Speeds Estimation of Series-Connected Five-Phase Two-Motor Drive System using Adaptive Flux Observers

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Abstract— Utilization of multi-phase machines in variable speed drives is nowadays extensively considered for electric ship propulsion, 'more-electric aircraft' and traction applications, including EVs and HEVs. In addition to well-known advantages, use of multi-phase machines enables independent control of a certain number of machines that are connected in series in an appropriate manner, with the supply coming from a single voltage source inverter (VSI). The concept was initially proposed for a five-phase series-connected two-motor drive, but is applicable to any system phase number greater than or equal to five. The number of connectable machines is a function of the VSI phase number and detailed theoretical and simulation studies have already been reported for various multi-phase multi-motor drive configurations of this 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 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 paper analyses operation of an adaptive flux observer-based sensorless control of vector controlled series connected two motor five-phase drive system with current control in the stationary reference frame. Performance, obtainable with hysteresis current control, is illustrated for a number of operating conditions on the basis of simulation results. The purpose of this paper is to present, for the first time, simulation results on a sensorless control of a five-phase two-motor series-connected drive system. A brief overview of the operating principles is provided first. This is followed by a description of the sensorless technique.

Keywords — Multi-motor drives, Multi-phase machines, Five-phase, Vector control.

I. INTRODUCTION

Concept of multi-phase motor drives is rather mature, with the origins traceable back to 1969. However, an upsurge in the interest in multi-phase motor drive applications has occurred during the last few years. The main driving forces behind this accelerated development are three application areas: railway traction and EV/HEV applications, 'more-electric aircraft' and 'more-electric ship'. The reasons for employing multi-phase drives vary from application to application and range from reduction of the inverter per-phase rating in high power drives (ship propulsion, traction) to improved efficiency (low power drives and integrated drives) [1] and to significantly improved fault tolerance ('more-electric aircraft') [2,3].

An additional possibility, opened up by the use of multi-phase machines, is independent control of a set of series-connected motors, supplied from a single VSI. The origins of the idea can be traced to [4], where a five-phase two-motor drive was analyzed. The idea stems from the fact that any n-phase machine requires only two currents for independent flux and torque control. Thus, in a multi-phase machine there are additional degrees of freedom, which can be used to control other machines, provided that an appropriate phase transposition is introduced when connecting the machines in series. The concept is applicable to all supply system phase numbers greater than or equal to five. Generalizations to all possible even and odd phase numbers have been reported in [5-7], where appropriate winding connections and the number of connectable machines as a function of the system phase number were investigated. Studies of [4-7] apply to series connection of symmetrical multi-phase machines (spatial displacement between any two consecutive phases is $2\pi/n$, where n is the number of phases) with sinusoidal flux spatial distribution. However, the concept of series connection can be extended to the asymmetrical machines as well, where stator winding consists of two or more three-phase windings shifted in space by an appropriate angle. A two-motor drive of this type, using asymmetrical six-phase machines (with two three-phase windings spatially shifted by 30º) has been considered in [8,9].

From the practical point of view it is only the five-phase or six-phase two-motor drives that hold potential for industrial applications. This is so since in the series connection flux/torque producing currents of one machine flow through the other machines in the group. Thus stator winding loss increases, causing a reduction in the efficiency. Most of the available work on series-connected drive systems therefore discusses either five-phase or one of the two possible six-phase (with asymmetrical or symmetrical six-phase machines) configurations. An investigation of the operating principles of the two-motor series-connected five-phase drive has been reported in [10-12], while a d-q model for this drive structure can be found in [13]. Inverter current control can be realized by using either synchronous current controllers or by means of phase current control in the stationary reference frame. A comparison of these two possibilities [14] has shown that phase current control in the stationary reference frame is advantageous for series-connected multi-motor drive systems, since synchronous current control leads to an increase in the parameter variation sensitivity in the decoupling circuit equations. This current control method is utilized here.

The available experimental results that illustrate dynamics of a vector-controlled series-connected multi-motor drive are those for a two-motor six-phase drive [9,15],

The paper first received 5 Nov 2007 and in revised form 30 Dec 2007
Digital ref: AI70201181
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comprising a symmetrical six-phase machine connected in series with a three-phase machine.

Additionally, [8] illustrates performance of a six-phase drive consisting of two series-connected asymmetrical six-phase machines under V/f control. This paper therefore concentrates on presentation of simulation results, collected from a vector-controlled series-connected five-phase two-motor drive system, which provide an ultimate proof of the decoupled dynamics within the system. A brief overview of the operating principles is provided first. A series of simulation test result, for various transients (acceleration, deceleration, speed reversal) is then presented. These prove that the coupling of control of the two machines is practically negligible, although they are connected in series and the supply is provided from a single five-phase VSI.

