\alpha = 2\pi/5 = 72°$).

According to the connection diagram of Fig. 1, inverter phase-to-neutral voltages are related to individual machine phase voltages by the relation:

$$v_A = v_{a1} + v_{a2} \qquad v_B = v_{b1} + v_{c2}$$
$$v_C = v_{c1} + v_{e2} \qquad v_D = v_{d1} + v_{b2} \qquad (1)$$
$$v_E = v_{e1} + v_{d2}$$

while the relationship between inverter output currents and machine phase currents is as follows:

$$i_A = i_{a1} = i_{a2} \qquad i_B = i_{b1} = i_{c2}$$
$$i_C = i_{c1} = i_{e2} \qquad i_D = i_{d1} = i_{b2} \qquad (2)$$
$$i_E = i_{e1} = i_{d2}$$

The simplest form of indirect rotor flux oriented control is considered for the control purpose. Fig. 2 shows the vector controller for an induction machine, as well as for a synchronous reluctance and a permanent magnet synchronous machine. Using the indirect vector controllers of Fig. 2, phase current references for the two machines are produced by means of ($k = \sqrt{2/5}$):

$$i_{a1}^* = k[i_{ds1}^* \cos\phi_{r1} - i_{qs1}^* \sin\phi_{r1}]$$
$$i_{b1}^* = k[i_{ds1}^* \cos(\phi_{r1} - \alpha) - i_{qs1}^* \sin(\phi_{r1} - \alpha)]$$
$$i_{c1}^* = k[i_{ds1}^* \cos(\phi_{r1} - 2\alpha) - i_{qs1}^* \sin(\phi_{r1} - 2\alpha)]$$
$$i_{d1}^* = k[i_{ds1}^* \cos(\phi_{r1} - 3\alpha) - i_{qs1}^* \sin(\phi_{r1} - 3\alpha)]$$
$$i_{e1}^* = k[i_{ds1}^* \cos(\phi_{r1} - 4\alpha) - i_{qs1}^* \sin(\phi_{r1} - 4\alpha)]$$
$$(3)$$
$$i_{a2}^* = k[i_{ds2}^* \cos\phi_{r2} - i_{qs2}^* \sin\phi_{r2}]$$
$$i_{b2}^* = k[i_{ds2}^* \cos(\phi_{r2} - \alpha) - i_{qs2}^* \sin(\phi_{r2} - \alpha)]$$
$$i_{c2}^* = k[i_{ds2}^* \cos(\phi_{r2} - 2\alpha) - i_{qs2}^* \sin(\phi_{r2} - 2\alpha)]$$
$$i_{d2}^* = k[i_{ds2}^* \cos(\phi_{r2} - 3\alpha) - i_{qs2}^* \sin(\phi_{r2} - 3\alpha)]$$
$$i_{e2}^* = k[i_{ds2}^* \cos(\phi_{r2} - 4\alpha) - i_{qs2}^* \sin(\phi_{r2} - 4\alpha)]$$

The inverter output phase current references are further produced by adding the individual machine phase current references, according to the connection diagram of Fig. 1,

$$i_A^* = i_{a1}^* + i_{a2}^* \qquad i_B^* = i_{b1}^* + i_{c2}^*$$
$$i_C^* = i_{c1}^* + i_{e2}^* \qquad i_D^* = i_{d1}^* + i_{b2}^* \qquad (4)$$
$$i_E^* = i_{e1}^* + i_{d2}^*$$

Assuming ideal inverter current control in the stationary reference frame, inverter reference currents of (4) equal inverter actual currents of (2). Thus each phase of each machine carries flux and/or torque producing currents of both machines. However, the particular connection of Fig. 1 means that the set of flux and/or torque producing currents of one machine produces a rotating magnetic field in that machine only, while in the other machine the resultant field adds to zero at any instant [4-10]. Hence both the machines can be controlled independently, although they are connected in series and fed from a single five-phase VSI.

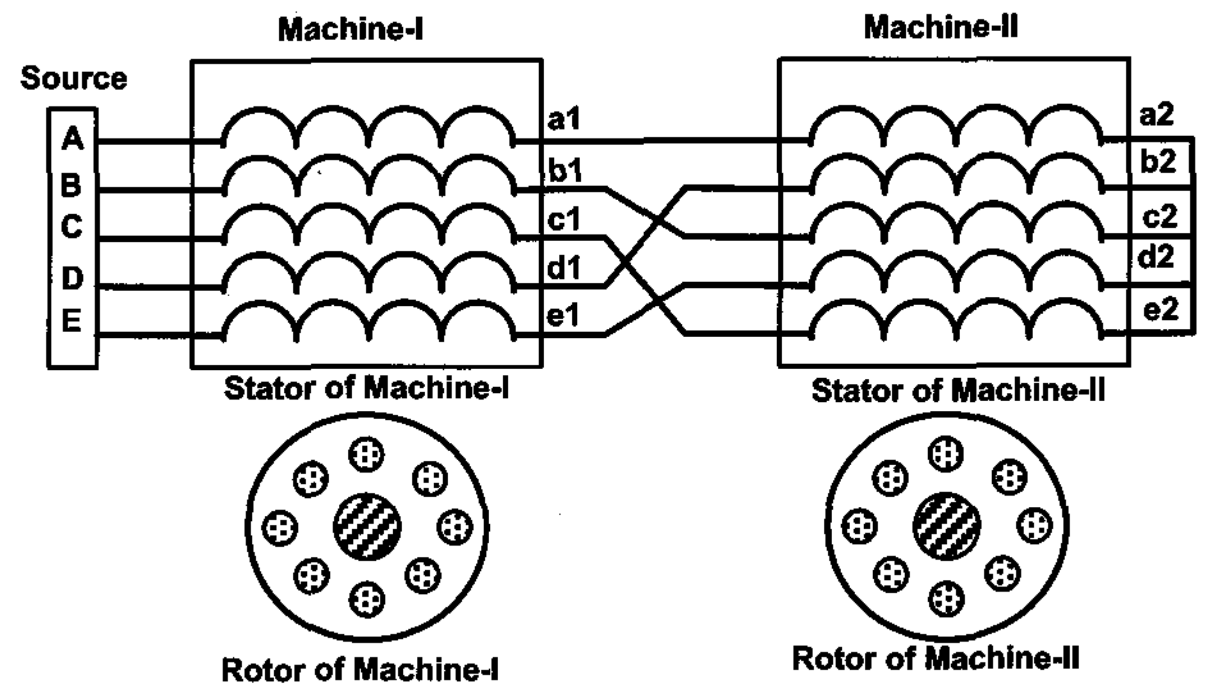


Fig. 1. Series connection of two five-phase machines.

