A Series-Connected Two-Motor Six-Phase Drive With Induction and Permanent Magnet Machines

Emil Levi, *Senior Member, IEEE*, Martin Jones, and Slobodan N. Vukosavic, *Member, IEEE*

***Abstract*—A novel concept for multimotor drives, based on utilization of multiphase machines, has been proposed recently. Independent vector control of all the machines of the group can be achieved while using a single multiphase inverter supply, provided that the stator windings are connected in series in an appropriate manner. One specific case of such a drive system is a two-motor drive, comprising a symmetrical six-phase machine connected in series with a three-phase machine. The group is supplied from a six-phase current-controlled voltage source inverter (VSI). The available considerations related to this two-motor drive system, consisting of two induction motors, are currently of purely theoretical nature, with the proof-of-concept provided by simulation only. This paper analyzes series-connected two-motor six-phase drive, comprising a six-phase symmetrical induction machine and a three-phase permanent magnet synchronous machine (PMSM) and provides, for the first time, detailed experimental verification of the possibility of independent control of the two motors. The operating principles of the drive system are at first reviewed and a brief description of the experimental system is then given. The emphasis is placed on an extensive presentation of experimental results, collected from a laboratory setup. It is shown that a truly independent and decoupled vector control of the two machines results, although a single supply source is used. The two-motor drive system of the proposed structure is seen as a potentially viable industrial solution for applications requiring one high-power and one low-power machine.**

***Index Terms*—Experimental verification, multimotor drives, multiphase machines, six-phase, vector control.**

I. INTRODUCTION

THE concept of multiphase motor drives is rather mature, with the origins traceable back to 1969. However, an upsurge in the interest in multiphase 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 multiphase 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].

A specific configuration of multiphase motor drives is the one with multiple three-phase windings on stator [4]. The most frequently discussed construction of this type is the one with two three-phase windings, displaced in space by 30°, which gives an asymmetrical six-phase winding [5]–[8]. Asymmetrical six-phase (dual three-phase) machines are predominantly seen as a feasible solution for traction and ship propulsion, where power ratings are high [1], [5].

A novel concept for multimotor drive systems, based on utilization of symmetrical multiphase machines (spatial displacement between any two consecutive phases is $2\pi/n$, where n is the number of phases) with sinusoidal flux spatial distribution, has been proposed recently in [9]–[11]. The idea stems from the fact that any n-phase machine requires only two currents for independent flux and torque control. Thus, in a multiphase machine there are additional degrees of freedom, which can be used to control other machines [12]. It has been suggested that, by connecting multiphase stator windings in series with an appropriate phase transposition, it becomes possible to control independently (using vector control principles) all the machines with the supply coming from a single multiphase inverter.

The multimotor drive system concept of [9]–[11] is applicable to any symmetrical supply phase number greater than or equal to five. One particular case is a symmetrical six-phase two-motor drive. It is realized by connecting in series, in an appropriate manner, stator windings of a symmetrical six-phase machine with stator windings of a standard three-phase machine. The supply is provided from a six-phase voltage source inverter (VSI) and, by applying vector control principles, independent control of the two machines can be achieved. This fact, introduced using physical considerations and intuitive reasoning in [9], has been confirmed by detailed mathematical modeling of the six-phase two-motor drive, reported in [13].

The idea of series connection for realization of multimotor drives is applicable not only to symmetrical but to asymmetrical multiphase machines as well. It has been shown in [14] that a six-phase series-connected two-motor drive can be realized by connecting in series two asymmetrical six-phase machines. Although V/f control rather than vector control was analyzed in [14], the basic idea is the same as for symmetrical series-connected multiphase motor drives. However, the configuration with two asymmetrical six-phase machines of [14] is believed to be much less suitable for real-world applications than the configuration discussed here, which consists of a symmetrical six-phase and an ordinary three-phase machine. This is so since here the three-phase machine will not suffer any adverse effects from the series connection and the reduction of efficiency of the six-phase machine due to series connection will be negligibly small if six-phase machine is of large power rating, while power rating of the three-phase machine is small. In contrast to this, in

Manuscript received September 24, 2004; revised November 10, 2004. This work was supported by the EPSRC (standard research Grant GR/R64452/01) and by Semikron Ltd. Paper no. TEC-00274-2004.

the configuration of [14] flux/torque producing currents of both machines flow through the windings of both machines, so that stator winding losses are increased in both machines, leading to a deterioration in the efficiency of the two-motor drive system, when compared to two individual single-motor drives.

Vector control of the two series-connected machines can be achieved by using either current control in the stationary reference frame or current control in the rotating reference frame. While both possibilities are viable, it has been shown recently that current control in the rotating reference frame for series-connected six-phase [15] (as well as five-phase [16]) two-motor drives leads to increased parameter sensitivity. This is so since the decoupling voltages become functions of parameters of both machines, due to the need to compensate voltage drops in one machine caused by the flow of the flux/torque producing currents of the other machine through its windings. The conclusion of [15], [16] is that current control in the stationary reference frame is better suited to series-connected multiphase multimotor drive systems. It is for this reason that current control based on inverter output phase currents is analyzed and implemented in this paper.

The theory of symmetrical multiphase series-connected multimotor drives, developed in [9]–[11], has so far been verified by simulation only and the symmetrical six-phase two-motor drive is no exception. Furthermore, although the concept has been postulated as valid for all types of ac machines with sinusoidal spatial flux distribution in [9]–[11], all the available considerations have assumed utilization of induction machines. This paper investigates combined use of induction and permanent magnet synchronous machines (PMSMs) and provides, for the first time, detailed experimental verification of the decoupled dynamic control of two machines within the series-connected two-motor drive. A symmetrical six-phase induction machine is connected in series with a three-phase servo PMSM and the supply is provided by a six-phase current-controlled VSI, obtained by paralleling two industrial three-phase VSIs to the common dc link.

A summary of the operating principles of the six-phase two-motor drive system, detailed in [9]–[15] and based on the assumption of sinusoidal spatial flux distribution in the ac machines, is provided first. This is followed by a brief description of the experimental system and the procedure used to verify the decoupling of dynamics of the two machines in the experimental investigation. Results of various experiments are then presented. These include acceleration, deceleration, speed reversal, and step loading/unloading. Excellent and independent dynamics are demonstrated, thus confirming that the control of the two machines is truly decoupled under all operating conditions.