The two-motor drive structure elaborated here is believed to hold a good prospect for industrial applications related to winders. In such an application use of two series-connected five-phase machines can not only save one inverter leg (when compared to an equivalent two-motor three-phase system) but also reduce the total installed inverter rating, thus reducing the capital outlay. The best results would be achievable with permanent magnet synchronous machines, since no machine de-rating would be needed to compensate for the increased stator winding losses.

Sensorless operation of a vector controlled three-phase induction machine drive is extensively discussed in the literature [16,17], but the same is not true for multi-phase induction machine. Only few application specific sensorless operation of multi-phase machine is elaborated in the literature The problem of using the position sensor in ‘more-electric’ aircraft fuel pump fault tolerant drive is highlighted in [18]. The drive utilises a 16 kW, 13000 rpm six-phase permanent magnet motor with six independent single-phase inverters supplying each of the six-phases. The authors proposed an alternative sensorless drive scheme. The proposed technique makes use of flux linkage-current-angle model to estimate the rotor position. Although several schemes are available for sensorless operation of a vector controlled drive, but the most popular is the MRAS because of ease of their implementation[17,18].

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. 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 [21-22] 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 reported in the paper.

II. FIVE-PHASE TWO-MOTOR DRIVE SYSTEM

A principal block-diagram of the series-connected five-phase two-motor drive system is shown in Fig. 1. Stator windings of the two five-phase machines (which can be of any type, i.e. induction, synchronous reluctance, or permanent magnet synchronous) are connected in series, in such a way that flux/torque producing currents of one machine appear as non-flux/torque producing currents in the other machine, and vice-versa [4,6,7,10]. It is assumed that the spatial flux distribution in both machines is perfectly sinusoidal. The supply is a five-phase VSI, whose outputs are identified with capital letters A, B, C, D, E, while lower case letters (a, b, c, d, e) identify phases of the two machines according to the spatial distribution 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 through

$$\begin{aligned} &v_A = v_{a1} + v_{a2} \qquad && v_B = v_{b1} + v_{c2} \\ &v_C = v_{c1} + v_{e2} \qquad && v_D = v_{d1} + v_{b2} \\ &v_E = v_{e1} + v_{d2} \end{aligned} \tag{1}$$

while the correlation between inverter output currents and machine phase currents is given with

$$\begin{aligned} &i_A = i_{a1} = i_{a2} \qquad && i_B = i_{b1} = i_{c2} \\ &i_C = i_{c1} = i_{e2} \qquad && i_D = i_{d1} = i_{b2} \\ &i_E = i_{e1} = i_{d2} \end{aligned} \tag{2}$$

The simplest form of indirect rotor flux oriented control is considered. Vector controller’s form depends on the type of the machine and is illustrated in Fig. 2 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 created by means of ($k = \sqrt{2/5}$):

$$
\begin{aligned}
i_{a1}^{*} &= k[i_{ds1}^{*}\cos\phi_{r1} - i_{qs1}^{*}\sin\phi_{r1}] \\
i_{b1}^{*} &= k[i_{ds1}^{*}\cos(\phi_{r1}-\alpha) - i_{qs1}^{*}\sin(\phi_{r1}-\alpha)] \\
i_{c1}^{*} &= k[i_{ds1}^{*}\cos(\phi_{r1}-2\alpha) - i_{qs1}^{*}\sin(\phi_{r1}-2\alpha)] \\
i_{d1}^{*} &= k[i_{ds1}^{*}\cos(\phi_{r1}-3\alpha) - i_{qs1}^{*}\sin(\phi_{r1}-3\alpha)] \\
i_{e1}^{*} &= k[i_{ds1}^{*}\cos(\phi_{r1}-4\alpha) - i_{qs1}^{*}\sin(\phi_{r1}-4\alpha)]
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
i_{a2}^{*} &= k[i_{ds2}^{*}\cos\phi_{r2} - i_{qs2}^{*}\sin\phi_{r2}] \\
i_{b2}^{*} &= k[i_{ds2}^{*}\cos(\phi_{r2}-\alpha) - i_{qs2}^{*}\sin(\phi_{r2}-\alpha)] \\
i_{c2}^{*} &= k[i_{ds2}^{*}\cos(\phi_{r2}-2\alpha) - i_{qs2}^{*}\sin(\phi_{r2}-2\alpha)] \\
i_{d2}^{*} &= k[i_{ds2}^{*}\cos(\phi_{r2}-3\alpha) - i_{qs2}^{*}\sin(\phi_{r2}-3\alpha)] \\
i_{e2}^{*} &= k[i_{ds2}^{*}\cos(\phi_{r2}-4\alpha) - i_{qs2}^{*}\sin(\phi_{r2}-4\alpha)]
\end{aligned}
$$