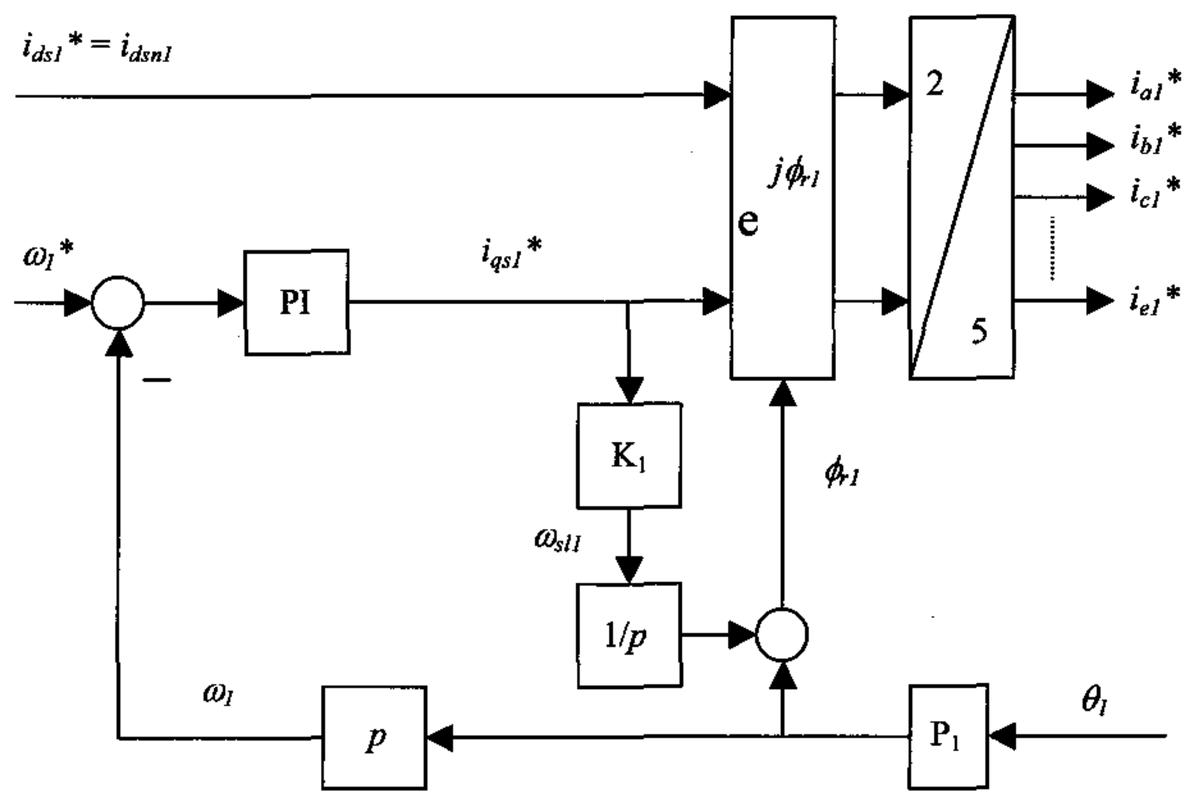


Fig. 2. Indirect rotor flux oriented controller for a five-phase induction machine ($K_1 = 1/(T_{r1}^* i_{ds1}^*)$, $p \equiv d/dt$).

3. Modelling of the Series-connected Five-phase Two-motor Drive

Phase variable model of two five-phase induction machines connected in series according to Fig. 1 is produced in state space form as follows:

$$\begin{aligned} v_A &= v_{as1} + v_{as2} \\ v_B &= v_{bs1} + v_{cs2} \\ v_C &= v_{cs1} + v_{es2} \\ v_D &= v_{ds1} + v_{bs2} \\ v_E &= v_{es1} + v_{ds2} \end{aligned} \quad \text{and} \quad \begin{aligned} i_A &= i_{as1} = i_{as2} \\ i_B &= i_{bs1} = i_{cs2} \\ i_C &= i_{cs1} = i_{es2} \\ i_D &= i_{ds1} = i_{bs2} \\ i_E &= i_{es1} = i_{ds2} \end{aligned} \qquad (5)$$

The two series-connected machines may be the same (both induction machine) or different and therefore may have different parameters. Let suffix '1' signify the induction machine directly connected to the five-phase inverter and suffix '2' signify the second induction machine, connected after the first machine through phase transposition.

The voltage equation for the entire system can be written in a compact matrix form as

$$\underline{v} = \underline{R}\underline{i} + \frac{d(\underline{L}\underline{i})}{dt} \tag{6}$$

where the system is of the 15th order and

$$\underline{v} = \begin{bmatrix} \underline{v}^{INV} \\ \underline{0} \\ \underline{0} \end{bmatrix} \qquad \underline{i} = \begin{bmatrix} \underline{i}^{INV} \\ \underline{i}_{r1} \\ \underline{i}_{r2} \end{bmatrix} \tag{7}$$

$$\begin{aligned} \underline{v}^{INV} &= \begin{bmatrix} v_A & v_B & v_C & v_D & v_E \end{bmatrix}^T \\ \underline{i}^{INV} &= \begin{bmatrix} i_A & i_B & i_C & i_D & i_E \end{bmatrix}^T \end{aligned} \tag{8}$$

$$\begin{aligned} \underline{i}_{r1} &= \begin{bmatrix} i_{ar1} & i_{br1} & i_{cr1} & i_{dr1} & i_{er1} \end{bmatrix}^T \\ \underline{i}_{r2} &= \begin{bmatrix} i_{ar2} & i_{br2} & i_{cr2} & i_{dr2} & i_{er2} \end{bmatrix}^T \end{aligned} \tag{9}$$

The resistance and inductance matrices of (6) can be written as

$$\underline{R} = \begin{bmatrix} \underline{R}_{s1} + \underline{R}_{s2} & \underline{0} & \underline{0} \\ \underline{0} & \underline{R}_{r1} & \underline{0} \\ \underline{0} & \underline{0} & \underline{R}_{r2} \end{bmatrix} \tag{10}$$

$$\underline{L} = \begin{bmatrix} \underline{L}_{s1} + \underline{L}_{s2}' & \underline{L}_{sr1} & \underline{L}_{sr2}' \\ \underline{L}_{rs1} & \underline{L}_{r1} & \underline{0} \\ \underline{L}_{rs2}' & \underline{0} & \underline{L}_{r2} \end{bmatrix} \tag{11}$$