II. CONFIGURATION AND OPERATING PRINCIPLES OF THE SIX-PHASE TWO-MOTOR DRIVE

The connection diagram for a six-phase series-connected two-motor drive is shown in Fig. 1 [9], [15]. Capital letters denote the inverter phases, while lower case letters identify the motor phases, according to the spatial distribution of phases. The first machine (Machine 1) is a symmetrical six-phase machine, with a spatial displacement between any two consecutive stator phases equal to 60°. The second machine (Machine 2) is a standard three-phase machine.

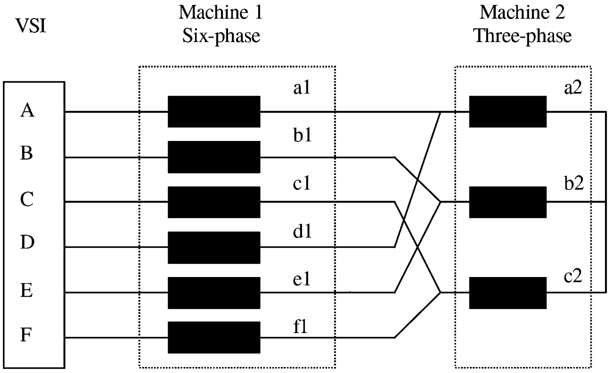

Fig. 1. Six-phase series-connected two-motor drive.

As can be seen in Fig. 1, each of the phases of the three-phase machine is connected to two phases of the six-phase machine. For example, phase $a2$ is connected to phases $a1$ and $d1$. Since the six-phase machine is symmetrical, phases $a1$ and $d1$ are in spatial opposition (displaced by 180 degrees) and flux/torque producing currents of the six-phase machine in these two phases will be in phase opposition. This means that the flux/torque producing current of Machine 1, flowing from the inverter phase A through phase $a1$, will return through phase $d1$ to inverter phase D and will therefore not flow through Machine 2. Alternatively, assuming positive current flow directions from the inverter to the Machine 1, one can say that flux/torque producing currents of phases $a1$ and $d1$ will cancel each other at the point of connection with $a2$. The same reasoning applies to the other two pairs of phases of the six-phase machine ($b1$-$e1$ and $c1$-$f1$). Hence, the flux/torque producing currents of the six-phase machine will not flow through the three-phase machine.

As far as the three-phase machine is concerned, each of its phases is connected to two phases of the six-phase machine. Thus, one half of the required flux/torque producing current for the three-phase machine needs to be supplied through each of the six phases of the six-phase machine. For example, 50% of the current required by phase $a2$ will be coming through each of the phases $a1$ and $d1$ of the six-phase machine. Since the same value of the current will be coming from two six-phase machine phases that are in spatial opposition, the net magnetomotive force created by these currents in the six-phase machine will be zero. The same applies to the other two phases.

The above given explanations can be easily verified by considering a steady state with sinusoidal flux/torque producing currents of both machines. Let the currents be of root mean square (rms) value and angular frequency I_1, ω_1 and I_2, ω_2 for the six-phase and the three-phase machine, respectively, and let each phase of the inverter (i.e., six-phase machine) carry one half of the current required for flux/torque production in the three-phase machine. Application of the decoupling transformation in power-invariant form for the six-phase system ($\alpha = 60°$) (see (1) at the bottom of the next page), produces stator current axis components which are summarized in Table I in space vector form (zero-sequence components are omitted since these

TABLE I
AXIS CURRENT COMPONENTS IN TWO MACHINES IN STEADY-STATE OPERATION

Currents in each supply phase	M1 – six-phase machine	M2 – three-phase machine
I_1, ω_1	$\underline{\alpha + j\beta}$ $\sqrt{6} I_1 e^{j(\omega_1 t - \pi/2)}$	——
$\frac{1}{2} I_2, \omega_2$	$\underline{x1 + jy1}$ $\sqrt{6} \frac{I_2}{2} e^{j(\omega_2 t - \pi/2)}$	$\underline{\alpha + j\beta}$ $\sqrt{3} I_2 e^{j(\omega_2 t - \pi/2)}$

are identically equal to zero). Flux/torque producing currents of Machine 2 (α-β currents) do not produce flux and torque in Machine 1 (where they appear as x–y components) while flux/torque producing currents of Machine 1 sum to zero at the point of connection with the three-phase machine. It therefore follows that independent vector control of the two machines can be realized with a single six-phase inverter.

On the basis of these considerations, one concludes that the flux/torque producing currents of the six-phase machine will not flow through the three-phase machine at all, meaning that the three-phase machine will not be adversely affected by the series connection. Flux/torque producing currents of the three-phase machine will flow through the phases of the six-phase machine, but will not create any rotating field and hence torque. These currents will appear for the six-phase machine, according to Table I, as x–y components, so that their net contribution to the six-phase motor's torque will be zero.

III. VECTOR CONTROL ALGORITHM AND REFERENCE CURRENT GENERATION

Any of the available vector control algorithms can be used for either of the two machines of the group. The simplest possibility, considered here, is the application of indirect rotor flux oriented (RFO) control. Fig. 2 illustrates indirect RFO controller for the six-phase induction machine assuming operation in the base speed region only. Since the three-phase machine is a PMSM with surface-mounted magnets and is operated in the base speed region as well, corresponding vector controller is as shown in Fig. 3. Individual phase current references of the two machines are then created, using the power invariant transformation ($k_1 = \sqrt{2/6}, k_2 = \sqrt{2/3}$) and Figs. 2 and 3, according to the following expressions:

$$\begin{aligned}
i_{a1}^* &= k_1[i_{ds1}^* \cos\phi_{r1} - i_{qs1}^* \sin\phi_{r1}]\\
i_{b1}^* &= k_1[i_{ds1}^* \cos(\phi_{r1} - \alpha) - i_{qs1}^* \sin(\phi_{r1} - \alpha)]\\
&\text{- -}\\
i_{f1}^* &= k_1[i_{ds1}^* \cos(\phi_{r1} - 5\alpha) - i_{qs1}^* \sin(\phi_{r1} - 5\alpha)]
\end{aligned}$$

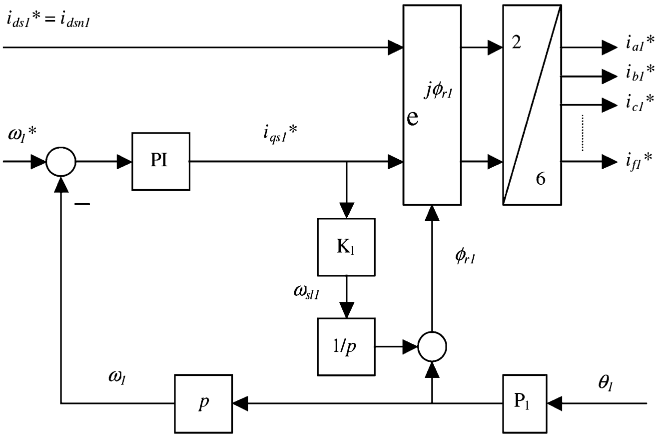

Fig. 2. Indirect (feed-forward) rotor flux oriented controller for the six-phase induction machine $(K_1 = 1/(T_{r1}^* i_{ds1}^*), p \equiv d/dt)$.

