VECTOR CONTROL SCHEMES FOR SERIES-CONNECTED SIX-PHASE TWO-MOTOR DRIVE SYSTEMS

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ABSTRACT
A novel concept for multi-drive systems, based on utilisation of multi-phase machines, has been introduced recently. It has been shown that, by connecting in series stator windings of the multi-phase machines in an appropriate manner, it becomes possible to control all the machines in the group independently using vector control principles, although the whole drive system is supplied from a single multi-phase voltage source inverter (VSI). The concept has been investigated so far only for true n-phase machines (i.e., machines with spatial displacement between any two consecutive phases equal to $2\pi/n$) and all the available considerations are restricted to the inverter current control in the stationary reference frame. Moreover, all the available proofs of the decoupled dynamic control within these multi-drive systems are simulation based. This paper concentrates on one specific case, a two-motor series-connected six-phase drive supplied from a six-phase VSI, and provides three main contributions. The two-motor drive system, based on utilisation of a true six-phase machine is considered first and, in addition to inverter current control in the stationary reference frame, inverter current control in the rotating reference frame is analysed as well. It is shown that this method of current control requires modifications of the decoupling voltage terms, compared to those valid for a single-motor drive, this being caused by series connection of the two machines. Next, two-motor drives based on utilisation of quasi six-phase machines (with two three-phase stator windings displaced by 30°) are discussed and appropriate connection diagrams are developed. Verification of these schemes is provided by simulation. Finally, an experimental rig, which utilises a true six-phase machine connected in series with a three-phase machine and inverter current control in the stationary reference frame, is described and experimental verification of the decoupled dynamics of the two machines is provided for the first time by extensive testing.

1 INTRODUCTION

Six-phase ac motor drives are often considered as a viable solution when reduction of the inverter per-phase rating is required due to the high motor power. Although the basic concept is old [1], there has been an upsurge in the interest in this type of ac motor drive in recent times [2]-[5]. The standard choice is a six-phase induction or synchronous machine with two three-phase windings on stator. The spatial displacement between the two three-phase windings is 30° (quasi six-phase, dual three-phase or split-phase machine). The main reason for selecting the asymmetrical six-phase winding instead of a true six-phase winding (60° displacement between
any two consecutive phases) has been discussed in detail in [1] and is in essence the possibility of reducing the torque ripple, caused by low order stator current harmonics. The torque ripple’s dominant frequency is shifted from six to twelve times the supply frequency and the magnitude is significantly attenuated. This advantage of a quasi six-phase machine arrangement was of great importance in pre-PWM era of VSI control, when six-step VSIs were used. However, with modern inverter current control techniques and operation of the VSI in PWM mode, this property of quasi six-phase machines becomes somewhat irrelevant, since the low frequency harmonics can be easily suppressed from the inverter output currents. Both true six-phase and quasi six-phase machines are considered in this paper, in the context of a series-connected two-motor drive system supplied from a single six-phase inverter.

Vector control of any ac machine, regardless of the number of phases, requires only two stator currents. This fact was utilized in [6] to develop a five-phase series-connected two-motor drive, supplied from a single five-phase VSI, with independent dynamic control of the two machines. In order to realise independent vector control it is necessary to introduce an appropriate phase transposition when connecting the stator windings in series. The concept has been further generalised to all the possible odd and even phase numbers in [7] and [8], respectively, where the rules for series connection have been established, maximum number of motors connectable in series as a function of the system phase number has been explored and appropriate connection diagrams for various phase numbers have been given. Some specific system phase numbers have been elaborated in more detail in [9], [10] and [11] (two-motor five-phase drive, seven-phase three-motor drive and nine-phase four motor drive, respectively). There are a couple of common features of all these studies. First of all, only true \( n \)-phase machines, with spatial displacement between any two consecutive phases equal to \( 2\pi/n \), have been considered. Secondly, it has been assumed that the inverter current control is exercised in the stationary reference frame upon inverter phase currents. Finally, the verification of the concept has always been provided by simulation only and there is no evidence of any experimental study that would confirm the existence of decoupled dynamic control within a series-connected multi-phase multi-motor drive system.