Superscript ' in (11) denotes sub-matrices of machine 2 that have been modified through the phase transposition operation compared to their original form. The sub-matrices of (10)-(11) are all five by five matrices and are given with the following expressions $(\alpha = 2\pi/5)$:

$$\begin{aligned} \underline{R}_{s1} &= diag(R_{s1} \quad R_{s1} \quad R_{s1} \quad R_{s1} \quad R_{s1}) \\ \underline{R}_{s2} &= diag(R_{s2} \quad R_{s2} \quad R_{s2} \quad R_{s2} \quad R_{s2}) \\ \underline{R}_{r1} &= diag(R_{r1} \quad R_{r1} \quad R_{r1} \quad R_{r1} \quad R_{r1}) \\ \underline{R}_{r2} &= diag(R_{r2} \quad R_{r2} \quad R_{r2} \quad R_{r2} \quad R_{r2}) \end{aligned} \tag{12}$$

$$\underline{L}_{s1} = \begin{bmatrix} L_{ls1}+M_1 & M_1\cos\alpha & M_1\cos2\alpha & M_1\cos2\alpha & M_1\cos\alpha \\ M_1\cos\alpha & L_{ls1}+M_1 & M_1\cos\alpha & M_1\cos2\alpha & M_1\cos2\alpha \\ M_1\cos2\alpha & M_1\cos\alpha & L_{ls1}+M_1 & M_1\cos\alpha & M_1\cos2\alpha \\ M_1\cos2\alpha & M_1\cos2\alpha & M_1\cos\alpha & L_{ls1}+M_1 & M_1\cos\alpha \\ M_1\cos\alpha & M_1\cos2\alpha & M_1\cos2\alpha & M_1\cos\alpha & L_{ls1}+M_1 \end{bmatrix} \tag{13}$$

$$\underline{L}_{s2}' = \begin{bmatrix} L_{ls2}+M_2 & M_2\cos2\alpha & M_2\cos\alpha & M_2\cos\alpha & M_2\cos2\alpha \\ M_2\cos2\alpha & L_{ls2}+M_2 & M_2\cos2\alpha & M_2\cos\alpha & M_2\cos\alpha \\ M_2\cos\alpha & M_2\cos2\alpha & L_{ls2}+M_2 & M_2\cos2\alpha & M_2\cos\alpha \\ M_2\cos\alpha & M_2\cos\alpha & M_2\cos2\alpha & L_{ls2}+M_2 & M_2\cos2\alpha \\ M_2\cos2\alpha & M_2\cos\alpha & M_2\cos\alpha & M_2\cos2\alpha & L_{ls2}+M_2 \end{bmatrix} \tag{14}$$

$$\underline{L}_{r1} = \begin{bmatrix} L_{lr1}+M_1 & M_1\cos\alpha & M_1\cos2\alpha & M_1\cos2\alpha & M_1\cos\alpha \\ M_1\cos\alpha & L_{lr1}+M_1 & M_1\cos\alpha & M_1\cos2\alpha & M_1\cos2\alpha \\ M_1\cos2\alpha & M_1\cos\alpha & L_{lr1}+M_1 & M_1\cos\alpha & M_1\cos2\alpha \\ M_1\cos2\alpha & M_1\cos2\alpha & M_1\cos\alpha & L_{lr1}+M_1 & M_1\cos\alpha \\ M_1\cos\alpha & M_1\cos2\alpha & M_1\cos2\alpha & M_1\cos\alpha & L_{lr1}+M_1 \end{bmatrix} \tag{15}$$

$$\underline{L}_{r2} = \begin{bmatrix} L_{lr2}+M_2 & M_2\cos\alpha & M_2\cos2\alpha & M_2\cos2\alpha & M_2\cos\alpha \\ M_2\cos\alpha & L_{lr2}+M_2 & M_2\cos\alpha & M_2\cos2\alpha & M_2\cos2\alpha \\ M_2\cos2\alpha & M_2\cos\alpha & L_{lr2}+M_2 & M_2\cos\alpha & M_2\cos2\alpha \\ M_2\cos2\alpha & M_2\cos2\alpha & M_2\cos\alpha & L_{lr2}+M_2 & M_2\cos\alpha \\ M_2\cos\alpha & M_2\cos2\alpha & M_2\cos2\alpha & M_2\cos\alpha & L_{lr2}+M_2 \end{bmatrix} \tag{16}$$

$$\begin{aligned} \underline{L}_{sr1} &= M_1 \begin{bmatrix} \cos\theta_1 & \cos(\theta_1+\alpha) & \cos(\theta_1+2\alpha) & \cos(\theta_1-2\alpha) & \cos(\theta_1-\alpha) \\ \cos(\theta_1-\alpha) & \cos\theta_1 & \cos(\theta_1+\alpha) & \cos(\theta_1+2\alpha) & \cos(\theta_1-2\alpha) \\ \cos(\theta_1-2\alpha) & \cos(\theta_1-\alpha) & \cos\theta_1 & \cos(\theta_1+\alpha) & \cos(\theta_1+2\alpha) \\ \cos(\theta_1+2\alpha) & \cos(\theta_1-2\alpha) & \cos(\theta_1-\alpha) & \cos\theta_1 & \cos(\theta_1+\alpha) \\ \cos(\theta_1+\alpha) & \cos(\theta_1+2\alpha) & \cos(\theta_1-2\alpha) & \cos(\theta_1-\alpha) & \cos\theta_1 \end{bmatrix} \\ \underline{L}_{rs1} &= \underline{L}_{sr1}^T \end{aligned} \tag{17}$$

$$\begin{aligned} \underline{L}_{sr2}' &= M_2 \begin{bmatrix} \cos\theta_2 & \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) \\ \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) & \cos\theta_2 & \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) \\ \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) & \cos\theta_2 \\ \cos(\theta_2-\alpha) & \cos\theta_2 & \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) \\ \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) & \cos\theta_2 & \cos(\theta_2+\alpha) \end{bmatrix} \\ \underline{L}_{rs2}' &= \underline{L}_{sr2}^{T}{}' \end{aligned} \tag{18}$$