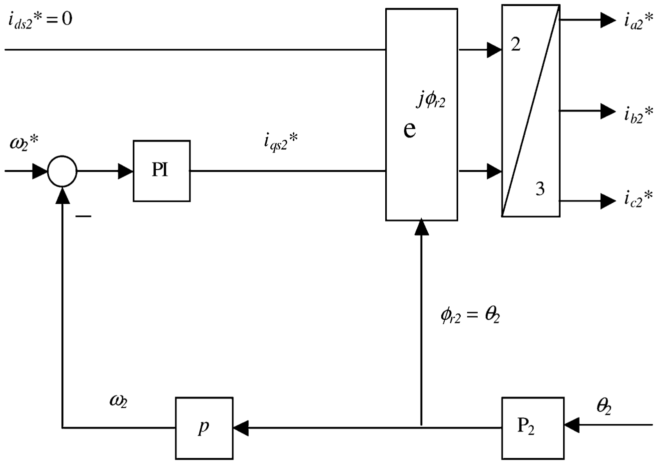

Fig. 3. Rotor flux oriented controller for the three-phase PMSM.

$$\begin{aligned}
i_{a2}^* &= k_2[-i_{qs2}^* \sin\phi_{r2}]\\
i_{b2}^* &= k_2[-i_{qs2}^* \sin(\phi_{r2} - 2\alpha)]\\
i_{c2}^* &= k_2[-i_{qs2}^* \sin(\phi_{r2} - 4\alpha)]
\end{aligned} \tag{2}$$

where $\alpha = 2\pi/6$. They are further summed according to the connection diagram of Fig. 1 in order to create the inverter phase current references

$$\begin{aligned}
i_A^* &= i_{a1}^* + 0.5 i_{a2}^* \quad & i_D^* &= i_{d1}^* + 0.5 i_{a2}^*\\
i_B^* &= i_{b1}^* + 0.5 i_{b2}^* \quad & i_E^* &= i_{e1}^* + 0.5 i_{b2}^*\\
i_C^* &= i_{c1}^* + 0.5 i_{c2}^* \quad & i_F^* &= i_{f1}^* + 0.5 i_{c2}^*
\end{aligned} \tag{3}$$

$$\underline{C} = \sqrt{\frac{2}{6}} \begin{array}{c|c} \alpha & \\ \beta & \\ x1 & \\ y1 & \\ 01 & \\ 02 & \end{array} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha & \cos 5\alpha\\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha & \sin 5\alpha\\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \cos 8\alpha & \cos 10\alpha\\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \sin 8\alpha & \sin 10\alpha\\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}\\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \tag{1}$$

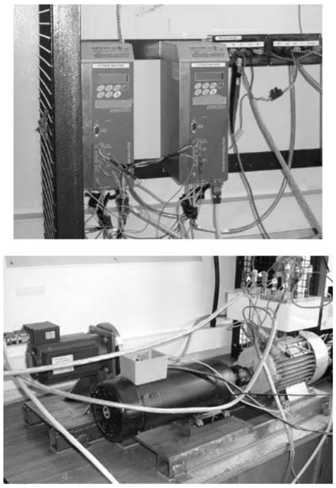

Fig. 4. Experimental setup: the two three-phase inverters in six-phase configuration and the six-phase (top) and three-phase (bottom) machine.

Inverter current references of (3) are further impressed by using a suitable current control method, as explained in the next section.

IV. EXPERIMENTAL SETUP

A laboratory setup is constructed in order to prove the existence of decoupled dynamic control in the series-connected two-motor drive system experimentally. The system incorporates a symmetrical six-phase machine and a three-phase PMSM, connected in series according to Fig. 1 and supplied from a double three-phase (six-phase inverter), and is illustrated in Fig. 4. Each of the two three-phase inverters is equipped with a digital signal processor (DSP). All six currents are measured using LEM sensors and DSPs perform closed loop inverter phase current control, using digital form of the ramp-comparison method. Inverter switching frequency is 10 kHz. The first inverter controls inverter A, C, E currents, while the second inverter controls B, D, F currents of Fig. 1. This means that all six currents are controlled, although there are only five independent currents. This is obviously not an ideal solution. However, it is an unavoidable consequence of the adopted realization, where internal DSPs of the two inverters are used for current control.

The inverter current references are passed to the DSPs from a PC, through a dedicated interface card. The control code operates on the PC and is written in C. It performs closed loop speed control and calculations according to (2) and (3), on the basis of the indirect rotor flux oriented control schemes of Figs. 2 and 3. The six-phase (50 Hz, 6-pole) induction machine and the three-phase (150 Hz, 6-pole) PMSM are equipped with resolvers and control operates in the position-sensored mode. Both machines run under no-load conditions, except for the loading/unloading transients. A series of experimental tests are performed in order to verify the independence of the control of the two machines. The six-phase machine is coupled to a dc generator, while the PMSM has an inertial wheel mounted on the shaft (Fig. 4).

V. EXPERIMENTAL RESULTS

The approach adopted in the experimental investigation is the following. The six-phase induction machine is excited and both machines are then brought to a certain steady-state operating speed. A speed transient is initiated next for one of the two machines, while the speed reference of the other machine is left unaltered. Provided that the control is truly decoupled, operating speed of the machine running at constant speed must not change when the transient is initiated for the other machine. However, due to the fast action of the speed controller, some very small variations of the speed could be unobservable. The ultimate proof of the truly decoupled control is therefore the absence of any variation in the stator q-axis current command of the machine running at constant speed, since this indicates absence of any speed error at the input of the speed controller. Experimental results, shown in what follows, include stator q-axis current commands (peak value) and measured speed responses of the both machines, inverter current reference and actual inverter current for one of the six phases, and individual phase current references of the two machines.