This paper deals with one specific series-connected multi-phase multi-motor drive system, the six-phase two-motor drive, and aims at advancing the current knowledge in this area by removing the three limitations of the existing studies, listed above. A two-motor drive based on a true six-phase machine is discussed first and, in addition to the inverter current control in the stationary reference frame, current control in the rotating reference frame is examined as well. It is shown that, when current control in the rotating reference frame is applied, it becomes necessary to modify the voltage decoupling terms used in creation of the inverter voltage \( d-q \) axis references in order to provide full decoupling of the control of the two machines. This need arises due to the series connection of the two machines. Simulation results are used to verify these findings. Next, a quasi six-phase machine is considered and it is shown that the possibility of independent vector control exists in this case as well. Again, two machines can be controlled independently provided that the stator windings are connected in an appropriate way. Connection diagrams are given and decoupling of the dynamics is verified by simulation. Finally, an experimental rig based on the true six-phase machine and current control in the stationary reference frame is described and experimental results related to the operation of the series-connected two-motor drive with a true six-phase machine are presented. The existence of the fully decoupled dynamic control within a series-connected multi-phase multi-motor drive is thus verified for the first time experimentally.
2 TWO-MOTOR DRIVE WITH A TRUE SIX-PHASE MACHINE

The connection diagram for stator windings of the two machines, which will enable independent vector control, has been established in [8] and is shown in Fig. 1. As explained in [8], the two-motor drive is realised by connecting in series with a true six-phase machine (Machine 1) a three-phase machine (Machine 2). Although the type of the ac machine is irrelevant (the only requirement is sinusoidal distribution of the field), induction machines are utilised throughout this paper. Indirect vector control in the constant rotor flux region is examined in all the cases. Source (VSI) phases are identified in Fig. 1 with capital letters, while lower case letters denote machine phases.

![Fig. 1. A six-phase series-connected two-motor drive.](image)

2.1 Current control in the stationary reference frame

The indirect vector controller is the same for both machines and is illustrated for an \( n \)-phase machine (\( n = 6 \) or \( n = 3 \)) in Fig. 2, [8]. Individual phase current references of the two machines are given with [8]:

\[
\begin{align*}
  i_{q1}^* &= k_1[i_{d1}^* \cos \phi_1 - i_{q1} \sin \phi_1] \\
  i_{b1}^* &= k_1[i_{d1}^* \cos(\phi_1 - \alpha) - i_{q1}^* \sin(\phi_1 - \alpha)] \\
  i_{f1}^* &= k_1[i_{d1}^* \cos(\phi_1 - 5\alpha) - i_{q1}^* \sin(\phi_1 - 5\alpha)] \\
  i_{q2}^* &= k_2[i_{d2}^* \cos \phi_2 - i_{q2}^* \sin \phi_2] \\
  i_{b2}^* &= k_2[i_{d2}^* \cos(\phi_2 - 2\alpha) - i_{q2}^* \sin(\phi_2 - 2\alpha)] \\
  i_{f2}^* &= k_2[i_{d2}^* \cos(\phi_2 - 4\alpha) - i_{q2}^* \sin(\phi_2 - 4\alpha)]
\end{align*}
\]

(1)

where \( \alpha = 2\pi/6 \) and \( k_1 = \sqrt{2}/6, k_2 = \sqrt{2}/3 \). They are further summed according to the connection diagram of Fig. 1 in order to create the inverter phase current references

\[
\begin{align*}
  i_{a1}^* &= i_{d1}^* + 0.5i_{d2}^* \\
  i_{b1}^* &= i_{d1}^* + 0.5i_{d2}^* \\
  i_{c2}^* &= i_{d1}^* + 0.5i_{d2}^* \\
  i_{a2}^* &= i_{d1}^* + 0.5i_{d2}^* \\
  i_{b2}^* &= i_{d1}^* + 0.5i_{d2}^* \\
  i_{c2}^* &= i_{d1}^* + 0.5i_{d2}^*
\end{align*}
\]

(2)

Inverter currents are impressed using either hysteresis current control or ramp-comparison control (the latter one is used in the experimental setup described in section 5).
2.2 Current control in the rotating reference frame

With current control in the stationary reference frame the inverter automatically adjusts the output voltages to the values required to impress currents equal to those of (2) through the series-connected stator windings. The situation however changes when current control is executed in the rotating reference frame. Individual indirect vector control scheme for the two machines is in principal the same and is illustrated in Fig. 3 for the six-phase machine. Stator \( d-q \) axis voltage references for each of the two machines are obtained by summing the outputs of stator \( d-q \) axis current PI controllers with decoupling voltages, which are, for constant rotor flux operation, given in the case of a single motor drive with

\[
e_d = -\omega_r \sigma L_s i_{q1}^*
\]

\[
e_q = \omega_r (L_s / L_r) \psi_r^*
\]