Expansion of (6) yields

$$\begin{aligned} \underline{v} = \begin{bmatrix} \underline{v}^{INV} \\ \underline{0} \\ \underline{0} \end{bmatrix} &= \begin{bmatrix} \underline{R}_{s1}+\underline{R}_{s2} & \underline{0} & \underline{0} \\ \underline{0} & \underline{R}_{r1} & \underline{0} \\ \underline{0} & \underline{0} & \underline{R}_{r2} \end{bmatrix} \begin{bmatrix} \underline{i}^{INV} \\ \underline{i}_{r1} \\ \underline{i}_{r2} \end{bmatrix} + \\ &\begin{bmatrix} \underline{L}_{s1}+\underline{L}_{s2}' & \underline{L}_{sr1} & \underline{L}_{sr2}' \\ \underline{L}_{rs1} & \underline{L}_{r1} & \underline{0} \\ \underline{L}_{rs2}' & \underline{0} & \underline{L}_{r2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} \underline{i}^{INV} \\ \underline{i}_{r1} \\ \underline{i}_{r2} \end{bmatrix} + \\ &\begin{bmatrix} \underline{0} & \frac{d}{dt}\underline{L}_{sr1} & \frac{d}{dt}\underline{L}_{sr2}' \\ \frac{d}{dt}\underline{L}_{rs1} & \underline{0} & \underline{0} \\ \frac{d}{dt}\underline{L}_{rs2}' & \underline{0} & \underline{0} \end{bmatrix} \begin{bmatrix} \underline{i}^{INV} \\ \underline{i}_{r1} \\ \underline{i}_{r2} \end{bmatrix} \end{aligned} \tag{19}$$

Torque equations of the two machines in terms of inverter currents and their respective rotor currents and rotor positions and replacing motor stator currents with corresponding inverter currents of (5) are:

$$T_{e1} = -P_1 M_1 \left\{ \begin{array}{l} \left(i_A i_{ar1} + i_B i_{br1} + i_C i_{cr1} + i_D i_{dr1} + i_E i_{er1}\right)\sin\theta_1 + \left(i_E i_{ar1} + i_A i_{br1} + i_B i_{cr1} + i_C i_{dr1} + i_D i_{er1}\right)\sin(\theta_1+\alpha) + \\ \left(i_D i_{ar1} + i_E i_{br1} + i_A i_{cr1} + i_B i_{dr1} + i_C i_{er1}\right)\sin(\theta_1+2\alpha) + \left(i_C i_{ar1} + i_D i_{br1} + i_E i_{cr1} + i_A i_{dr1} + i_B i_{er1}\right) \\ \sin(\theta_1-2\alpha) + \left(i_B i_{ar1} + i_C i_{br1} + i_D i_{cr1} + i_E i_{dr1} + i_A i_{er1}\right)\sin(\theta_1-\alpha) \end{array} \right\}$$

$$T_{e2} = -P_2 M_2 \left\{ \begin{array}{l} \left(i_A i_{ar2} + i_D i_{br2} + i_B i_{cr2} + i_E i_{dr2} + i_C i_{er2}\right)\sin\theta_2 + \left(i_C i_{ar2} + i_A i_{br2} + i_D i_{cr2} + i_B i_{dr2} + i_E i_{er2}\right)\sin(\theta_2+\alpha) + \\ \left(i_E i_{ar2} + i_C i_{br2} + i_A i_{cr2} + i_D i_{dr2} + i_B i_{er2}\right)\sin(\theta_2+2\alpha) + \left(i_B i_{ar2} + i_E i_{br2} + i_C i_{cr2} + i_A i_{dr2} + i_D i_{er2}\right) \\ \sin(\theta_2-2\alpha) + \left(i_D i_{ar2} + i_B i_{br2} + i_E i_{cr2} + i_C i_{dr2} + i_A i_{er2}\right)\sin(\theta_2-\alpha) \end{array} \right\} \tag{20}$$

In order to simplify the phase-domain model, decoupling transformation is used. The new variables are defined as:

$$\underline{v}^{INV}_{\alpha\beta} = \underline{C}\underline{v}^{INV} \qquad \underline{v}^{r1}_{\alpha\beta} = \underline{C}\underline{v}^{r1} \qquad \underline{v}^{r2}_{\alpha\beta} = \underline{C}\underline{v}^{r2}$$

$$\underline{i}^{INV}_{\alpha\beta} = \underline{C}\underline{i}^{INV} \qquad \underline{i}^{r1}_{\alpha\beta} = \underline{C}\underline{i}_{r1} \qquad \underline{i}^{r2}_{\alpha\beta} = \underline{C}\underline{i}_{r2} \tag{21}$$

Clark's decoupling transformation matrix in power invarient form is:

$$\underline{C} = \sqrt{\frac{2}{5}}\; \begin{array}{c} \alpha \\ \beta \\ x \\ y \\ 0 \end{array} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \cos 8\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \sin 8\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{22}$$

The inverter/stator voltage equations are:

$$v^{INV}_\alpha = \left(R_{s1}+R_{s2}\right)i^{INV}_\alpha + \left(L_{ls1}+L_{ls2}+L_{m1}\right)\frac{di^{INV}_\alpha}{dt} + L_{m1}\cos\left(\theta_1\right)\frac{di_{\alpha r1}}{dt} - L_{m1}\sin\left(\theta_1\right)\frac{di_{\beta r1}}{dt} -$$
$$\omega_1 L_{m1}\left(\sin\left(\theta_1\right)i_{\alpha r1} + \cos\left(\theta_1\right)i_{\beta r1}\right)$$
$$v^{INV}_\beta = \left(R_{s1}+R_{s2}\right)i^{INV}_\beta + \left(L_{ls1}+L_{m1}+L_{ls2}\right)\frac{di^{INV}_\beta}{dt} + L_{m1}\sin\left(\theta_1\right)\frac{di_{\alpha r1}}{dt} + L_{m1}\cos\left(\theta_1\right)\frac{di_{\beta r1}}{dt} +$$
$$\omega_1 L_{m1}\left(\cos\left(\theta_1\right)i_{\alpha r1} - \sin\left(\theta_1\right)i_{\beta r1}\right)$$
$$v^{INV}_x = \left(R_{s1}+R_{s2}\right)i^{INV}_x + \left(L_{ls1}+L_{ls2}+L_{m2}\right)\frac{di^{INV}_x}{dt} + L_{m2}\cos\left(\theta_2\right)\frac{di_{\alpha r2}}{dt} - L_{m2}\sin\left(\theta_2\right)\frac{di_{\beta r2}}{dt} -$$
$$\omega_2 L_{m2}\left(\sin\left(\theta_2\right)i_{\alpha r2} + \cos\left(\theta_2\right)i_{\beta r2}\right)$$
$$v^{INV}_y = \left(R_{s1}+R_{s2}\right)i^{INV}_y + \left(L_{ls1}+L_{ls2}+L_{m2}\right)\frac{di^{INV}_y}{dt} + L_{m2}\sin\left(\theta_2\right)\frac{di_{\alpha r2}}{dt} + L_{m2}\cos\left(\theta_2\right)\frac{di_{\beta r2}}{dt} +$$
$$\omega_2 L_{m2}\left(\cos\left(\theta_2\right)i_{\alpha r2} - \sin\left(\theta_2\right)i_{\beta r2}\right)$$
$$v^{INV}_0 = \left(R_{s1}+R_{s2}\right)i^{INV}_0 + \left(L_{ls1}+L_{ls2}\right)\frac{di^{INV}_0}{dt} \tag{23}$$