In the first test, six-phase machine runs at 500 rpm and the three-phase PMSM is initially at 0 rpm. Step speed command of 800 rpm is then given to the PMSM. Results of this acceleration test are shown in Fig. 5. Since the PMSM is not loaded, its steady-state current is practically zero at all speeds, as evidenced by its phase c current reference in Fig. 5. Speed of the six-phase machine, as well as its stator q-axis current reference, remain completely undisturbed during the acceleration transient of the PMSM, indicating complete decoupling of the control. Measured and reference inverter phase current are in excellent agreement in both steady state and transient operation (a small dc offset, related to the measurement procedure, is present in some traces of the measured inverter current and is to be disregarded in the comparison).

The situation is reversed in the second test, where the speed of the PMSM is held constant (at 300 rpm), while the six-phase machine is accelerated from 0 to 600 rpm. The results are given in Fig. 6, from which it can be observed that there is some minor impact of the transient on the three-phase PMSM. It is reflected in the change of the ripple characteristics of the speed response and the stator q-axis current reference and its source will be discussed later. However, this coupling is sufficiently small to be regarded as negligible for practical purposes.

In the subsequent two tests one machine is held at standstill, while the other machine is reversed. At first the PMSM is reversed from -500 to 500 rpm (Fig. 7). Next, the six-phase machine is reversed from -500 to 500 rpm, with the PMSM at standstill (Fig. 8). Reversing transients of Figs. 7 and 8 indicate practically perfect decoupling of the control of the two machines.

Deceleration of the PMSM from 900 to 0 rpm, with the six-phase machine running at 500 rpm, is depicted in Fig. 9. Again, excellent decoupling of dynamics is achieved, since no variation whatsoever of the six-phase machine's speed and q-axis current takes place. Thus initiation of a transient for a three-phase

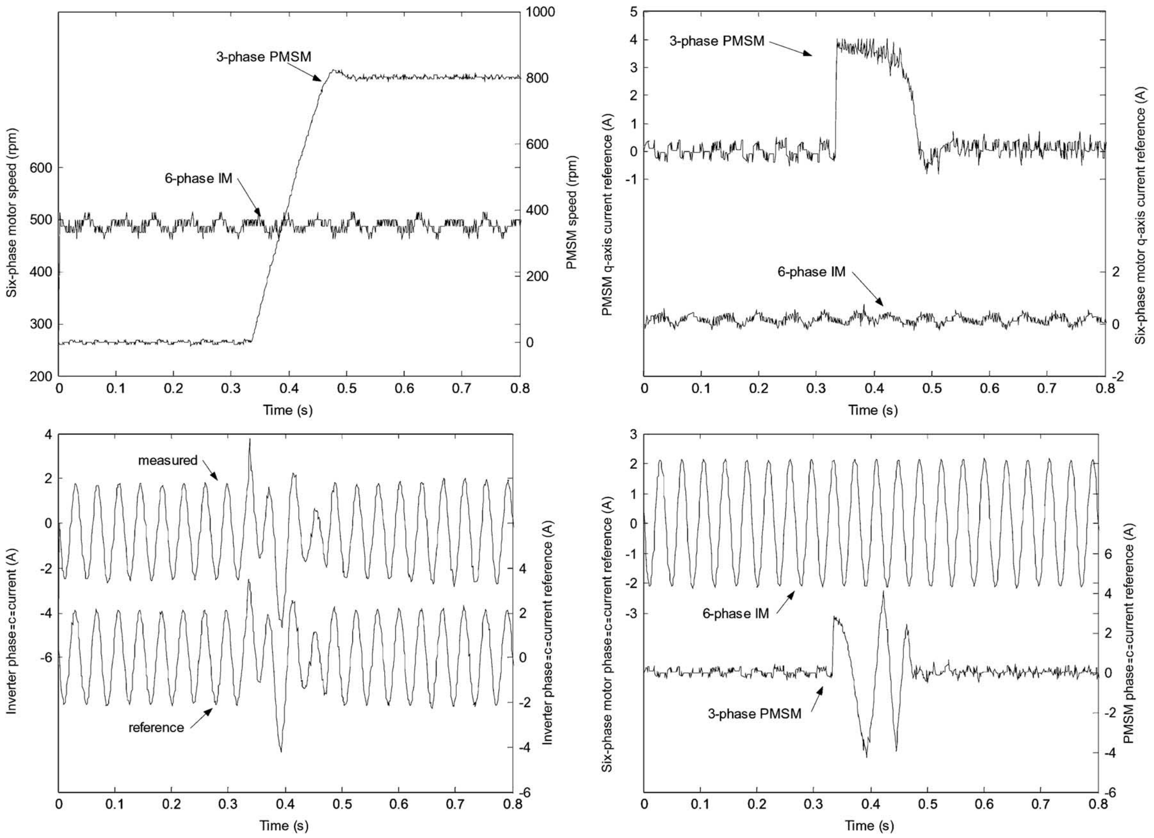

Fig. 5. Behavior of the two-motor drive during PMSMs acceleration from 0 to 800 rpm (six-phase machine at 500 rpm).