(3)

Machine phase voltage references are created using

\[
v_{q1} = k_1 [v_{d1}^* \cos \phi_{1} - v_{q1}^* \sin \phi_{1}]
\]

\[
v_{b1} = k_1 [v_{d1}^* \cos (\phi_{1} - \alpha) - v_{q1}^* \sin (\phi_{1} - \alpha)]
\]

\[
v_{q1} = k_1 [v_{d1}^* \cos (\phi_{1} - 5\alpha) - v_{q1}^* \sin (\phi_{1} - 5\alpha)]
\]

(4)

\[
v_{a2} = k_2 [v_{d2}^* \cos \phi_{2} - v_{q2}^* \sin \phi_{2}]
\]

\[
v_{b2} = k_2 [v_{d2}^* \cos (\phi_{2} - 2\alpha) - v_{q2}^* \sin (\phi_{2} - 2\alpha)]
\]

\[
v_{c2} = k_2 [v_{d2}^* \cos (\phi_{2} - 4\alpha) - v_{q2}^* \sin (\phi_{2} - 4\alpha)]
\]

and the overall inverter phase voltage references are finally calculated on the basis of the connection diagram in Fig. 1 as

\[
v_A^* = v_{a1}^* + v_{a2}^*
\]

\[
v_B^* = v_{b1}^* + v_{b2}^*
\]

\[
v_C^* = v_{c1}^* + v_{c2}^*
\]

\[
v_D^* = v_{d1}^* + v_{d2}^*
\]

\[
v_E^* = v_{e1}^* + v_{e2}^*
\]

\[
v_F^* = v_{f1}^* + v_{f2}^*
\]

(5)

A PWM method (say, space vector modulation) is further applied to impress the voltages of (5).

With current control in the rotating reference frame a problem arises due to the series connection of the two machines. The algorithm described by Fig. 3 and (3)-(5) does not recognise the existence of the additional
voltage drops in the six-phase machine, caused by the flow of the flux/torque producing currents of the three-phase machine. Since in any steady state d-q axis currents of both machines will eventually equal their references, these additional voltage drops will get compensated, through an appropriate change in the d-q axis voltage references of the three-phase machine. However, this will be accomplished at the expense of the worsened dynamics of the three-phase machine (there are no problems with regard to the six-phase machine control, since flux/torque producing currents of this machine cancel at the point of connection with the three-phase machine). In simple terms, the control is not aware of the need to create in advance the additional voltages that will be dropped on the six-phase machine. Hence compensation takes place through appearance of unwanted transient errors in the d-q axis currents of the three-phase machine.

There is a simple solution to this problem. It can be shown, using rigorous mathematical derivations that are beyond the scope of this paper, that the compensation can be achieved through a modification of the decoupling voltage terms for the three-phase machine. Instead of using (3), one now needs to calculate the decoupling voltages as

\[
\begin{align*}
ed_2 &= -\omega_r \left( \sigma_2 L_{12} \psi_{r2}^* + 0.5 L_{ib} \right) \\
\epsilon_{q2} &= \omega_r \left( L_{12} / L_{m2} \right) \psi_{r2}^* + 0.5 L_{ib} i_{dib2}^*
\end{align*}
\]  

(6)

Decoupling voltages for the six-phase machine remain the same as in (3), i.e.

\[
\begin{align*}
ed_1 &= -\omega_r \sigma_1 L_{s1} i_{q1}^* \\
\epsilon_{q1} &= \omega_r \left( L_{r1} / L_{m} \right) \psi_{r1}^*
\end{align*}
\]  

(7)

The additional terms of (6) represent the voltage dropped on the stator leakage reactance of the six-phase machine due to the flow of flux/torque producing currents of the three-phase machine through the six-phase machine. Since the terms are frequency dependent, their omission from the decoupling voltages will have more pronounced effects at higher speeds of rotation. Coefficient 0.5 takes into account that only 50% of the three-phase machine current flows through any of the phases of the six-phase machine.