The rotor voltage equations of machine 1 are:

$$v_{\alpha r1} = 0 = R_{r1}i_{\alpha r1} + L_{m1}\cos\left(\theta_1\right)\frac{di^{INV}_\alpha}{dt} + L_{m1}\sin\left(\theta_1\right)\frac{di^{INV}_\beta}{dt} + \left(L_{lr1}+L_{m1}\right)\frac{di_{\alpha r1}}{dt} -$$
$$\omega_1 L_{m1}\left(\sin\left(\theta_1\right)i^{INV}_\alpha - \cos\left(\theta_1\right)i^{INV}_\beta\right)$$
$$v_{\beta r1} = 0 = R_{r1}i_{\beta r1} - L_{m1}\sin\left(\theta_1\right)\frac{di^{INV}_\alpha}{dt} + L_{m1}\cos\left(\theta_1\right)\frac{di^{INV}_\beta}{dt} + \left(L_{lr1}+L_{m1}\right)\frac{di_{\beta r1}}{dt} -$$
$$\omega_1 L_{m1}\left(\cos\left(\theta_1\right)i^{INV}_\alpha + \sin\left(\theta_1\right)i^{INV}_\beta\right)$$
$$v_{xr1} = 0 = R_{r1}i_{xr1} + L_{lr1}\frac{di_{xr1}}{dt}$$
$$v_{yr1} = 0 = R_{r1}i_{yr1} + L_{lr1}\frac{di_{yr1}}{dt} \tag{24}$$
$$v_{0r1} = 0 = R_{r1}i_{0r1} + L_{lr1}\frac{di_{0r1}}{dt}$$

The rotor voltage equations of machine 2 are:

$$v_{\alpha r2} = 0 = R_{r2}i_{\alpha r2} + L_{m2}\cos\left(\theta_2\right)\frac{di^{INV}_x}{dt} + L_{m2}\sin\left(\theta_2\right)\frac{di^{INV}_y}{dt} + \left(L_{lr2}+L_{m2}\right)\frac{di_{\alpha r2}}{dt} -$$
$$\omega_2 L_{m2}\left(\sin\left(\theta_2\right)i^{INV}_x - \cos\left(\theta_2\right)i^{INV}_y\right)$$
$$v_{\beta r2} = 0 = R_{r2}i_{\beta r2} - L_{m2}\sin\left(\theta_2\right)\frac{di^{INV}_x}{dt} + L_{m2}\cos\left(\theta_2\right)\frac{di^{INV}_y}{dt} + \left(L_{lr2}+L_{m2}\right)\frac{di_{\beta r2}}{dt} -$$
$$\omega_2 L_{m2}\left(\cos\left(\theta_2\right)i^{INV}_x + \sin\left(\theta_2\right)i^{INV}_y\right)$$
$$v_{xr2} = 0 = R_{r2}i_{xr2} + L_{lr2}\frac{di_{xr2}}{dt} \tag{25}$$
$$v_{yr2} = 0 = R_{r2}i_{yr2} + L_{lr2}\frac{di_{yr2}}{dt}$$
$$v_{0r2} = 0 = R_{r2}i_{0r2} + L_{lr2}\frac{di_{0r2}}{dt}$$

The electromagnetic torque equations are:

$$T_{e1} = P_1 L_{m1}\left\{\cos\left(\theta_1\right)\left(i_{\alpha r1}i^{INV}_\beta - i_{\beta r1}i^{INV}_\alpha\right) - \sin\left(\theta_1\right)\left(i_{\alpha r1}i^{INV}_\alpha + i_{\beta r1}i^{INV}_\beta\right)\right\}$$
$$T_{e2} = P_2 L_{m2}\left\{\cos\left(\theta_2\right)\left(i_{\alpha r2}i^{INV}_y - i_{\beta r2}i^{INV}_x\right) - \sin\left(\theta_2\right)\left(i_{\alpha r2}i^{INV}_x + i_{\beta r2}i^{INV}_y\right)\right\} \tag{26}$$

4. Sensorless Operation of Series-connected Two five-phase Induction Machines

The developed model of a series-connected two five-phase induction machine suggests that a speed estimator used for five-phase machines can be easily extended to multi-phase, multi-motor machines. For multi-phase machines MRAS speed estimator requires only *d* and *q* components of stator voltages and currents for the first machine. From the model of a five-phase induction machine [20]-[21], it has been shown that the stator and rotor *d* and *q* axis flux linkages are a function of magnetizing inductance *Lm* and stator and rotor *d* and *q* axis currents, whereas the *x* and *y* axis flux linkages are a function of only their respective currents. Therefore, in speed estimation for multi-phase multi-motor machines, the x and y components of voltages and currents are required for speed estimation of the second machine. As such 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 a series-connected five-phase two-motor drive system is shown in Fig. 3.