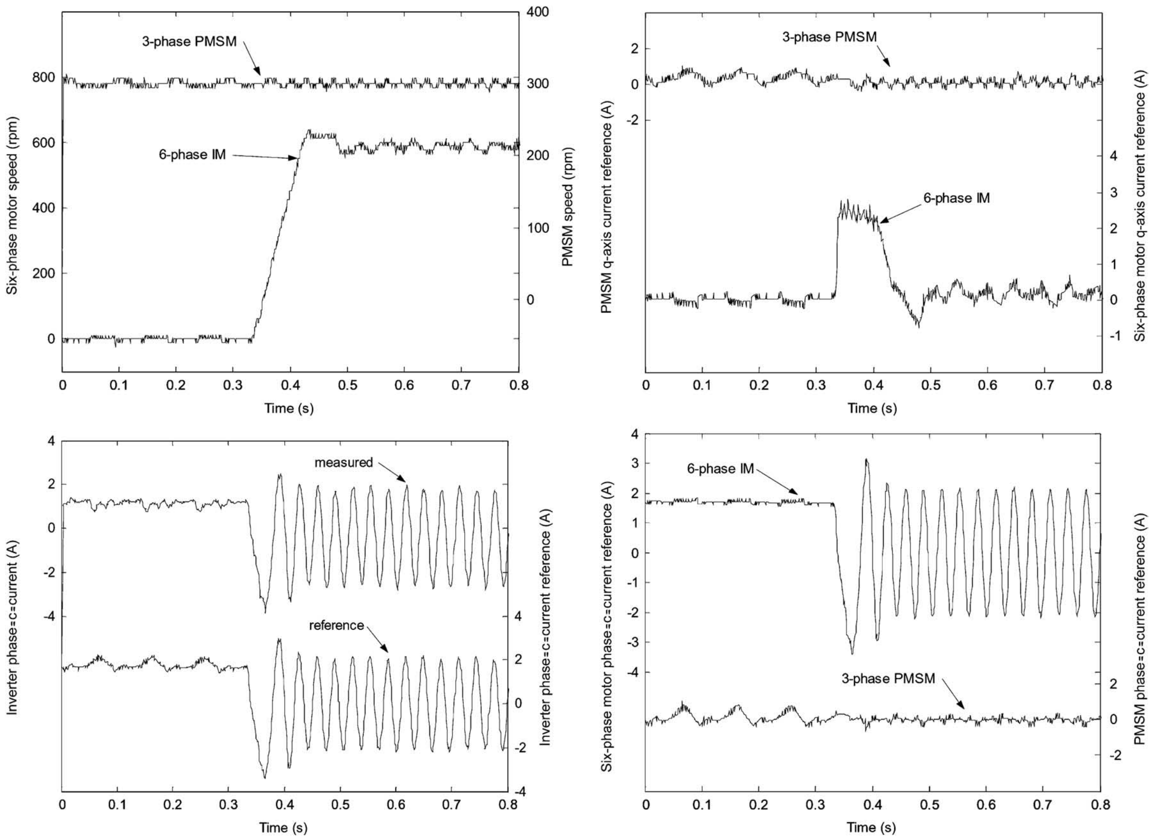

Fig. 6. Behavior of the two-motor drive during six-phase machine’s acceleration from 0 to 600 rpm (PMSM at 300 rpm).

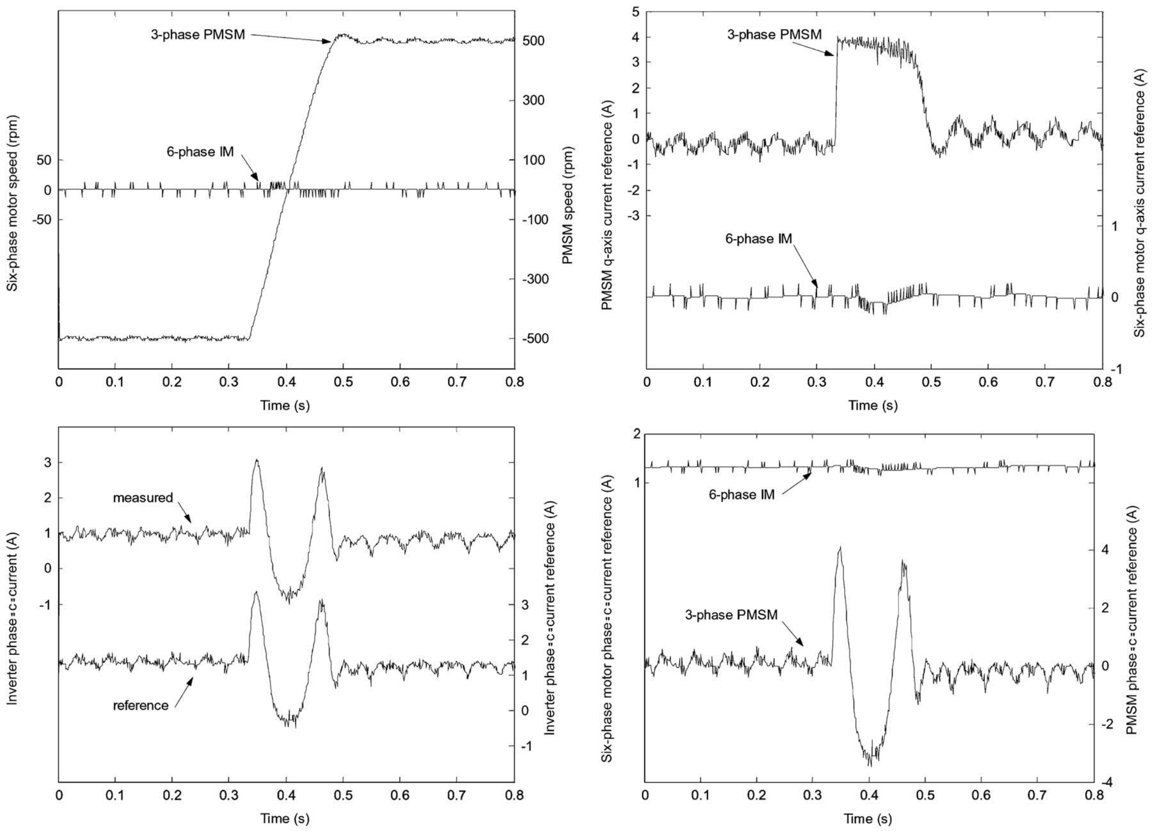

Fig. 7. Drive behavior during PMSM's reversal from −500 to 500 rpm with six-phase machine at standstill.