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

$$
\begin{aligned}
i_{A}^{*} &= i_{a1}^{*} + i_{a2}^{*} & \quad i_{B}^{*} &= i_{b1}^{*} + i_{c2}^{*} \\
i_{C}^{*} &= i_{c1}^{*} + i_{e2}^{*} & \quad i_{D}^{*} &= i_{d1}^{*} + i_{b2}^{*} \\
i_{E}^{*} &= i_{e1}^{*} + i_{d2}^{*}
\end{aligned}
\tag{4}
$$

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/torque producing currents of both machines. However, the specific connection of Fig. 1 means that the set of flux/torque producing currents of one machine produces rotating field in that machine only,

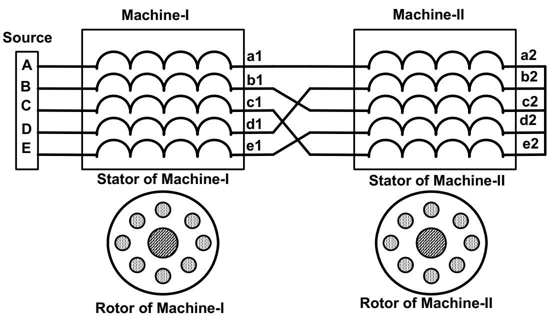


Fig. 1: Series connection of two five-phase machines.

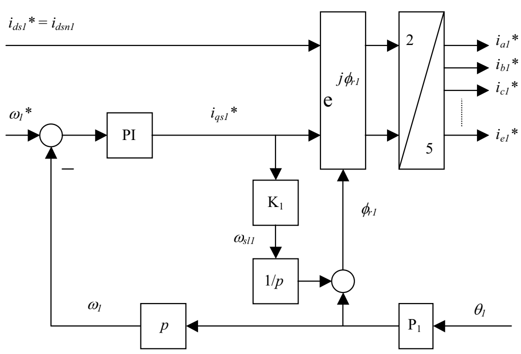


Fig. 2: Indirect rotor flux oriented controller for a five-phase induction machine ($K_1 = 1/(T_{r1}^{*} i_{ds1}^{*})$, $p \equiv d/dt$).

while in the other machine the resultant field sums to zero at any instant in time [4,10]. Hence the two machines can be controlled independently, although they are connected in series and supplied from a single five-phase VSI.

III. 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 developed in state space form as follows:

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

In a general case the two machines, although both five-phase, may be different and therefore may be with different parameters. Let the index ‘1’ denote induction machine directly connected to the five-phase inverter and let the index ‘2’ stand for the second induction machine, connected after the first machine through phase transposition.

Voltage equation for the complete 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 15$^{\text{th}}$ 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 $(\alpha = 2\pi/5)$:

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

$$\underline{L}_{s1} = \begin{bmatrix} L_{ls1}+M_1 & M_1\cos\alpha & M_1\cos 2\alpha & M_1\cos 2\alpha & M_1\cos\alpha \\ M_1\cos\alpha & L_{ls1}+M_1 & M_1\cos\alpha & M_1\cos 2\alpha & M_1\cos 2\alpha \\ M_1\cos 2\alpha & M_1\cos\alpha & L_{ls1}+M_1 & M_1\cos\alpha & M_1\cos 2\alpha \\ M_1\cos 2\alpha & M_1\cos 2\alpha & M_1\cos\alpha & L_{ls1}+M_1 & M_1\cos\alpha \\ M_1\cos\alpha & M_1\cos 2\alpha & M_1\cos 2\alpha & M_1\cos\alpha & L_{ls1}+M_1 \end{bmatrix} \tag{13}$$

$$\underline{L}_{s2}' = \begin{bmatrix} L_{ls2}+M_2 & M_2\cos 2\alpha & M_2\cos\alpha & M_2\cos\alpha & M_2\cos 2\alpha \\ M_2\cos 2\alpha & L_{ls2}+M_2 & M_2\cos 2\alpha & M_2\cos\alpha & M_2\cos\alpha \\ M_2\cos\alpha & M_2\cos 2\alpha & L_{ls2}+M_2 & M_2\cos 2\alpha & M_2\cos\alpha \\ M_2\cos\alpha & M_2\cos\alpha & M_2\cos 2\alpha & L_{ls2}+M_2 & M_2\cos 2\alpha \\ M_2\cos 2\alpha & M_2\cos\alpha & M_2\cos\alpha & M_2\cos 2\alpha & L_{ls2}+M_2 \end{bmatrix} \tag{14}$$