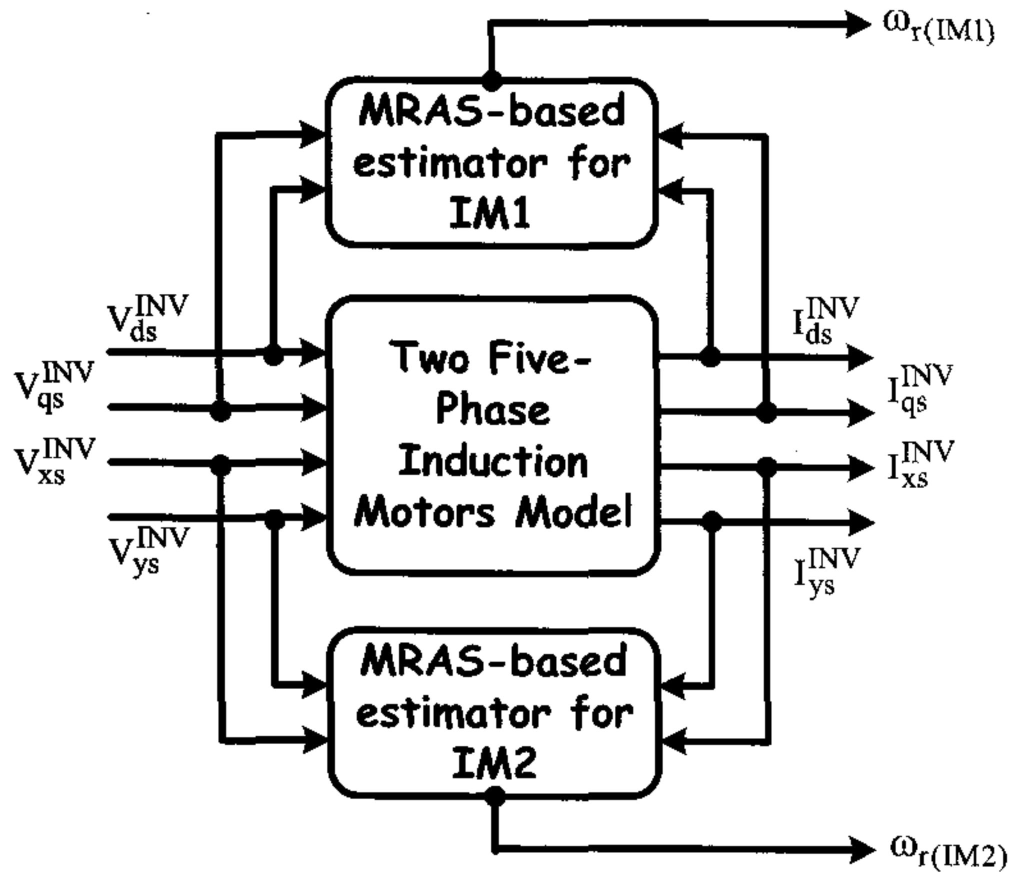


Fig. 3. Sensorless control of two series connected five-phase machines.

5. MRAS Speed Estimator

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 to as a reference model. The other estimator, which involves the estimated quantity, is referred to 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 [19, 20]. The schematic block diagram of a MRAS based speed estimator is presented in Fig. 4.

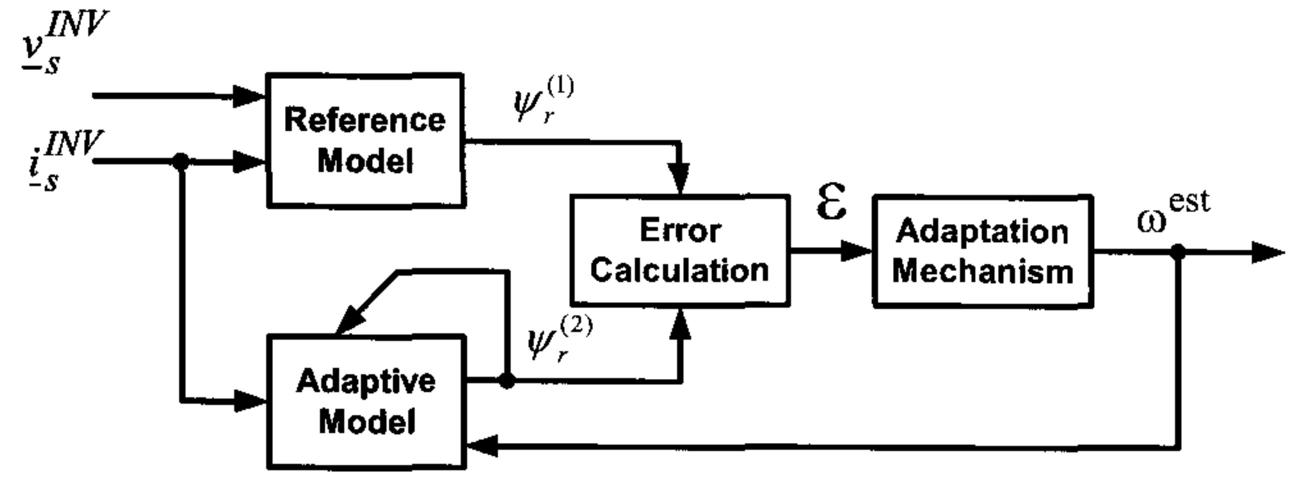


Fig. 4. Schematic block diagram of a MRAS estimator.

In this estimator the outputs of the reference and the adaptive models denoted in Fig. 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 $\omega_a = 0$ the following two space vector equations are:

$$\begin{aligned} \underline{v}_s^{INV} &= R_s \underline{i}_s^{INV} + \frac{d\underline{\psi}_s}{dt} \\ 0 &= R_r \underline{i}_r + \frac{d\underline{\psi}_r}{dt} - j\omega\underline{\psi}_r \end{aligned} \tag{27}$$

where $\underline{v}_s^{INV}$ and $\underline{i}_s^{INV}$ are inverter voltage and current fed to both motors. Elimination of the stator flux vector and rotor current vector enables the rotor flux vector to be expressed in the form of:

$$\begin{aligned} \frac{d\underline{\psi}_r}{dt} &= \frac{L_r^{TM}}{L_m^{TM}}\left[\underline{v}_s^{INV} - R_s^{TM}\underline{i}_s^{INV} - \sigma.L_s^{TM}\frac{d\underline{i}_s^{INV}}{dt}\right] \\ \frac{d\underline{\psi}_r}{dt} &= \left[-\frac{1}{T_r} + j\omega\right]\underline{\psi}_r + \frac{L_m^{TM}}{T_r}\underline{i}_s^{INV} \end{aligned} \tag{28}$$

where L_m^{TM} = two motor mutual inductance, L_s^{TM} = two motor stator inductance and R_s^{TM} = two motor resistance.

The first equation of (28) can be used to calculate the 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. 4.

On the other hand, calculation of rotor flux from the second equation of (28) requires stator currents only and is dependent on the rotor speed. Hence the second equation of (28) represents the adaptive model of Fig. 4.

By resolving the two equations of (28) into two-axis components, the rotor flux components in the stationary reference frame are obtained as:

$$\begin{aligned} p\begin{bmatrix}\psi_{\alpha r}\\ \psi_{\beta r}\end{bmatrix} &= \frac{L_r}{L_{m1}}\left[\begin{bmatrix}v_{\alpha s}^{INV}\\ v_{\beta s}^{INV}\end{bmatrix} - \begin{bmatrix}(A+Bp) & 0\\ 0 & (A+Bp)\end{bmatrix}\begin{bmatrix}i_{\alpha s}^{INV}\\ i_{\beta s}^{INV}\end{bmatrix}\right] \\ p\begin{bmatrix}\psi_{\alpha r}\\ \psi_{\beta r}\end{bmatrix} &= \left[\begin{bmatrix}-C & -\omega_r\\ \omega_r & -C\end{bmatrix}\begin{bmatrix}\psi_{\alpha r}\\ \psi_{\beta r}\end{bmatrix} + \frac{L_{m1}}{T_r}\begin{bmatrix}i_{\alpha s}^{INV}\\ i_{\beta s}^{INV}\end{bmatrix}\right] \end{aligned} \tag{29}$$

where $A = R_{s1} + R_{s2}$, $B = \sigma.(L_{ls1} + L_{ls2} + L_{m1})$, $C = \frac{1}{T_r}$

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 the MRAS based speed estimation method is a simple PI controller algorithm.

$$\omega^{est} = K_p\varepsilon + K_i \int \varepsilon dt \tag{30}$$

where the input of the PI controller is

$$\varepsilon = \psi_{\beta r}^{(1)}\psi_{\alpha r}^{(2)} - \psi_{\alpha r}^{(1)}\psi_{\beta r}^{(2)} \ , \tag{31}$$

K_p and K_i are any positive constants, and ε is error signal. In the expressions $\alpha = \mathrm{d}$ and $\beta = \mathrm{q}$ apply to the first machine and $\alpha = \mathrm{x}$ and $\beta = \mathrm{y}$ apply to the second machine.