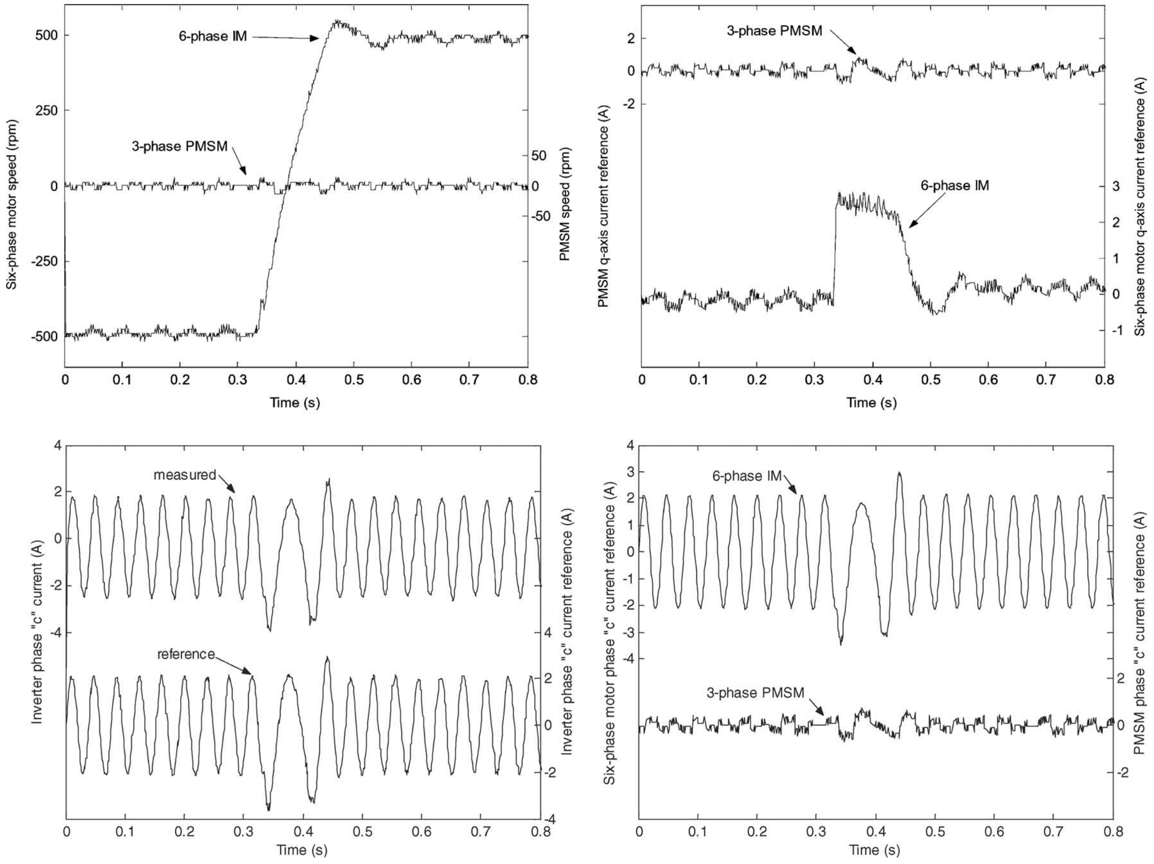

Fig. 8. Drive behavior during six-phase machine's reversal from −500 to 500 rpm with PMSM at standstill.

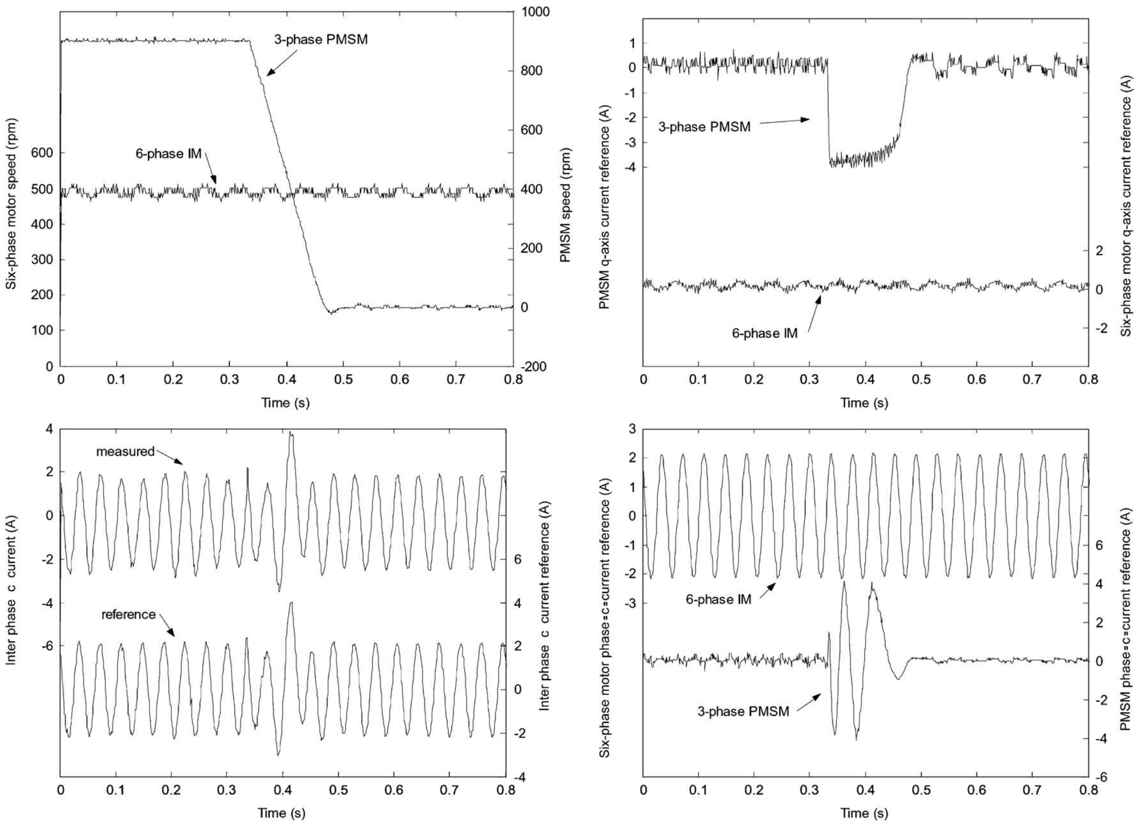

Fig. 9. Deceleration of the PMSM from 900 to 0 rpm, with the six-phase machine running at 500 rpm.

machine does not affect the behavior of the six-phase machine at all.

The last two transients, illustrated in Figs. 10 and 11 (only speed and stator q-axis current reference are shown), are the step loading and step unloading of the six-phase machine, with the PMSM running at constant speed. Traces of the PMSM's stator q-axis current reference and speed response in Figs. 10 and 11 show that loading/unloading of the six-phase machine has no consequence on the operation of the PMSM, since no disturbance of any kind appears in these traces.

VI. DISCUSSION

The theory of independent control of series-connected multiphase multimotor drives is developed under the assumption of sinusoidal flux distribution in the air-gap. One can therefore expect that any deviation from such a distribution will lead to the interaction of the higher spatial harmonics in one machine with flux/torque producing currents of the other machines of the group. However, it can be shown that the specific six-phase two-motor drive configuration, considered here, is an exception from this rule. No interaction between the higher spatial magnetomotive force harmonics of the six-phase machine and the flux/torque producing currents of the three-phase machine can take place as long as the spatial distribution is symmetrical around the air-gap, so that only odd harmonics exist. In other words, even a concentrated winding machine with rectangular winding functions can be used. The experimental results, related to transients of the three-phase PMSM (Figs. 5, 7, and 9)