$$\underline{L}_{r1} = \begin{bmatrix} L_{lr1}+M_1 & M_1\cos\alpha & M_1\cos 2\alpha & M_1\cos 2\alpha & M_1\cos\alpha \\ M_1\cos\alpha & L_{lr1}+M_1 & M_1\cos\alpha & M_1\cos 2\alpha & M_1\cos 2\alpha \\ M_1\cos 2\alpha & M_1\cos\alpha & L_{lr1}+M_1 & M_1\cos\alpha & M_1\cos 2\alpha \\ M_1\cos 2\alpha & M_1\cos 2\alpha & M_1\cos\alpha & L_{lr1}+M_1 & M_1\cos\alpha \\ M_1\cos\alpha & M_1\cos 2\alpha & M_1\cos 2\alpha & M_1\cos\alpha & L_{lr1}+M_1 \end{bmatrix} \tag{15}$$

$$\underline{L}_{r2} = \begin{bmatrix} L_{lr2}+M_2 & M_2\cos\alpha & M_2\cos 2\alpha & M_2\cos 2\alpha & M_2\cos\alpha \\ M_2\cos\alpha & L_{lr2}+M_2 & M_2\cos\alpha & M_2\cos 2\alpha & M_2\cos 2\alpha \\ M_2\cos 2\alpha & M_2\cos\alpha & L_{lr2}+M_2 & M_2\cos\alpha & M_2\cos 2\alpha \\ M_2\cos 2\alpha & M_2\cos 2\alpha & M_2\cos\alpha & L_{lr2}+M_2 & M_2\cos\alpha \\ M_2\cos\alpha & M_2\cos 2\alpha & M_2\cos 2\alpha & M_2\cos\alpha & L_{lr2}+M_2 \end{bmatrix} \tag{16}$$

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

$$\underline{L}_{rs1} = \underline{L}_{sr1}^{T}$$

$$\underline{L}_{sr2}' = M_2 \begin{bmatrix} \cos\theta_2 & \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) \\ \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) & \cos\theta_2 & \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) \\ \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) & \cos\theta_2 \\ \cos(\theta_2-\alpha) & \cos\theta_2 & \cos(\theta_2+\alpha) & \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) \\ \cos(\theta_2+2\alpha) & \cos(\theta_2-2\alpha) & \cos(\theta_2-\alpha) & \cos\theta_2 & \cos(\theta_2+\alpha) \end{bmatrix} \tag{18}$$

$$\underline{L}_{rs2}' = \underline{L}_{sr2}^{T}{}'$$

Expansion of (6) yields

$$\underline{v} = \begin{bmatrix} \underline{v}^{INV} \\ \underline{0} \\ \underline{0} \end{bmatrix}$$

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

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):

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

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

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

$$\underline{v}_{\alpha\beta}^{INV} = \underline{C}\underline{v}^{INV}, \quad \underline{v}_{\alpha\beta}^{r1} = \underline{C}\underline{v}^{r1}, \quad \underline{v}_{\alpha\beta}^{r2} = \underline{C}\underline{v}^{r2} \quad \underline{i}_{\alpha\beta}^{INV} = \underline{C}\underline{i}^{INV}, \quad \underline{i}_{\alpha\beta}^{r1} = \underline{C}\underline{i}_{r1}, \quad \underline{i}_{\alpha\beta}^{r2} = \underline{C}\underline{i}_{r2} \quad (21)$$

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

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

The inverter/stator voltage equations are:

$$v_\alpha^{INV} = \left(R_{s1} + R_{s2}\right)i_\alpha^{INV} + \left(L_{ls1} + L_{ls2} + L_{m1}\right)\frac{di_\alpha^{INV}}{dt} + L_{m1}\cos\left(\theta_1\right)\frac{di_{\alpha r1}}{dt} - L_{m1}\sin\left(\theta_1\right)\frac{di_{\beta r1}}{dt} - \omega_1 L_{m1}\left(\sin\left(\theta_1\right)i_{\alpha r1} + \cos\left(\theta_1\right)i_{\beta r1}\right)$$

$$v_\beta^{INV} = \left(R_{s1} + R_{s2}\right)i_\beta^{INV} + \left(L_{ls1} + L_{m1} + L_{ls2}\right)\frac{di_\beta^{INV}}{dt} + L_{m1}\sin\left(\theta_1\right)\frac{di_{\alpha r1}}{dt} + L_{m1}\cos\left(\theta_1\right)\frac{di_{\beta r1}}{dt} + \omega_1 L_{m1}\left(\cos\left(\theta_1\right)i_{\alpha r1} - \sin\left(\theta_1\right)i_{\beta r1}\right)$$

$$v_x^{INV} = \left(R_{s1} + R_{s2}\right)i_x^{INV} + \left(L_{ls1} + L_{ls2} + L_{m2}\right)\frac{di_x^{INV}}{dt} + L_{m2}\cos\left(\theta_2\right)\frac{di_{\alpha r2}}{dt} - L_{m2}\sin\left(\theta_2\right)\frac{di_{\beta r2}}{dt} - \omega_2 L_{m2}\left(\sin\left(\theta_2\right)i_{\alpha r2} + \cos\left(\theta_2\right)i_{\beta r2}\right)$$