Simulation studies, verifying the findings of this section, are reported in section 4.
3. TWO-MOTOR DRIVE WITH A QUASI SIX-PHASE MACHINE

Stator winding of a quasi six-phase machine consists of two three-phase windings, mutually displaced in space by 30°, as illustrated in Fig. 4. The phases of the first three-phase winding are identified with symbols \(a, b, c\), while symbols \(d, e, f\) stand for the second three-phase winding displaced by 30° with respect to the first one. The neutral points of the two windings are normally kept isolated to prevent the stator current harmonics of the order divisible by three from flowing. The decoupling transformation matrix for such a six-phase machine is given with [4]

\[
C = \begin{bmatrix}
1 & \cos 2\pi/3 & \cos 4\pi/3 & \cos \pi/6 & \cos 5\pi/6 & \cos 9\pi/6 \\
0 & \sin 2\pi/3 & \sin 4\pi/3 & \sin \pi/6 & \sin 5\pi/6 & \sin 9\pi/6 \\
1 & \cos 4\pi/3 & \cos 8\pi/3 & \cos 5\pi/6 & \cos \pi/6 & \cos 9\pi/6 \\
0 & \sin 4\pi/3 & \sin 8\pi/3 & \sin 5\pi/6 & \sin \pi/6 & \sin 9\pi/6 \\
1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1
\end{bmatrix}
\]  

(8)

where the phase ordering is \(a, b, c, d, e, f\). Indirect vector controller for a quasi six-phase machine remains to be as shown in Fig. 2, the only difference being in the transformation block ‘2/n’ where individual phase current references for each machine are now created by applying (8). The possibility of connecting two machines, of the structure shown in Fig. 4, in series is investigated next. For that purpose it is assumed that both machines operate in steady state and that the required phase currents for flux and torque production in the two machines are given with sinusoidal functions of the form \((\alpha = 2\pi/3)\):

\[
\begin{align*}
    i_{a1}^* &= \sqrt{2}I_1 \sin(\omega_1 t) \\
    i_{b1}^* &= \sqrt{2}I_1 \sin(\omega_1 t - \alpha) \\
    i_{c1}^* &= \sqrt{2}I_1 \sin(\omega_1 t - 2\alpha) \\
    i_{d1}^* &= \sqrt{2}I_1 \sin(\omega_1 t - \pi/6) \\
    i_{e1}^* &= \sqrt{2}I_1 \sin(\omega_1 t - \alpha - \pi/6) \\
    i_{f1}^* &= \sqrt{2}I_1 \sin(\omega_1 t - 2\alpha - \pi/6) \\
    i_{a2}^* &= \sqrt{2}I_2 \sin(\omega_2 t) \\
    i_{b2}^* &= \sqrt{2}I_2 \sin(\omega_2 t - \alpha) \\
    i_{c2}^* &= \sqrt{2}I_2 \sin(\omega_2 t - 2\alpha) \\
    i_{d2}^* &= \sqrt{2}I_2 \sin(\omega_2 t - \pi/6) \\
    i_{e2}^* &= \sqrt{2}I_2 \sin(\omega_2 t - \alpha - \pi/6) \\
    i_{f2}^* &= \sqrt{2}I_2 \sin(\omega_2 t - 2\alpha - \pi/6)
\end{align*}
\]

(9)

**Fig. 4.** Schematic representation of a quasi six-phase (split phase, dual three-phase) machine’s stator winding.
These phase current references are generated by two vector controllers of the structure shown in Fig. 2. Next, let the inverter current references be created according to

\[
\begin{align*}
    i_a^* &= i_{a1}^* + i_{a2}^* \\
    i_b^* &= i_{b1}^* + i_{b2}^* \\
    i_c^* &= i_{c1}^* + i_{c2}^* \\
    i_d^* &= i_{d1}^* + i_{d2}^* \\
    i_e^* &= i_{e1}^* + i_{e2}^* \\
    i_f^* &= i_{f1}^* + i_{f2}^*
\end{align*}
\]  

(10)

and let the current control be ideal, so that the inverter output currents may be taken as equal to the inverter current references of (10). The inverter phase currents are identically equal to the phase currents flowing through machine 1. However, for the second machine, due to the phase transposition introduced in (10) the following holds true:

\[
\begin{align*}
    i_{a2} &= i_A^* \\
    i_{b2} &= i_C^* \\
    i_{c2} &= i_B^* \\
    i_{d2} &= i_E^* \\
    i_{e2} &= i_D^* \\
    i_{f2} &= i_F^*
\end{align*}
\]  