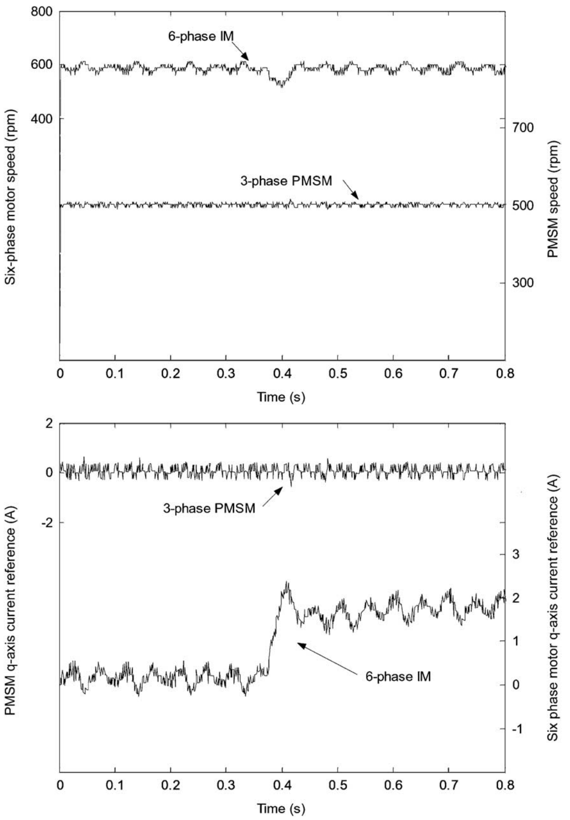

Fig. 10. Step loading of the six-phase machine at 600 rpm, with PMSM running at 500 rpm.

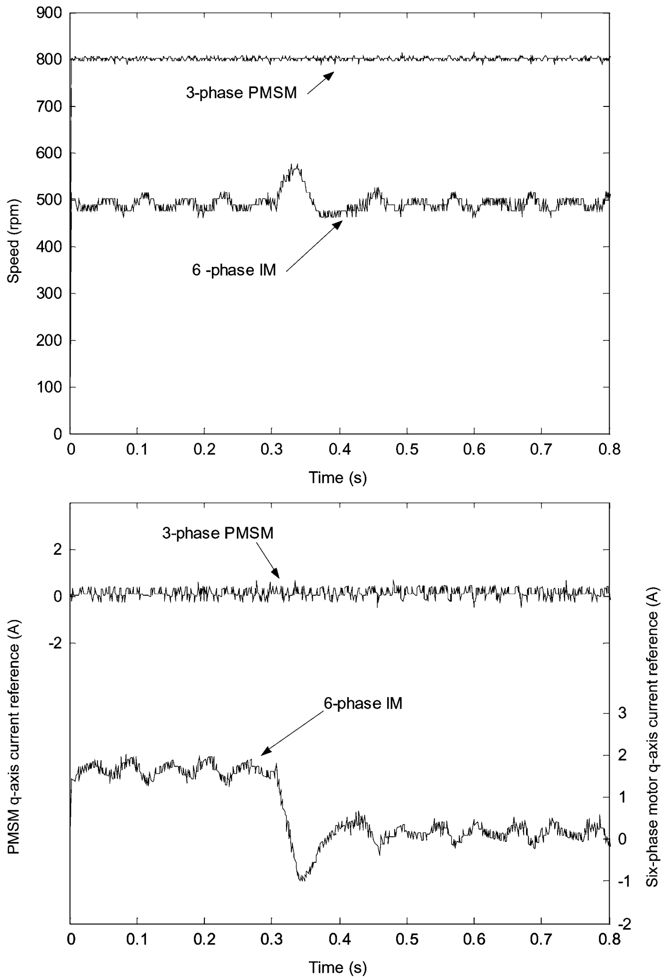

Fig. 11. Step unloading of the six-phase machine at 500 rpm with PMSM running at 800 rpm.

fully confirm this statement, since initiation of a transient for the PMSM does not have any impact on speed and stator q-axis current of the six-phase machine.

Six-phase motor flux/torque producing currents should, according to the presented theory, cancel at the point of connection with the three-phase machine. Hence, six-phase machine transients should not have any impact on the three-phase machine behavior. While this is satisfied completely in Figs. 10 and 11 and to a large extent in Fig. 8, some minor interaction, leading to a change in the ripple characteristics in speed and stator q-axis current of the PMSM, can be observed in Fig. 6. It has been established during the course of experimental work that the cancellation of the six-phase machine's flux/torque producing currents at the points of connection with the three-phase machine is not always perfect and this is believed to be the source of this minute interaction, caused by the control of all six inverter phase currents (instead of only five current axis components).

Last, but not least, certain amount of ripple is present at all times in the traces of the six-phase machine's speed and stator q-axis current, in addition to the measurement noise. However, these ripples are not in any way associated with the three-phase PMSM, since they exist even when the six-phase machine is operated on its own (i.e., with the three-phase PMSM disconnected). To prove this statement, Fig. 12 illustrates a reversing transient for the six-phase machine operated as a single vector-controlled drive, which corresponds to the transient of Fig. 8 (except for the q-axis current limit, which is set to a higher value in Fig. 12). Comparison of Figs. 8 and 12 clearly shows that the speed and stator q-axis current traces are the same, regardless of whether the three-phase PMSM is connected in series or not. Hence the ripples are inherent to the six-phase machine and are assigned to some asymmetries in the machine design.

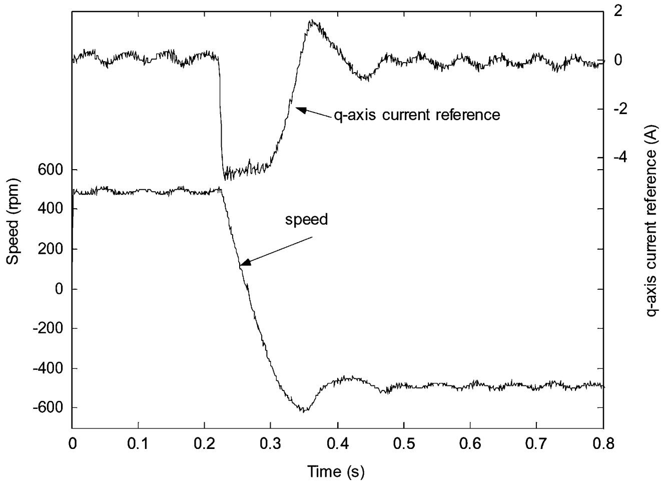

Fig. 12. Speed reversal of the six-phase machine (from 500 rpm to −500 rpm) with disconnected three-phase PMSM.

VII. CONCLUSION

The paper examines a six-phase series-connected two-motor drive system, comprising a custom-made symmetrical six-phase machine and a commercially available three-phase servo PMSM, supplied from a single six-phase current controlled voltage source inverter. Basic operating principles of this system are reviewed and a brief description of the experimental setup is given. This is followed by presentation of results collected in the experiments, for a range of transients (acceleration, deceleration, speed reversal, step loading/unloading). Practically perfect decoupling of the control of two machines is achieved, as verified by the experimental results.

