A Five-Phase Two-Machine Vector Controlled Induction Motor Drive Supplied from a Single Inverter

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Summary

Two-motor drive systems, which require independent control of the two machines, are nowadays traditionally realised by using two three-phase voltage source inverters supplying independently two machines, paralleled to the common DC-link (Fig. 1). However, application of power electronics in electric drives enables utilisation of AC-machines with a phase number higher than three. If the number of phases is increased to five, an entirely different solution for the realisation of a two-motor drive system becomes feasible. It is shown in the paper that an increase of the stator phase number to five enables completely independent vector control of two five-phase machines that are supplied from a single current-controlled voltage source inverter. In order to achieve such an independent control it is necessary to connect five-phase stator windings of the two machines in series and perform an appropriate phase sequence transposition (Fig. 2). The concept is equally applicable to any five-phase AC machine type and its major advantage, compared with an equivalent two-motor three-phase drive, is the saving of one inverter leg. Instead of six inverter legs, only five are required. Detailed verification of the novel five-phase two-motor drive configuration is provided by simulating the operation in the torque and speed mode, using indirect rotor flux oriented control principles. The concept can be extended to higher number of phases in a simple manner. Its main advantages and drawbacks are addressed as well.

Introduction

Numerous applications, such as in textile manufacturing, paper mills, winders and electric vehicles, require more than one variable speed electric drive. In the existing solutions a multi-drive system is realised with a common DC-link, while each AC-machine has its own voltage source inverter (VSI) as the supply. Machines and inverters used in these multi-drive systems are nowadays three-phase. Each machine can be controlled independently from the other machines. The standard concept of a multi-drive system is illustrated in Fig. 1 for the two three-phase machines. A method that would enable completely independent control of at least two AC machines of different ratings and under different speed and loading conditions, while using only one VSI, does not exist. Such an algorithm is not possible in the three-phase case. The existing attempts to utilise a single three-phase inverter for supply and vector control of two or more three-phase machines connected in parallel are restricted to situations where speeds and loading of the machines are ideally the same [1-3]. In traditional electric machine applications a three-phase stator winding is selected, since the three-phase supply is readily available. However, when an AC-machine is supplied from an inverter, the need for a pre-defined number of phases on stator, such as three, disappears and other phase numbers can be chosen.

Probably the first proposal of a multiphase variable-speed electric drive dates back to 1969 [4]. While [4] proposed a five-phase induction machine, six-phase (double star) stator winding supplied from a six-phase inverter was examined in [5, 6]. The early interest in multiphase machines was caused by the possibility of reducing the torque ripple in inverter fed machines, when compared to the three-phase case. Another advantage of a multiphase motor drive over a three-phase motor drive is the improved reliability [7-10]. If one phase is open-circuited due to a fault, the machine can still be operated satisfactorily [10], in contrast to three-phase machines. Fault tolerance is one of the main reasons

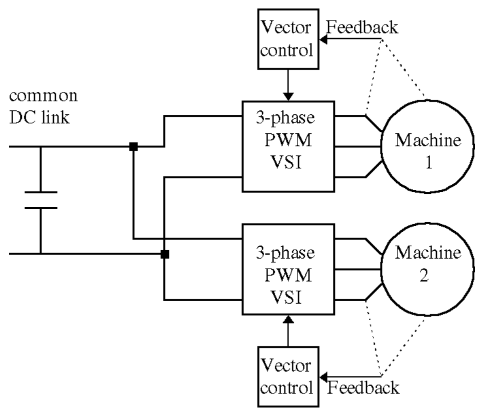


Fig. 1: Standard multi-motor drive system (two machines) with common DC link and a separate inverter for each machine.