(11)

Application of the decoupling transformation matrix (8) on inverter currents of (10) produces two pairs of inverter current components, which are simultaneously corresponding current components of machine 1. Let the first pair be denoted with symbols \(\alpha\), \(\beta\) and let the second pair have indices \(x\), \(y\), in accordance with notation used in [7-11]. Then

\[
\begin{align*}
    i_a^{INV} + ji_b^{INV} &= i_{a1}^{M1} + ji_{b1}^{M1} = \sqrt{6}I_1\left(\sin\omega_2t - j\cos\omega_2t\right) \\
    i_x^{INV} + ji_y^{INV} &= i_{x1}^{M1} + ji_{y1}^{M1} = \sqrt{6}I_2\left(\sin\omega_2t - j\cos\omega_2t\right)
\end{align*}
\]  

(12)

Similarly, application of (8) in conjunction with (11) produces

\[
\begin{align*}
    i_{a2}^{M2} + ji_{b2}^{M2} &= \sqrt{6}I_1\left(\sin\omega_2t - j\cos\omega_2t\right) = i_{a2}^{INV} + ji_{b2}^{INV} \\
    i_{x2}^{M2} + ji_{y2}^{M2} &= \sqrt{6}I_2\left(\sin\omega_2t - j\cos\omega_2t\right) = i_{x2}^{INV} + ji_{y2}^{INV}
\end{align*}
\]  

(13)

Expressions (12)-(13) show that the flux/torque producing stator current \(\alpha\), \(\beta\) components of machine 1 appear as non flux/torque producing currents for the machine 2, and vice versa. Hence the formation of the inverter current references according to (10) leads to the possibility of independent vector control of the two series-connected quasi six-phase machines. The connection diagram, which follows directly from (10), is shown in Fig. 5. It should be noted that, due to the isolated neutral points, zero sequence stator current components (described with the last two rows of the transformation matrix (8)) cannot exist.

It is interesting to note that the same result is possible with an alternative series connection of stator windings, illustrated in Fig. 6. While in Fig. 5 series connection with an appropriate phase transposition involves interfacing of \(a\), \(b\), \(c\) three-phase windings of the two machines and interfacing of \(d\), \(e\), \(f\) three-phase windings, connection diagram of Fig. 6 involves connection of \(a\), \(b\), \(c\) windings of one machine with \(d\), \(e\), \(f\) windings of the other machine. Inverter reference current generation for the scheme of Fig. 6 is governed with

\[
\begin{align*}
    i_a^* &= i_{a1}^* + i_{a2}^* \\
    i_b^* &= i_{b1}^* + i_{b2}^* \\
    i_c^* &= i_{c1}^* + i_{c2}^* \\
    i_d^* &= i_{d1}^* + i_{d2}^* \\
    i_e^* &= i_{e1}^* + i_{e2}^* \\
    i_f^* &= i_{f1}^* + i_{f2}^*
\end{align*}
\]  

(14)

The phase currents of machine 2 are now
It can be easily verified, by application of (8) in conjunction with (14) and (15), that the same result as in (12)-(13) is obtained again (with some additional phase shifts).

The scheme shown in Fig. 5 will be verified by simulation in the next section, assuming ideal current control in the stationary reference frame. Corresponding scheme with current control in the rotating reference frame can be developed using the same approach as in section 2.2. In this case a modification of the voltage decoupling terms will be required for both machines. Decoupling voltages for the two machines are given with

\[
\begin{align*}
e_{d1} &= -\omega_1 L_{r1} \left( \sigma_1 L_{s1} + L_{b1} \right) i_{q1}^* \\
e_{q1} &= \omega_1 \left( L_{s1} / L_{m1} \right) i_{r1}^* + L_{b1} i_{d1}^* \\
e_{d2} &= -\omega_2 \left( \sigma_2 L_{s2} + L_{b2} \right) i_{q2}^* \\
e_{q2} &= \omega_2 \left( L_{s2} / L_{m2} \right) i_{r2}^* + L_{b2} i_{d2}^*
\end{align*}
\]
4 SIMULATION STUDIES

Simulation studies, described in this section, are aimed at verifying the existence of decoupled dynamic control in the two-motor series-connected six-phase drives discussed in sections 2.2 and 3. Parameters and ratings of all the machines involved are taken as equal on per-phase basis and are available in [8]. The six-phase inverter is regarded as an ideal voltage source for simulations reported in section 4.1 and as an ideal current source for simulations of section 4.2. Thus the inverter phase voltage references of (5) equal the inverter output phase voltages for current control in the rotating reference frame, and inverter phase current references of (10) equal the inverter output phase currents for current control in the stationary reference frame.