The two-motor drive of the type described in this paper is seen as particularly well suited to applications requiring independent control of a large power motor for main motion control and a small power motor for auxiliary motion control. In the context of the existing six-phase motor drive applications and trends, surveyed in the Introduction, the future for the proposed two-motor drive is seen in traction and EV/HEV applications, as well as in electric ship propulsion. The six-phase high-power machine would be used as the main source of propulsion power, while the three-phase low-power motor would perform an auxiliary function. This is so since the three-phase motor remains unaffected by the series connection. On the other hand, as the three-phase machine's flux/torque producing currents flow through the six-phase machine, the inevitable consequence of the series connection is an increase in the stator winding losses of the six-phase machine. However, the increase in the stator winding losses will be negligible provided that the six-phase machine is of a large power rating while the three-phase machine is of a comparably small power rating.

REFERENCES

[1] S. Williamson and S. Smith, "Pulsating torques and losses in multiphase induction machines," *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 986–993, 2003.

[2] S. Green, D. J. Atkinson, A. G. Jack, B. C. Mecrow, and A. King, "Sensorless operation of a fault tolerant PM drive," *Inst. Elec. Eng. Proc.—Electr. Power Appl.*, vol. 150, no. 2, pp. 117–125, Sep. 2003.

[3] J. B. Wang, K. Atallah, and D. Howe, "Optimal torque control of fault-tolerant permanent magnet brushless machines," *IEEE Trans. Magn.*, vol. 39, no. 5, pp. 2962–2964, Sep. 2003.

[4] R. H. Nelson and P. C. Krause, "Induction machine analysis for arbitrary displacement between multiple winding sets," *IEEE Trans Power App. Syst.*, vol. PAS-93, pp. 841–848, 1974.

[5] M. Steiner, R. Deplazes, and H. Stemmler, "A new transformerless topology for AC-fed traction vehicles using multi-star induction motors," *EPE J.*, vol. 10, no. 3–4, pp. 45–53, 2000.

[6] R. O. C. Lyra and T. A. Lipo, "Torque density improvement in a six-phase induction motor with third harmonic current injection," *IEEE Trans. Ind. Appl.*, vol. 38, pp. 1351–1360, 2002.

[7] D. Hadiouche, H. Razik, and A. Rezzoug, "On the modelling and design of dual-stator windings to minimize circulating harmonic currents for VSI fed AC machines," *IEEE Trans. Ind. Appl.*, vol. 40, no. 2, pp. 506–515, 2004.

[8] R. Bojoi, M. Lazzari, F. Profumo, and A. Tenconi, "Digital field-oriented control for dual three-phase induction motor drives," *IEEE Trans. Ind. Appl.*, vol. 39, no. 3, pp. 752–760, 2003.

[9] E. Levi, M. Jones, and S. N. Vukosavic, "Even-phase multi-motor vector controlled drive with single inverter supply and series connection of stator windings," *Inst. Elec. Eng. Proc.—Electr. Power Appl.*, vol. 150, no. 5, pp. 580–590, 2003.

[10] E. Levi, M. Jones, S. N. Vukosavic, and H. A. Toliyat, "A novel concept of a multi-phase, multi-motor vector controlled drive system supplied from a single voltage source inverter," *IEEE Trans. Power Electron.*, vol. 19, pp. 320–335, 2004.

[11] ——, "Operating principles of a novel multi-phase multi-motor vector controlled drive," *IEEE Trans. Energy Convers.*, vol. 19, no. 3, pp. 508–517, 2004.

[12] S. Gataric, "A polyphase Cartesian vector approach to control of polyphase AC machines," in *Proc. IEEE Ind. Appl. Soc. Annual Meeting IAS*, Rome, Italy, 2000, Paper 38-02.

[13] A. Iqbal and E. Levi, "Modelling of a six-phase series-connected two-motor drive system," in *Proc. Int. Conf. on Electrical Machines ICEM*, Krakow, Poland, 2004, CD-ROM Paper 98.

[14] K. K. Mohapatra, M. R. Baiju, and K. Gopakumar, "Independent speed control of two six-phase induction motors using a single six-phase inverter," *EPE J.*, vol. 14, no. 3, pp. 49–62, 2004.

[15] M. Jones, S. N. Vukosavic, and E. Levi, "Independent vector control of a six-phase series-connected two-motor drive," in *Proc. 2nd IEE Int. Conf. Power Electronics, Machines and Drives PEMD*, Edinburgh, U.K., 2004, pp. 879–884.

[16] M. Jones, E. Levi, and A. Iqbal, "A five-phase series-connected two-motor drive with current control in the rotating reference frame," in *Proc. IEEE Power Elec. Spec. Conf. (PESC)*, Aachen, Germany, 2004, pp. 3278–3284.

Emil Levi (S'89–M'92–SM'99) was born in Zrenjanin, Yugoslavia in 1958. He received the Dipl.Ing. degree from the University of Novi Sad, Yugoslavia, in 1982 and the M.Sc. and Ph.D. degrees from the University of Belgrade, Yugoslavia, in 1986 and 1990, respectively.

From 1982 to 1992, he was with the Department of Electrical Engineering, University of Novi Sad. He joined Liverpool John Moores University, Liverpool, U.K., in May 1992 and since September 2000, he has been Professor of Electric Machines and Drives. He has published extensively in major journals and conference proceedings.

Martin Jones was born in Liverpool, U.K., in 1970. He received the B.Eng. degree (Hons.) from the Liverpool John Moores University, Liverpool, in 2001. He received the Ph.D. degree in 2005.

Currently, he is a Postdoctoral Research Associate with Liverpool John Moores University. He was a Research Student with the Liverpool John Moores University from 2001 until 2005. His areas of research interest are vector control of ac machines and power electronics.

Dr. Jones is a recipient of the IEE Robinson Research Scholarship for his Ph.D. studies.

Slobodan N. Vukosavic (M'93) was born in Sarajevo, Bosnia and Hercegovina, Yugoslavia, in 1962. He received the B.S., M.S., and Ph.D. degrees from the University of Belgrade, Yugoslavia, in 1985, 1987, and 1989, respectively.

He was employed in the Nikola Tesla Institute, Belgrade, until 1988, when he joined the ESCD Laboratory of Emerson Electric, St. Louis, MO. Since 1991, he has been the Project Leader with the Vickers Co., Milano, Italy. He has published extensively and has completed over 40 large R/D andbreak industrial projects.