$$v_y^{INV} = \left(R_{s1} + R_{s2}\right)i_y^{INV} + \left(L_{ls1} + L_{ls2} + L_{m2}\right)\frac{di_y^{INV}}{dt} + L_{m2}\sin\left(\theta_2\right)\frac{di_{\alpha r2}}{dt} + L_{m2}\cos\left(\theta_2\right)\frac{di_{\beta r2}}{dt} + \omega_2 L_{m2}\left(\cos\left(\theta_2\right)i_{\alpha r2} - \sin\left(\theta_2\right)i_{\beta r2}\right)$$

$$v_0^{INV} = \left(R_{s1} + R_{s2}\right)i_0^{INV} + \left(L_{ls1} + L_{ls2}\right)\frac{di_0^{INV}}{dt} \quad (23)$$

The rotor voltage equations of machine 1:

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

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

$$v_{xr1} = 0 = R_{r1}i_{xr1} + L_{lr1}\frac{di_{xr1}}{dt}$$

$$v_{yr1} = 0 = R_{r1}i_{yr1} + L_{lr1}\frac{di_{yr1}}{dt} \quad (24)$$

$$v_{0r1} = 0 = R_{r1}i_{0r1} + L_{lr1}\frac{di_{0r1}}{dt}$$

The rotor voltage equations of machine 2:

$$v_{\alpha r2} = 0 = R_{r2}i_{\alpha r2} + L_{m2}\cos\left(\theta_2\right)\frac{di_x^{INV}}{dt} + L_{m2}\sin\left(\theta_2\right)\frac{di_y^{INV}}{dt} + \left(L_{lr2} + L\right.$$

$$v_{\beta r2} = 0 = R_{r2}i_{\beta r2} - L_{m2}\sin\left(\theta_2\right)\frac{di_x^{INV}}{dt} + L_{m2}\cos\left(\theta_2\right)\frac{di_y^{INV}}{dt} + \left(L_{lr2} + L_{m2}\right)\frac{di_{\beta r2}}{dt} - \omega_2 L_{m2}\left(\cos\left(\theta_2\right)i_x^{INV} + \sin\left(\theta_2\right)i_y^{INV}\right)$$

$$v_{xr2} = 0 = R_{r2} i_{xr2} + L_{lr2} \frac{di_{xr2}}{dt} \qquad (25)$$

$$v_{yr2} = 0 = R_{r2} i_{yr2} + L_{lr2} \frac{di_{yr2}}{dt}$$

$$v_{0r2} = 0 = R_{r2} i_{0r2} + L_{lr2} \frac{di_{0r2}}{dt}$$

The electromagnetic torque equations:

$$T_{e1} = P_1 L_{m1} \left\{ \cos(\theta_1)\left(i_{\alpha r1} i_{\beta}^{INV} - i_{\beta r1} i_{\alpha}^{INV}\right) - \sin(\theta_1)\left(i_{\alpha r1} i_{\alpha}^{INV} + i_{\beta r1} i_{\beta}^{INV}\right)\right\}$$

$$T_{e2} = P_2 L_{m2} \left\{ \cos(\theta_2)\left(i_{\alpha r2} i_{y}^{INV} - i_{\beta r2} i_{x}^{INV}\right) - \sin(\theta_2)\left(i_{\alpha r2} i_{x}^{INV} + i_{\beta r2} i_{y}^{INV}\right)\right\} \qquad (26)$$

IV. Sensorless Operation Of Series-Connected Two Five-Phase Induction Machines

The developed model of a series-connected two five-phase induction machines indicates that an observer used for five-phase machines can be easily extended to multi-phase , multi-motor machines. For multi-phase machines observer -based 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 , it has been shown that the stator and rotor *d* and *q* axis flux linkages are function of magnetising inductance *Lm* 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 is shown in Fig. 3.

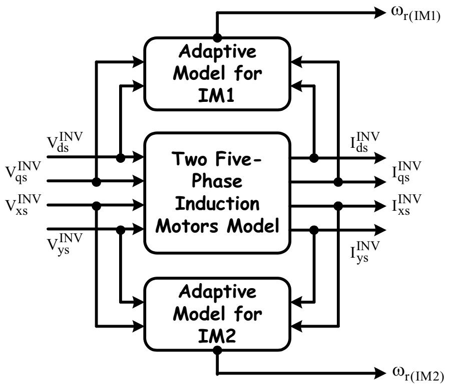


Fig. 3: Sensorless control of Series connected two five-phase machines.

V. Observer-based speed estimator

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 feed back 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.