4.1 Two-motor drive with a true six-phase machine and current control in the rotating reference frame

Speed mode of operation (PI speed control) is analysed, with torque limit set to twice the rated value (20 Nm and 10 Nm, respectively, for the six-phase and the three-phase machine). Excitation is initiated first, by applying rated stator $d$-axis current references. Acceleration transients under no-load conditions are studied next. Six-phase machine (IM1) is accelerated to the rated speed (299 rad/s elec.), while three-phase machine (IM2) is accelerated to one half of the rated speed (149 rad/s elec.). Simulation results for current control in the rotating reference frame, using calculation of decoupling voltages according to (3) for both machines, are shown in Fig. 7 (rotor flux and torque responses). As can be seen from Fig. 7, a disturbance in the rotor flux of the three-phase machine appears during sudden torque reduction towards zero. It is a consequence of the incomplete decoupling, provided by (3). Stator $q$-axis current rapidly changes, causing a rapid change in the $x$-$y$ voltage drops in the six-phase machine. Since decoupling circuit is not aware of the $x$-$y$ voltage drop existence, a disturbance in the rotor flux appears. How pronounced the effect is depends on a number of the drive parameters (PI current controller parameters, stator leakage inductance of the six-phase machine, three-phase machine operating frequency, etc.). Due to the PI current control the disturbance gets compensated rather quickly. The deterioration in the dynamics is expected to be significantly more pronounced in actual realisations where it would affect the torque dynamics as well.

The same simulation is repeated once more, this time with decoupling voltage calculation according to (6)-(7). Since there are no observable differences in torque responses, these are not included and speed responses are given instead, together with rotor flux responses, in Fig. 8. As is evident from Fig. 8, the undesirable disturbance caused by the incomplete decoupling, depicted in Fig. 7, is now completely eliminated. Additional simulation results for this case are provided in Fig. 9, in order to shed more light on the occurrences within this series-connected two-motor drive. In particular, stator phase $a$ voltage references and stator phase $a$ voltages of the two machines are shown, together with inverter phase voltages and output currents for the first two phases. As can be seen from Fig. 9a, stator phase $a$ voltage of the three-phase machine almost equals the reference, the small difference only being caused by the addition of the voltage drops in the six-phase machine through modified decoupling voltage calculation in (6)-(7). However, in the case of the six-phase machine there is a much more pronounced difference, caused by the flow of the three-phase machine flux/torque producing currents through the windings of the six-phase machine. This essentially means that in the final steady state the six-phase machine phase voltage contains two sinusoidal components of two different frequencies. Inverter output voltages and currents, shown in Fig. 9b, further corroborate this statement. The existence of two
components of two different frequencies is more than evident. It should be noted however that, due to cancellation of the six-phase machine flux/torque producing currents at the point of entry into the three-phase machine, the three-phase machine is not adversely affected by the series connection with the six-phase machine. The opposite however applies to the six-phase machine, since the three-phase machine flux/torque producing currents flow through it.

![Graph](image1.png)

**Fig. 7.** Dynamics of the two-motor drive using current control in the rotating reference frame with decoupling voltage calculation according to (3).

![Graph](image2.png)

**Fig. 8.** Dynamics of the two-motor drive using current control in the rotating reference frame with decoupling voltage calculation according to (6)-(7).