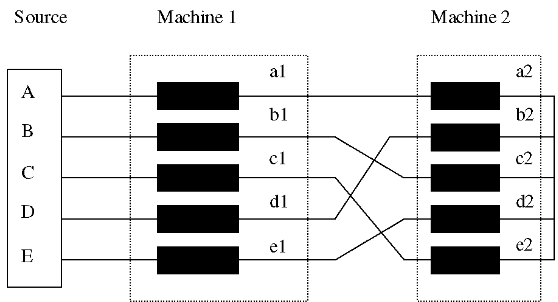


Fig. 2: Connection of two five-phase machines

behind the application of six-phase (double-star) and nine-phase (triple-star) induction motor drives in locomotives [7, 8]. The other main reason is that for a given motor power an increase of the number of phases enables reduction of the power per phase, which translates into a reduction of the power per inverter leg (that is, a semiconductor rating). Multiphase machines are therefore often considered for and applied in high power applications. A 1400 kW permanent magnet nine-phase synchronous generator is described in [11], while a six-phase 25 MW synchronous motor drive for a turbo-compressor set is elaborated in [12]. Other advantages of multiphase machines over their three-phase counterparts include an improvement in the noise characteristics [13] and a possibility of reduction in the stator copper loss, leading to an improvement in the efficiency [14].

The most frequently discussed multiphase machines are five-phase and six-phase (double-star). A seven-phase machine was considered in [15], while a nine-phase drive (triple-star) was proposed in [8, 11]. Multiphase configurations for all the AC-machine types are covered in the existing literature. Recent surveys of the state-of-the art in this area [16, 17] indicate an ever increasing interest in multiphase machines within the scientific community world-wide. Vector control principles can be extended from a three-phase to a multiphase machine in a simple manner. For example, a vector control scheme for a five-phase synchronous reluctance machine is detailed in [18], while vector control of a five-phase induction machine is elaborated in [19].

The purpose of this paper is to develop a five-phase vector controlled induction motor drive in which stator windings of the two machines are connected in series, with an appropriate phase transposition, and the supply is a single current-controlled VSI. Such a connection, as shown in the paper, enables completely independent vector control of the two machines, meaning that there are no restrictions on the power rating, speeds and loading of the two machines. The machine type is irrelevant in the context of this paper, since the basic idea applies equally to multiphase induction and synchronous motors (all versions) with sinusoidal field distribution. The only requirement is that the supply currents are sinusoidal (neglecting harmonics due to PWM inverter supply) and that the applied VSI is current-controlled, since vector control is applied. The idea behind this drive system was for the first time floated in [20], where the concept of an *n*-dimensional space for an *n*-phase machine [21, 22] was applied in the analysis. The concept is developed here using general theory of electric machines [23, 24] in a systematic way. The proposed two-motor drive system is verified by detailed simulation studies for torque and speed mode of operation. The advantages and shortcomings of the concept are highlighted.

Since the inception of the original version of this paper in 2002 and its subsequent presentation at EPE 2003, the authors have significantly advanced the knowledge in the area of series-connected multi-phase multi-motor drives [25-28]. The case considered in this paper in detail is only one particular configuration, since series-connected multi-phase multi-motor drive systems can be realised for any phase number greater than or equal to five. The number of connectable machines and the configurations for series connection are detailed in [25] and [26], for all possible odd and even supply phase numbers, respectively. Detailed d-q modelling of the complete series-connected five-phase two-motor drive is reported in [27], where simulation model, in contrast to this paper, includes current controllers and the voltage source inverter. Finally, the experimental proof of the existence of the decoupled dynamic control within a series-connected two motor drive system is contained in [28], where a six-phase two-motor drive is examined (consisting of a three-phase motor connected in series with a six-phase motor and supplied from a six-phase inverter). The experimental rig comprising two five-phase series-connected induction machines is currently in the commissioning stage and experimental results for the drive system considered in this paper will be reported in near future.