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:

$$\frac{dx}{dt} = Ax + Bv \qquad (27)$$

and the output vector is

$$i_s = Cx \qquad (28)$$

By using the derived mathematical model of the induction machine, e.g. if the component form of the equations (27), 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:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bv + G(i_s - \hat{i}_s) \qquad (29)$$

and the output vector is

$$\hat{i}_s = C\hat{x} \qquad (30)$$

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 (27) and (28) the different terms are explained as follows:

$$\hat{A} = \begin{bmatrix} -\left[1/T_s' + (1-\sigma)/T_r'\right] I_2 & \left[L_m/(L_s' L_r)\right]\left[I_2/T_r - \hat{\omega}_r J\right] \\ L_m I_2/T_r & -I_2/T_r + \hat{\omega}_r J \end{bmatrix}$$

$$B = \left[I_2 / L_s', O_2\right]^T$$

$$C = \left[I_2, O_2\right]^T$$

$$v^{INV} = v_s^{INV} = \left[v_{\alpha s}^{INV}, v_{\beta s}^{INV}\right]^T \tag{31}$$

$$\hat{x} = \left[\hat{i}_s, \hat{\psi}_r^{'}\right]^T$$

$$i_s^{INV} = \left[i_{\alpha s}^{INV}, i_{\beta s}^{INV}\right]^T, \quad \hat{i}_s = \left[\hat{i}_{\alpha s}, \hat{i}_{\beta s}\right]^T$$

$$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

$I_2 = \mathrm{diag}(1,1)$, 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_m and L_r are the magnetising inductance and rotor self-inductance respectively, $L_s^{'}$ is the stator transient inductance, $T_s^{'} = L_s^{'} / R_s$ and $T_r^{'} = L_r^{'} / R_r$ are the stator and rotor transient time constants respectively, and $\sigma = 1 - L_m^2 /(L_s L_r)$ is the leakage factor.

The observer gain matrix is defined as

$$G = -\begin{bmatrix} g_1 I_2 + g_2 J \\ g_3 I_2 + g_4 J \end{bmatrix}$$

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

$$g_1 = -(k-1)\left(\frac{1}{T_s^{'}} + \frac{1}{T_r^{'}}\right)$$

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

$$g_3 = (k^2 - 1)\left\{-\left[\frac{1}{T_s^{'}} + \frac{(1-\sigma)}{T_r^{'}}\right]\frac{L_s^{'} L_m}{L_r} + \frac{L_m}{T_r}\right\} \tag{32}$$

$$+ \frac{L_s^{'} L_m}{L_r}(k-1)\left(\frac{1}{T_s^{'}} + \frac{1}{T_r^{'}}\right)$$

$$g_4 = -(k-1)\hat{\omega}_r \frac{L_s^{'} L_m}{L_r}$$

It follows that the four gains depend on the estimated speed, $\hat{\omega}_r$. By using eqns (27) and (28) 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. 4 [16].

In Fig. 4 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:

$\underline{\hat{\psi}}_r = \hat{\psi}_{\alpha r} + j\hat{\psi}_{\beta r}$ and $\underline{e} = e_{\alpha s} + je_{\beta s}$. The estimated speed is obtained from the speed tuning signal by using a PI controller thus,

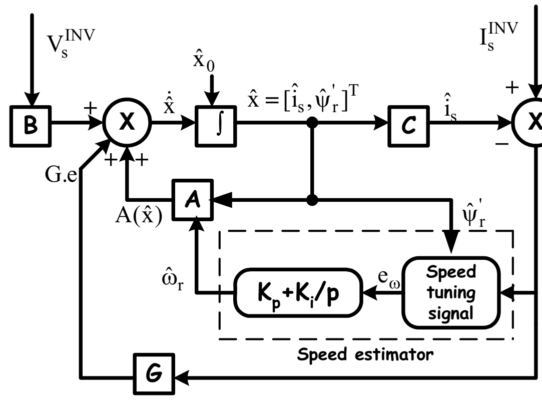


Fig. 4: Adaptive speed observer (speed-adaptive flux observer)

$$\hat{\omega}_r = K_p(\hat{\psi}_{\beta r} e_{\alpha s} - \hat{\psi}_{\alpha r} e_{\beta s}) + K_i \int (\hat{\psi}_{\beta r} e_{\alpha s} - \hat{\psi}_{\alpha r} e_{\beta s}) dt \tag{33}$$

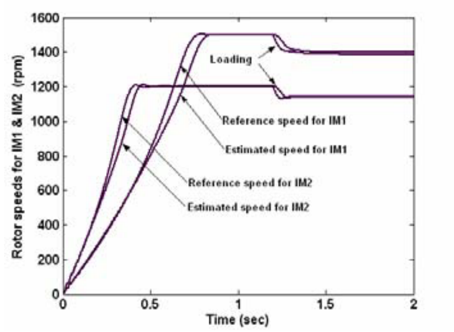
where K_p and K_i are proportional and integral gain constants respectively, $e_{\alpha s} = i_{\alpha s}^{INV} - \hat{i}_{\alpha s}$ and $e_{\beta s} = i_{\beta s}^{INV} - \hat{i}_{\beta s}$ are the stator current errors respectively.
The adaptation mechanism is similar to that as used in the MRAS-based 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.