### 4.2 Two-motor drive with quasi six-phase machines and current control in the stationary reference frame

A very similar study to the one reported in the previous section is repeated once more, this time for the two quasi six-phase machines connected in series according to the connection diagram of Fig. 5. Ideal current control in the stationary reference frame is assumed, so that the inverter current references of (10) are directly inputs of the two-motor drive model. Forced excitation is applied to machine 1, while machine 2 is excited with the rated rotor flux (stator $d$-axis current) reference. Upon completion of the magnetisation process, speed commands equal to rated and one half of the rated speed are applied to machine 1 and 2, respectively, in different instants in time. Rotor flux, torque and speed responses are illustrated in Fig. 10, which clearly shows a complete decoupling of the control of the two machines. To further illustrate the behaviour of the system, Fig. 11 shows stator phase $a$ current references of both machines, total inverter phase current references for the first two phases and total required inverter output phase voltages for the first two phases (obtained by calculating individual machine’s phase voltages and by summing them according to the scheme of Fig. 5). While phase current references, generated by vector controllers, have a familiar waveform, inverter phase current references...
are highly distorted due to the summation described with (10). In essence, these currents contain in final steady state two fundamental harmonics of different frequencies. The waveform of inverter currents is reflected in inverter output voltages, which again contain two fundamentals at two different frequencies. Each of these two fundamentals has two components, voltage across the machine for which the currents at the given frequency are flux/torque producing currents and voltage drop across the machine for which these currents are non flux/torque producing currents.

**Fig. 9.** Stator phase ‘a’ reference and actual voltages (a.) and inverter output voltages and currents for the first two phases (b.).

### 5 EXPERIMENTAL INVESTIGATION

A laboratory rig is constructed in order to prove the existence of decoupled dynamic control in the series-connected two-motor drive system experimentally. The rig incorporates a true six-phase machine and a three-phase machine, supplied from a double three-phase (six-phase inverter) and is illustrated in Fig. 12. Each of the two three-phase inverters is equipped with a DSP. All six currents are measured using LEM sensors and DSPs perform closed loop current control in the stationary reference frame, using 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. The inverter current references are passed to the DSPs from a PC, through a dedicated interface card. The control code is written in C and it performs closed loop speed control and calculations according to (1) and (2), on the basis of the indirect rotor flux oriented control scheme of Fig. 2. The six-phase (50 Hz, 6-pole) and the three-phase (120 Hz, 4-pole) induction machine are equipped with resolvers and control operates in the sensored mode. Both machines are running under no-load conditions, except for the loading transient. The experimental rig verifies the drive control structure of section 2.1.
Fig. 10. *Dynamics of the series-connected two-motor drive with two quasi six-phase machines and current control in the stationary reference frame.*

Fig. 11. *Stator phase ‘a’ current references of the two machines, inverter current references and inverter output voltages (two phases are illustrated) for the transients of Fig. 10.*

The approach adopted in the experimental investigation is the following. Both machines are excited and brought to a certain steady state operating speed. A speed transient is then initiated 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 the stator $q$-axis current command of both machines, measured speed responses of both machines and, in some cases, inverter current reference and actual inverter current for one of the six phases as well as individual phase current references of the two machines.
In the first test six-phase machine runs at \(-500\) rpm and acceleration transient, from 0 to 1200 rpm, is initiated for the three-phase machine. In the second test three-phase machine runs at 800 rpm while the six-phase machine is accelerated from 0 to 500 rpm. The results for the two tests are shown in Figs. 13 and 14, respectively. As can be seen from the traces of stator $q$-axis current references, initiation of the acceleration transient for one machine does not impact on dynamics of the other machine at all. This is confirmed with the corresponding speed traces as well.

The next two tests, illustrated in Figs. 15 and 16, involve reversing transients. Current traces are included in both figures, in addition to speed and stator $q$-axis reference traces. At first the six-phase machine runs at \(-600\) rpm, while the thee-phase machine is reversed from \(-300\) rpm to 300 rpm (Fig. 15). Next, the three-phase machine is kept at standstill while the six-phase machine is reversed from 300 to \(-400\) rpm (Fig. 16). As can be seen from these two figures, initiation of a reversing transient for one machine has no impact on the other machine since stator $q$-axis current reference remains unchanged. Stator phase current references for this machine therefore do not change either. Inverter current references, being determined with the summation given with (2), are complex functions which contain two sinusoidal components of different frequencies in any steady state. As is evident from Figs. 15 and 16, reference and measured inverter phase currents are in very good agreement, confirming the ability of the inverter to impose required current waveform.