Modelling of a five-phase induction machine

A five-phase induction machine is characterised with the spatial displacement between phases of 72 degrees. The rotor winding is, for the sake of generality, treated as an equivalent five-phase winding, of the same properties as the stator winding. It is assumed that the rotor winding has already been referred to stator winding, using winding transformation ratio, so that the maximum value of the mutual stator to rotor inductance terms equals in value mutual inductance within the five-phase stator winding and mutual inductance within the five-phase rotor winding (M). The standard assumptions are applied in the modelling, inclusive of those assuming linearity of the magnetic circuit and sinusoidal spatial distribution of the field. A five-phase induction machine can then be described with the following equations in matrix form (underlined symbols) in terms of phase variables:

$$
\begin{aligned}
\underline{v}^{s}_{abcde} &= \underline{R}_{s}\,\underline{i}^{s}_{abcde} + \frac{d\underline{\psi}^{s}_{abcde}}{dt} \\
\underline{\psi}^{s}_{abcde} &= \underline{L}_{s}\,\underline{i}^{s}_{abcde} + \underline{L}_{sr}\,\underline{i}^{r}_{abcde} \\
\underline{v}^{r}_{abcde} &= \underline{R}_{r}\,\underline{i}^{r}_{abcde} + \frac{d\underline{\psi}^{r}_{abcde}}{dt} \\
\underline{\psi}^{r}_{abcde} &= \underline{L}_{r}\,\underline{i}^{r}_{abcde} + \underline{L}_{rs}\,\underline{i}^{s}_{abcde}
\end{aligned}
\tag{1}
$$

The following definition of phase voltages, currents and flux linkages applies to (1):

$$
\begin{aligned}
\underline{v}^{s}_{abcde} &= \begin{bmatrix} v_{as} & v_{bs} & v_{cs} & v_{ds} & v_{es} \end{bmatrix}^{T} \\
\underline{i}^{s}_{abcde} &= \begin{bmatrix} i_{as} & i_{bs} & i_{cs} & i_{ds} & i_{es} \end{bmatrix}^{T} \\
\underline{\psi}^{s}_{abcde} &= \begin{bmatrix} \psi_{as} & \psi_{bs} & \psi_{cs} & \psi_{ds} & \psi_{es} \end{bmatrix}^{T} \\
\underline{v}^{r}_{abcde} &= \begin{bmatrix} v_{ar} & v_{br} & v_{cr} & v_{dr} & v_{er} \end{bmatrix}^{T} \\
\underline{i}^{r}_{abcde} &= \begin{bmatrix} i_{ar} & i_{br} & i_{cr} & i_{dr} & i_{er} \end{bmatrix}^{T} \\
\underline{\psi}^{r}_{abcde} &= \begin{bmatrix} \psi_{ar} & \psi_{br} & \psi_{cr} & \psi_{dr} & \psi_{er} \end{bmatrix}^{T}
\end{aligned}
\tag{2}
$$

The inductance matrices of (1) are given with ($\alpha = 2\pi/5$):

$$
\underline{L}_{s} = \begin{bmatrix}
L_{ls}+M & M\cos\alpha & M\cos2\alpha & M\cos2\alpha & M\cos\alpha \\
M\cos\alpha & L_{ls}+M & M\cos\alpha & M\cos2\alpha & M\cos2\alpha \\
M\cos2\alpha & M\cos\alpha & L_{ls}+M & M\cos\alpha & M\cos2\alpha \\
M\cos2\alpha & M\cos2\alpha & M\cos\alpha & L_{ls}+M & M\cos\alpha \\
M\cos\alpha & M\cos2\alpha & M\cos2\alpha & M\cos\alpha & L_{ls}+M
\end{bmatrix}
\tag{3}
$$

$$
\underline{L}_{r} = \begin{bmatrix}
L_{lr}+M & M\cos\alpha & M\cos2\alpha & M\cos2\alpha & M\cos\alpha \\
M\cos\alpha & L_{lr}+M & M\cos\alpha & M\cos2\alpha & M\cos2\alpha \\
M\cos2\alpha & M\cos\alpha & L_{lr}+M & M\cos\alpha & M\cos2\alpha \\
M\cos2\alpha & M\cos2\alpha & M\cos\alpha & L_{lr}+M & M\cos\alpha \\
M\cos\alpha & M\cos2\alpha & M\cos2\alpha & M\cos\alpha & L_{lr}+M
\end{bmatrix}
\tag{4}
$$