6. 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 identical and is revealed in Fig. 2. Many simulation tests are performed in order to confirm the independence of the control of the two machines in sensorless mode (MRAS). The results obtained are reported in this section. Motor operation under the 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:

6.1. Fixed voltage and fixed frequency supply

In this case both machines are connected to two five-phase ideal supply systems. If the 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 two series-connected motors are

$$V_A = v_{a1} + v_{a2}\,,\ V_B = v_{b1} + v_{c2}\,,\ V_C = v_{c1} + v_{e2}\,,$$
$$V_D = v_{d1} + v_{b2}\,,\ V_E = v_{e1} + v_{d2}\,.$$

The simulation time for the test is 2 seconds. The first machine is loaded at t=1.2s and the second machine is 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 5, (a) to (c). Each test result shows both reference and estimated speeds for IM1 and IM2.

6.2. Vector controlled series connected two-motor

In this case both machines are vector controlled. Two vector controllers are used for the control of series connected motors. If the output currents of the first controller for IM-1 are $i_{a1}^*, i_{b1}^*, i_{c1}^*, i_{d1}^*, i_{e1}^*$ and the output currents of the 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 motors are

$$i_A^* = i_{a1}^* + i_{a2}^* \qquad i_B^* = i_{b1}^* + i_{c2}^*$$
$$i_C^* = i_{c1}^* + i_{e2}^* \qquad i_D^* = i_{d1}^* + i_{b2}^*$$
$$i_E^* = i_{e1}^* + i_{d2}^*$$

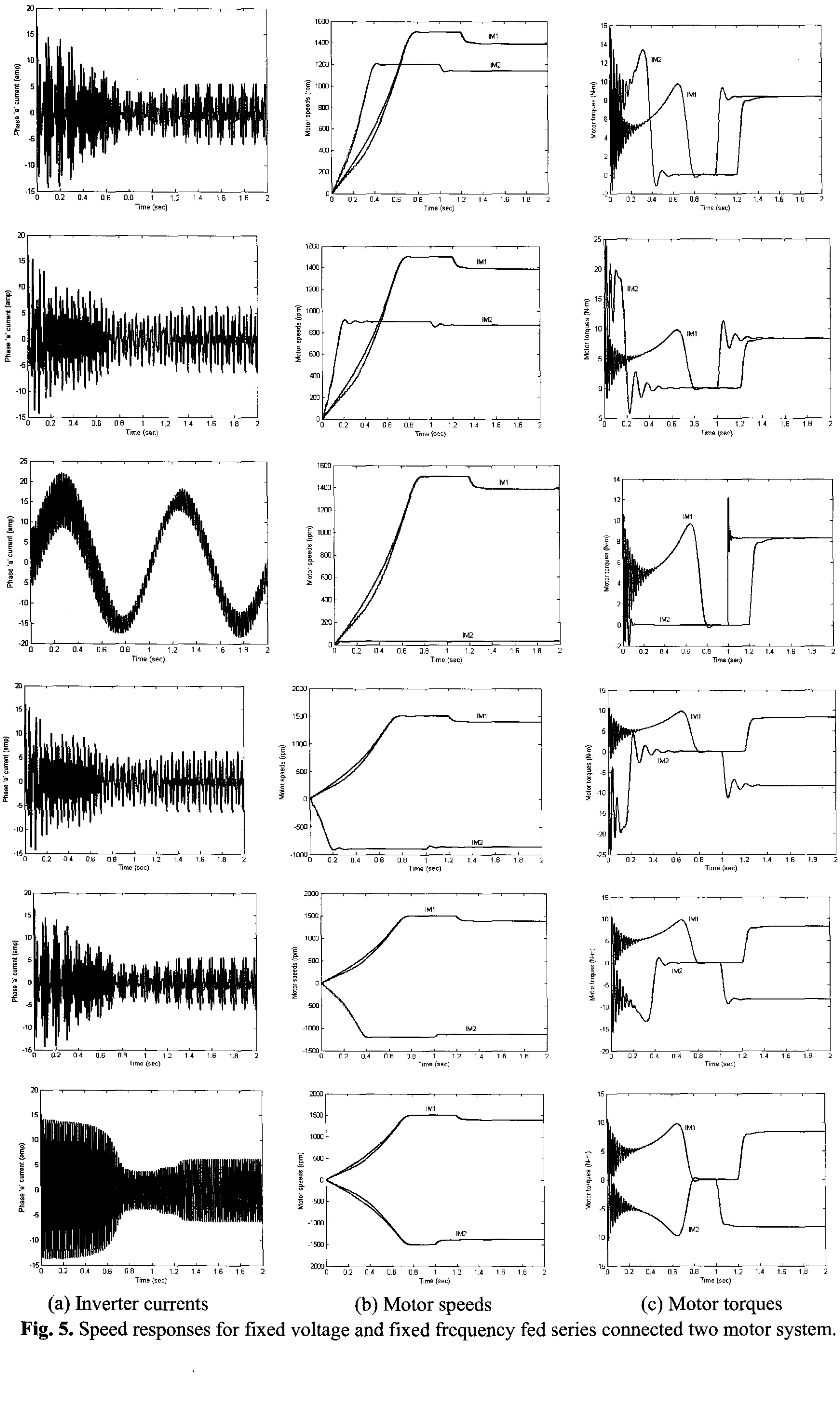
The simulation time for the test is 2 sec. and both machines are loaded simultaneously at t=1s. The machines are running under acceleration transient from t=0.3s and 0.4s and steady-state at no-load and load conditions. Both the machines are reversing from t=1.2s and 1.3s. Both the machines are running under different test conditions to verify the decoupling of both machines. The corresponding test results are shown in Figure 6, (a) to (c).

Each test result shows both reference and estimated speeds for IM1 and IM2.