VI. Simulation Results

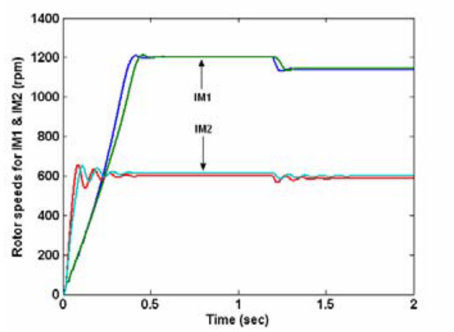
The results of the simulation given in this section are obtained using two identical 4-pole, 50 Hz five-phase induction machines. The indirect vector controller for both machines is the same and is the one shown in figure 2. Various simulation tests are performed in order to verify the independence of 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:

A. Fixed voltage and fixed frequency supply

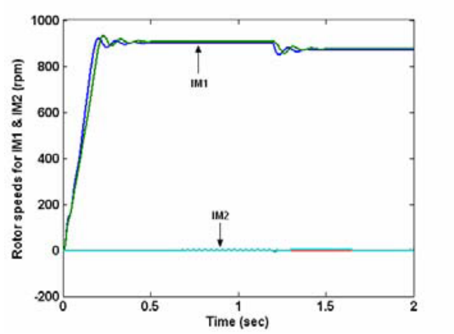
In this case both machines are connected to two five-phase supply system. If the supply voltages for machine-1 are $v_{a1}, v_{b1}, v_{c1}, v_{d1}, v_{e1}$ and for machine-2 are $v_{a2}, v_{b2}, v_{c2}, v_{d2}, v_{e2}$ then the resultant supply voltages applied to the series-connected two motors are $V_A = v_{a1} + v_{a2}$, $V_B = v_{b1} + v_{c2}$, $V_C = v_{c1} + v_{e2}$, $V_D = v_{d1} + v_{b2}$, $V_E = v_{e1} + v_{d2}$.
The simulation time for 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 5(a) to (f). Each test results shows both reference and estimated speeds for IM1 and IM2.



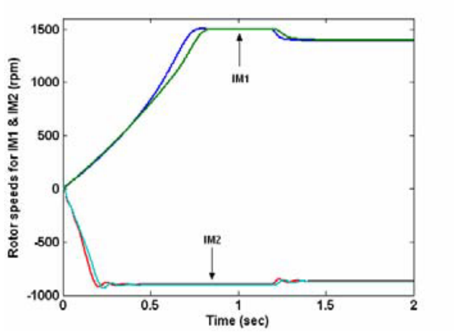
(a)



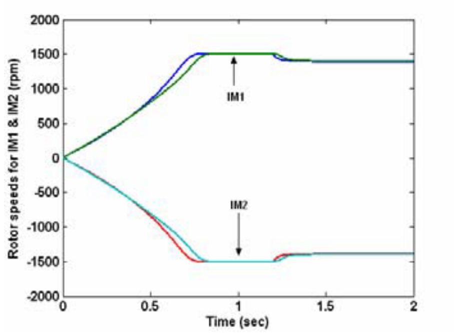
(b)



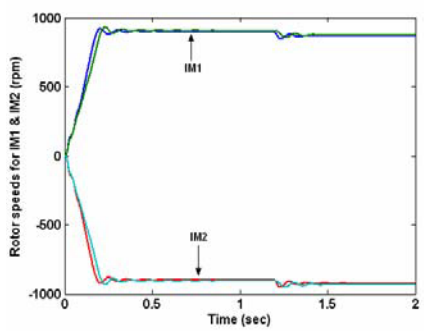
(c)



(d)



(e)



(f)

Fig. 5: Speed responses for fixed voltage and fixed frequency series connected two motors system.