$$\underline{L}_{\mathrm{sr}} = \underline{L}_{\mathrm{rs}}^{\mathrm{T}} = M \begin{bmatrix} \cos\theta & \cos(\theta+\alpha) & \cos(\theta+2\alpha) & \cos(\theta-2\alpha) & \cos(\theta-\alpha) \\ \cos(\theta-\alpha) & \cos\theta & \cos(\theta+\alpha) & \cos(\theta+2\alpha) & \cos(\theta-2\alpha) \\ \cos(\theta-2\alpha) & \cos(\theta-\alpha) & \cos\theta & \cos(\theta+\alpha) & \cos(\theta+2\alpha) \\ \cos(\theta+2\alpha) & \cos(\theta-2\alpha) & \cos(\theta-\alpha) & \cos\theta & \cos(\theta+\alpha) \\ \cos(\theta+\alpha) & \cos(\theta+2\alpha) & \cos(\theta-2\alpha) & \cos(\theta-\alpha) & \cos\theta \end{bmatrix} \tag{5}$$

The angle θ is the position of the rotor phase "a" magnetic axis with respect to the stator phase "a" stationary magnetic axis (i.e. the rotor position). Stator and rotor resistance matrices are

$$\begin{aligned} \underline{R}_{\mathrm{s}} &= diag(R_{\mathrm{s}} \quad R_{\mathrm{s}} \quad R_{\mathrm{s}} \quad R_{\mathrm{s}} \quad R_{\mathrm{s}}) \\ \underline{R}_{\mathrm{r}} &= diag(R_{\mathrm{r}} \quad R_{\mathrm{r}} \quad R_{\mathrm{r}} \quad R_{\mathrm{r}} \quad R_{\mathrm{r}}) \end{aligned} \tag{6}$$

Motor torque can be expressed in terms of phase currents as

$$T_{\mathrm{e}} = -PM \begin{Bmatrix} \left(i_{\mathrm{as}}i_{\mathrm{ar}} + i_{\mathrm{bs}}i_{\mathrm{br}} + i_{\mathrm{cs}}i_{\mathrm{cr}} + i_{\mathrm{ds}}i_{\mathrm{dr}} + i_{\mathrm{es}}i_{\mathrm{er}}\right)\sin\theta + \\ \left(i_{\mathrm{es}}i_{\mathrm{ar}} + i_{\mathrm{as}}i_{\mathrm{br}} + i_{\mathrm{bs}}i_{\mathrm{cr}} + i_{\mathrm{cs}}i_{\mathrm{dr}} + i_{\mathrm{ds}}i_{\mathrm{er}}\right)\sin(\theta+\alpha) + \\ \left(i_{\mathrm{ds}}i_{\mathrm{ar}} + i_{\mathrm{es}}i_{\mathrm{br}} + i_{\mathrm{as}}i_{\mathrm{cr}} + i_{\mathrm{bs}}i_{\mathrm{dr}} + i_{\mathrm{cs}}i_{\mathrm{er}}\right)\sin(\theta+2\alpha) + \\ \left(i_{\mathrm{cs}}i_{\mathrm{ar}} + i_{\mathrm{ds}}i_{\mathrm{br}} + i_{\mathrm{es}}i_{\mathrm{cr}} + i_{\mathrm{as}}i_{\mathrm{dr}} + i_{\mathrm{bs}}i_{\mathrm{er}}\right)\sin(\theta-2\alpha) + \\ \left(i_{\mathrm{bs}}i_{\mathrm{ar}} + i_{\mathrm{cs}}i_{\mathrm{br}} + i_{\mathrm{ds}}i_{\mathrm{cr}} + i_{\mathrm{es}}i_{\mathrm{dr}} + i_{\mathrm{as}}i_{\mathrm{er}}\right)\sin(\theta-\alpha) \end{Bmatrix} \tag{7}$$

where P is the number of pole pairs. Machine model described with (1)-(7) is further transformed using Clark's decoupling transformation in power invariant form [24]:

$$\underline{C} = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \cos 8\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \sin 8\alpha \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{8}$$