The final test, illustrated in Fig. 17, is the step load application to the six-phase machine, which runs at 900 rpm, while the three-phase machine runs at 400 rpm. The applied load torque is approximately 60% of the rated six-phase machine torque. As can be seen from Fig. 17, three-phase machine is undisturbed during the loading.
Fig. 14. Three-phase machine runs at 800rpm, while six-phase machine accelerates from 0 to 500 rpm (speeds and stator q-axis current references).

Fig. 15. Six-phase machine runs at –600 rpm, while the speed of the three-phase machine is reversed from –300 to 300 rpm: a. Speed responses and stator q-axis current references; b. Stator phase current references of the two machines; c. Comparison of inverter reference and measured current.
transient, while the six-phase machine’s speed recovers to the reference in a very short time interval with a very small dip, due to the rapid build-up of the stator $q$-axis current reference. Phase current references of the two machines and the inverter reference and measured current are included again and these confirm the undisturbed operation of the three-phase machine.

6 CONCLUSION

The paper deals with six-phase two-motor drives, supplied from a single six-phase inverter, in which independent vector control of the machines can be realised by an appropriate series connection of stator windings. Both true six-phase and quasi six-phase machines are encompassed by the study. The main contributions of the paper are the development of a vector control scheme with current control in the rotating
The scheme based on a true six-phase machine is believed to hold a very good prospect for industrial applications. Six-phase motor drives are normally used in the high power region. Provided that the three-phase machine is of a low power rating, the series connection with a three-phase machine enables utilisation of the same inverter and the same controller for the two rather than one machine control. It should be noted that the three-phase machine has to be of a considerably smaller rating than the six-phase machine. This is so since the six-phase machine’s stator winding losses increase due to the series connection with the three-phase machine. On the other hand, the three-phase machine is not adversely affected in any way by the series connection. Provided that the power rating of the three-phase machine is relatively small (meaning a negligible reduction in the six-phase machine efficiency due to the series connection) and that, additionally, the three-phase motor is of low voltage rating, it should be possible to use an inverter with the more or less same voltage rating as the one that would have been used just for the six-phase machine. If the process is such that when one machine runs at high speed the other machine runs at low speed and vice versa, there should be no problem with the existing inverter voltage rating and the control of the second machine can then be accomplished at no extra cost.

On the basis of the studies reported in the paper, it is believed that the series-connected multi-motor drives are better suited to the application of inverter current control in the stationary reference frame. This is so since
full decoupling of control requires, in the case of current control in the rotating reference frame, decoupling voltages that are dependent on parameters of all the machines in the group. This applies not only to the two-motor drives covered here, but to all the other possible multi-phase multi-motor drive systems with a higher number of motors, discussed in the surveyed references.

As shown in the paper, a series-connected two-motor drive system can be realised using quasi six-phase machines as well. However, both machines are in this case quasi six-phase, meaning that both machines will suffer a loss in efficiency due to the series connection with the other machine. Whether or not the scheme is economically viable is impossible to say at this stage, but it is believed that the configuration does deserve a further research effort.

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8 LIST OF PRINCIPAL SYMBOLS

\[ v, i, \quad \text{voltage and current, respectively} \]
\[ \omega_{\delta}, \omega, \omega \quad \text{angular slip frequency, angular speed of the rotor flux space vector and rotor speed, respectively} \]
\[ L_{ls}, L_s, L_m \quad \text{stator leakage inductance, stator self-inductance and magnetising inductance, respectively} \]
\[ L_r \quad \text{rotor self-inductance} \]
\[ \sigma \quad \text{total leakage coefficient (} \sigma = 1 - \frac{L_m^2}{L_s L_r} \text{)} \]
\[ P \quad \text{number of pole pairs} \]
\[ p \quad \text{Laplace operator} \]
\[ \phi \quad \text{instantaneous angular position of the rotor flux} \]
\[ \psi_r \quad \text{rotor flux magnitude} \]
\[ e \quad \text{decoupling voltages} \]

Indices:
\[ s \quad \text{stator} \]
\[ \alpha, \beta \quad \text{the first pair of axis components after decoupling transformation} \]
\[ d, q \quad \text{the first pair of axis components in rotor flux oriented reference frames} \]
\[ x, y \quad \text{the second pair of axis components} \]
\[ n \quad \text{rated value} \]
\[ 1, 2 \quad \text{machine 1, machine 2} \]

Superscripts:
\[ * \quad \text{reference values} \]
\[ \text{INV} \quad \text{inverter} \]

9 REFERENCES