7. Discussion

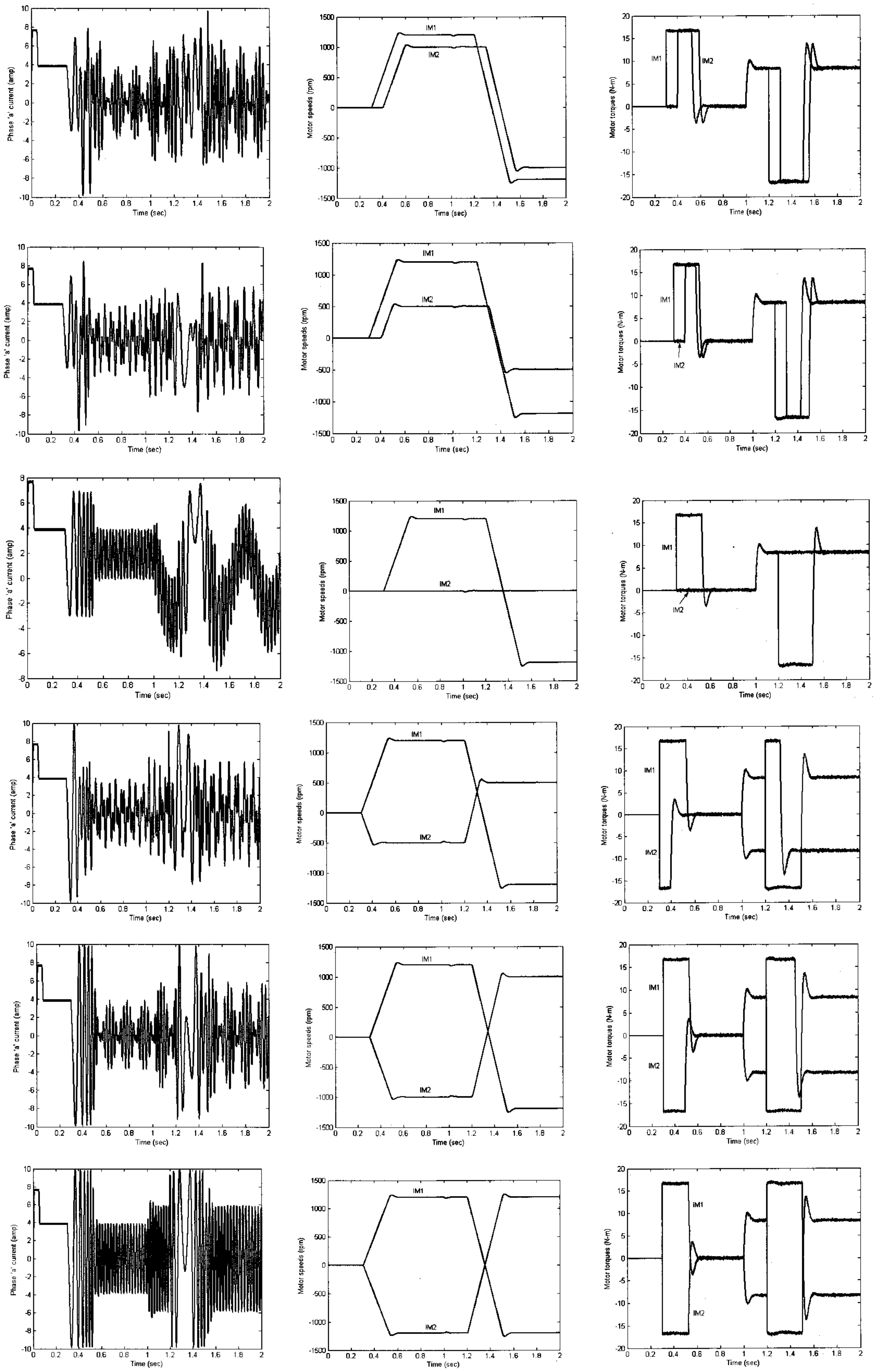
Fig. 5, (a) to (c) shows the test results for a fixed voltage and fixed frequency supply fed series connected two motor system. The machine operates at six different test conditions: (i) IM1 is running at 1500 rpm and IM2 at 1200 rpm with the first machine loaded at t=1.2s and the second machine loaded 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 are both running at 1500 rpm but in opposite direction.

When both machines are running at different test conditions and the corresponding currents are supplied by the inverter, their speeds and torques are shown in Fig. 5(a)-5(c) respectively. Each speed figure shows four different characteristics, two reference speeds and two estimated speeds for each machine. These test results



(a) Inverter currents (b) Motor speeds (c) Motor torques

Fig. 5. Speed responses for fixed voltage and fixed frequency fed series connected two motor system.



(a) Inverter currents (b) Motor speeds (c) Motor torques

Fig. 6. Speed responses for vector-controlled series connected two motor system.

indicate that the estimated speeds are very close to the measured speeds. There is a slight deviation in speed in the acceleration transient period for higher speeds (1500 rpm). This discussion is true for both conditions i.e. when a machine is running in forward direction or in reverse direction. These test results also show 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 the second machine is stalled (very low speed). In this case, the current supplied by the inverter is of oscillating nature. The current fluctuation is from +23 amps to -18 amps. This behavior can also be seen in case of vector controlled series connected two motor drive systems when load is applied to machines.

Fig. 6, (a) to (c) shows the test results for vector controlled series connected two motor systems. In all tests, IM1 is set at ±1200 rpm and both machines are loaded at t=1.0s. In the 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. Vector controlled results show that the estimated speeds are also very close to the measured speeds. These test results again show that both machines IM1 and IM2 are independently controlled in vector controlled technique in sensorless mode.

8. Conclusion

This paper presents sensorless control of a series-connected five-phase two-motor drive and shows full simulation verification of the independent fixed voltage and fixed frequency supply and vector control of the two machines in sensorless mode. A short review of the operating principles is given. The importance is further shown on presentation of simulation results for various test conditions. By presenting the results of the series-connected two-motor five-phase drive it is totally confirmed that the control of the two series-connected machines is truly decoupled even in sensorless mode.

The investigated drive configuration is applicable to all types of five-phase ac machines 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.

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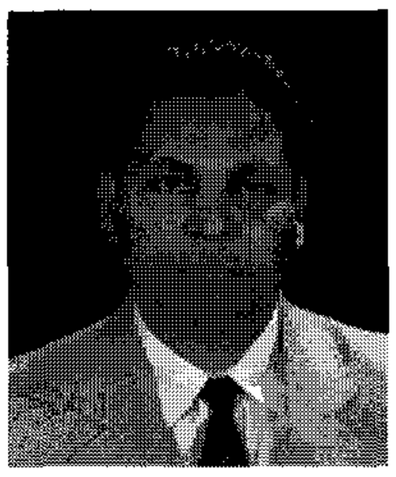

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