$$\underline{C}^{-1} = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & 0 & 1 & 0 & \frac{1}{\sqrt{2}} \\ \cos\alpha & \sin\alpha & \cos 2\alpha & \sin 2\alpha & \frac{1}{\sqrt{2}} \\ \cos 2\alpha & \sin 2\alpha & \cos 4\alpha & \sin 4\alpha & \frac{1}{\sqrt{2}} \\ \cos 3\alpha & \sin 3\alpha & \cos 6\alpha & \sin 6\alpha & \frac{1}{\sqrt{2}} \\ \cos 4\alpha & \sin 4\alpha & \cos 8\alpha & \sin 8\alpha & \frac{1}{\sqrt{2}} \end{bmatrix}$$

where the new variables are defined as

$$\begin{aligned} \underline{v}_{\alpha\beta}^{\mathrm{s}} &= \underline{C}\underline{v}_{\mathrm{abcde}}^{\mathrm{s}} & \underline{i}_{\alpha\beta}^{\mathrm{s}} &= \underline{C}\underline{i}_{\mathrm{abcde}}^{\mathrm{s}} & \underline{\psi}_{\alpha\beta}^{\mathrm{s}} &= \underline{C}\underline{\psi}_{\mathrm{abcde}}^{\mathrm{s}} \\ \underline{v}_{\alpha\beta}^{\mathrm{r}} &= \underline{C}\underline{v}_{\mathrm{abcde}}^{\mathrm{r}} & \underline{i}_{\alpha\beta}^{\mathrm{r}} &= \underline{C}\underline{i}_{\mathrm{abcde}}^{\mathrm{r}} & \underline{\psi}_{\alpha\beta}^{\mathrm{r}} &= \underline{C}\underline{\psi}_{\mathrm{abcde}}^{\mathrm{r}} \end{aligned} \tag{9}$$

Upon application of the transformation, the machine model (1)-(7) becomes

$$\begin{aligned} v_{\alpha s} &= R_{\mathrm{s}} i_{\alpha s} + \frac{d\psi_{\alpha s}}{dt} = R_{\mathrm{s}} i_{\alpha s} + \left(L_{\mathrm{ls}} + L_{\mathrm{m}}\right)\frac{di_{\alpha s}}{dt} \\ &\quad + L_{\mathrm{m}} \frac{d}{dt}\left(i_{\alpha r}\cos\theta - i_{\beta r}\sin\theta\right) \\ v_{\beta s} &= R_{\mathrm{s}} i_{\beta s} + \frac{d\psi_{\beta s}}{dt} = R_{\mathrm{s}} i_{\beta s} + \left(L_{\mathrm{ls}} + L_{\mathrm{m}}\right)\frac{di_{\beta s}}{dt} \\ &\quad + L_{\mathrm{m}} \frac{d}{dt}\left(i_{\alpha r}\sin\theta + i_{\beta r}\cos\theta\right) \end{aligned} \tag{10}$$

$$\begin{aligned} v_{\mathrm{xs}} &= R_{\mathrm{s}} i_{\mathrm{xs}} + \frac{d\psi_{\mathrm{xs}}}{dt} = R_{\mathrm{s}} i_{\mathrm{xs}} + L_{\mathrm{ls}} \frac{di_{\mathrm{xs}}}{dt} \\ v_{\mathrm{ys}} &= R_{\mathrm{s}} i_{\mathrm{ys}} + \frac{d\psi_{\mathrm{ys}}}{dt} = R_{\mathrm{s}} i_{\mathrm{ys}} + L_{\mathrm{ls}} \frac{di_{\mathrm{ys}}}{dt} \\ v_{0\mathrm{s}} &= R_{\mathrm{s}} i_{0\mathrm{s}} + \frac{d\psi_{0\mathrm{s}}}{dt} = R_{\mathrm{s}} i_{0\mathrm{s}} + L_{\mathrm{ls}} \frac{di_{0\mathrm{s}}}{dt} \end{aligned}$$