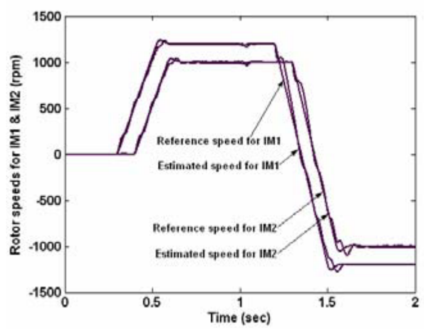
B. Vector controlled series-connected two motors:

In this case both machines are vector controlled. Two vector controller 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

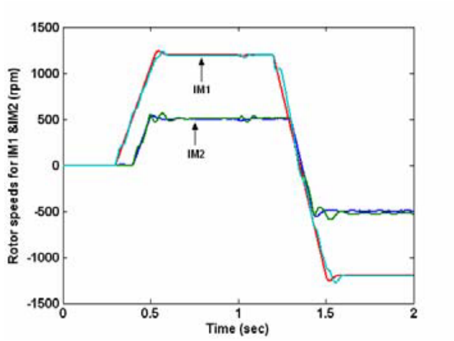
$$i^*_A = i^*_{a1} + i^*_{a2} \qquad i^*_B = i^*_{b1} + i^*_{c2}$$
$$i^*_C = i^*_{c1} + i^*_{e2} \qquad i^*_D = i^*_{d1} + i^*_{b2}$$
$$i^*_E = i^*_{e1} + i^*_{d2}$$

The simulation time for 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 figure 6(a) to (f). Each test results shows both reference and estimated speeds for IM1 and IM2.



(a)



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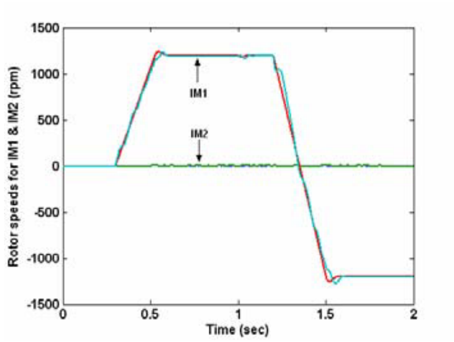
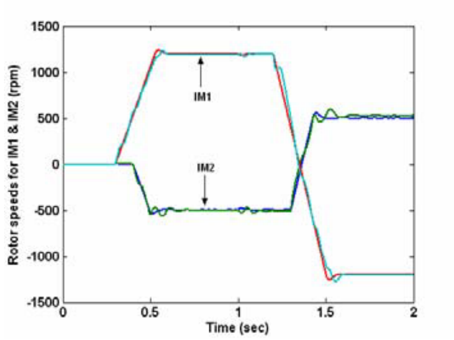
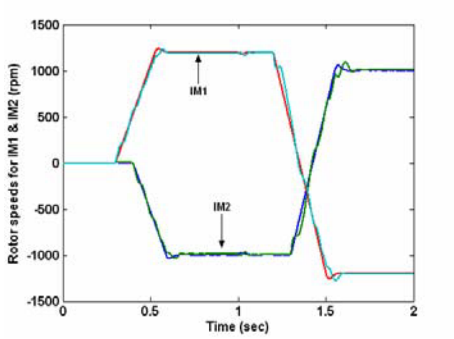


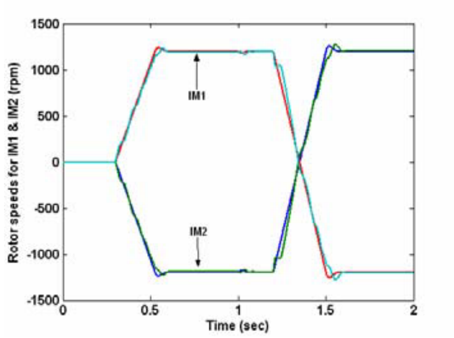
(c)



(d)



(e)



(f)

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

VII. DISCUSSION

Fig. 5(a) to (f) shows the test results for fixed voltage and fixed frequency supply fed series connected two motor system. In first test fig. (a), IM1 is running at 1500 rpm and IM2 at 1200 rpm and both machines are loaded at t=1s. In fig. (b), IM1 is running at 1200 rpm and IM2 at 600 rpm. In fig. (c), IM1 is running at 900 rpm and IM2 at 0 rpm. In fig. (d), IM1 is running at 1500 rpm and IM2 at -900 rpm. In fig. (e), IM1 and IM2 both are running at 1500 rpm but in opposite direction. In fig. (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 0.1sec. Also under loading condition, a 10rpm 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. 6(a) to (f) shows the test results for vector controlled series connected two motor system. In all test, IM1 is set at ±1200 rpm and both machines are loaded at t=1.0s. In first test fig. (a), IM2 is set at ±1000 rpm. In fig. (b), IM2 is set at ±500 rpm. In fig. (c), IM2 is set at 0 rpm. In fig. (d), IM2 is set at ∓ 500 rpm. In fig. (e), IM2 is set at ∓ 1000 rpm. In fig. (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.

VIII. CONCLUSION

The paper 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 and vector control of the two machines in sensorless mode. A brief 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 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.

ACKNOWLEDGEMENT

The authors gratefully acknowledge support provided for the work on this project by the AICTE, File No. 8023/BOR/RPS-86/2006-07.

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