$$\begin{aligned} v_{\alpha r} &= 0 = R_{\mathrm{r}} i_{\alpha r} + \frac{d\psi_{\alpha r}}{dt} = R_{\mathrm{r}} i_{\alpha r} + \left(L_{\mathrm{lr}} + L_{\mathrm{m}}\right)\frac{di_{\alpha r}}{dt} \\ &\quad + L_{\mathrm{m}} \frac{d}{dt}\left(i_{\alpha s}\cos\theta + i_{\beta s}\sin\theta\right) \\ v_{\beta r} &= 0 = R_{\mathrm{r}} i_{\beta r} + \frac{d\psi_{\beta r}}{dt} = R_{\mathrm{r}} i_{\beta r} + \left(L_{\mathrm{lr}} + L_{\mathrm{m}}\right)\frac{di_{\beta r}}{dt} \\ &\quad + L_{\mathrm{m}} \frac{d}{dt}\left(-i_{\alpha s}\sin\theta + i_{\beta s}\cos\theta\right) \end{aligned} \tag{11}$$

$$\begin{aligned} v_{\mathrm{xr}} &= 0 = R_{r} i_{\mathrm{xr}} + \frac{d\psi_{\mathrm{xr}}}{dt} = R_{\mathrm{r}} i_{\mathrm{xr}} + L_{\mathrm{lr}} \frac{di_{\mathrm{xr}}}{dt} \\ v_{\mathrm{yr}} &= 0 = R_{\mathrm{r}} i_{\mathrm{yr}} + \frac{d\psi_{\mathrm{yr}}}{dt} = R_{\mathrm{r}} i_{\mathrm{yr}} + L_{\mathrm{lr}} \frac{di_{\mathrm{yr}}}{dt} \\ v_{0\mathrm{r}} &= 0 = R_{\mathrm{r}} i_{0\mathrm{r}} + \frac{d\psi_{0\mathrm{r}}}{dt} = R_{\mathrm{r}} i_{0\mathrm{r}} + L_{\mathrm{lr}} \frac{di_{0\mathrm{r}}}{dt} \end{aligned}$$

$$T_{\mathrm{e}} = PL_{\mathrm{m}}\left[\cos\theta\left(i_{\alpha r}i_{\beta s} - i_{\beta r}i_{\alpha s}\right) - \sin\theta\left(i_{\alpha r}i_{\alpha s} + i_{\beta r}i_{\beta s}\right)\right] \tag{12}$$

Per-phase equivalent circuit magnetising inductance is introduced in (10)-(12) as $L_{\mathrm{m}} = (5/2)M$. Torque equation (12) shows that the torque is entirely developed due to interaction of stator/rotor α–β current components and is independent of the value of x-y current components. From rotor equations (11) it follows that, since the rotor is short-circuited and stator x-y components are decoupled from rotor x-y components, equations for rotor x-y components and zero sequence component equation can be omitted from further considerations. The same applies to the stator zero sequence component equation. This leaves the first four equations in (10), the first two equations of (11) and the torque equation (12) as relevant for further considerations. Rotational transformation is applied next, using

$$\underline{D}_{\mathrm{s}} = \begin{bmatrix} \cos\theta_s & \sin\theta_s & & & \\ -\sin\theta_s & \cos\theta_s & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & 1 \end{bmatrix}$$

$$\underline{D}_{\mathrm{r}} = \begin{bmatrix} \cos\beta & \sin\beta & & & \\ -\sin\beta & \cos\beta & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & 1 \end{bmatrix}$$

$$\underline{D}_{\mathrm{s}}^{-1} = \begin{bmatrix} \cos\theta_s & -\sin\theta_s & & & \\ \sin\theta_s & \cos\theta_s & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & 1 \end{bmatrix}$$

$$\underline{D}_{\mathrm{r}}^{-1} = \begin{bmatrix} \cos\beta & -\sin\beta & & & \\ \sin\beta & \cos\beta & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & 1 \end{bmatrix} \tag{13}$$

where the angles of transformation are $\theta_{\mathrm{s}} = \int \omega_{\mathrm{a}}\,\mathrm{d}t$ and $\beta = \theta_{\mathrm{s}} - \theta$ ($\theta = \int \omega\,\mathrm{d}t$) for stator and rotor variables, respectively, and ω_{a} is the arbitrary speed of rotation of the common reference frame (note that x-y stator component equations are not transformed). Application of (13) in conjunction with the model (10)-(12) produces the following set of equation for a five phase induction machine in the common rotational reference frame (rotor x-y component equations and stator and rotor zero sequence component equations are omitted):

$$\begin{aligned} v_{\mathrm{ds}} &= R_{\mathrm{s}} i_{\mathrm{ds}} - \omega_{\mathrm{a}} \psi_{\mathrm{qs}} + p\psi_{\mathrm{ds}} \\ v_{\mathrm{dr}} &= 0 = R_{\mathrm{r}} i_{\mathrm{dr}} - (\omega_{\mathrm{a}} - \omega)\psi_{\mathrm{qr}} + p\psi_{\mathrm{dr}} \\ v_{\mathrm{qs}} &= R_{\mathrm{s}} i_{\mathrm{qs}} + \omega_{\mathrm{a}} \psi_{\mathrm{ds}} + p\psi_{\mathrm{qs}} \\ v_{\mathrm{qr}} &= 0 = R_{\mathrm{r}} i_{\mathrm{qr}} + (\omega_{\mathrm{a}} - \omega)\psi_{\mathrm{dr}} + p\psi_{\mathrm{qr}} \\ v_{\mathrm{xs}} &= R_{\mathrm{s}} i_{\mathrm{xs}} + p\psi_{\mathrm{xs}} \\ v_{\mathrm{ys}} &= R_{\mathrm{s}} i_{\mathrm{ys}} + p\psi_{\mathrm{ys}} \end{aligned} \tag{14}$$

$$\begin{aligned} \psi_{\mathrm{ds}} &= (L_{\mathrm{ls}} + L_{\mathrm{m}}) i_{\mathrm{ds}} + L_{\mathrm{m}} i_{\mathrm{dr}} \\ \psi_{\mathrm{dr}} &= (L_{\mathrm{lr}} + L_{\mathrm{m}}) i_{\mathrm{dr}} + L_{\mathrm{m}} i_{\mathrm{ds}} \\ \psi_{\mathrm{qs}} &= (L_{\mathrm{ls}} + L_{\mathrm{m}}) i_{\mathrm{qs}} + L_{\mathrm{m}} i_{\mathrm{qr}} \\ \psi_{\mathrm{qr}} &= (L_{\mathrm{lr}} + L_{\mathrm{m}}) i_{\mathrm{qr}} + L_{\mathrm{m}} i_{\mathrm{qs}} \\ \psi_{\mathrm{xs}} &= L_{\mathrm{ls}} i_{\mathrm{xs}} \\ \psi_{\mathrm{ys}} &= L_{\mathrm{ls}} i_{\mathrm{ys}} \end{aligned} \tag{15}$$

$$T_{\mathrm{e}} = PL_{\mathrm{m}} \left[i_{\mathrm{dr}} i_{\mathrm{qs}} - i_{\mathrm{ds}} i_{\mathrm{qr}} \right] \tag{16}$$

The principles of independent vector control of two series-connected five-phase induction machines with phase transposition are developed next utilising the models given with (10)-(12) and (14)-(16).

Independent control of two series connected induction motors

An important property of the five-phase machine model, given with (10)-(12), is that the new set of equations contains only two components (α–β) which lead to stator to rotor coupling, while the remaining three components are not coupled [20, 23, 24]. The situation remains the same after application of the rotational transformation, as is evident from the model given with (14)-(16).

Vector control enables independent control of flux and torque of an AC machine by means of only two stator current components (one component pair: d-q). This leaves one pair of components as additional degrees of freedom. Hence, if it is possible to connect stator windings of two five-phase machines in such a way that what one machine sees as the d-q axis stator current components the other machine sees as x-y current components, and vice versa, it would become possible to completely independently control speed (position, torque) of these two machines while supplying the machines from a single current-controlled voltage source inverter. In simple terms, it is possible to independently realise vector control of two five phase machines using a single voltage source inverter, provided that the stator windings of the two machines are connected in series and that an appropriate phase transposition is introduced so that the set of five five-phase currents that produce rotating mmf in the first machine, does not produce rotating mmf in the second machine and vice versa. This explanation constitutes the basis of the two-motor five-phase drive system that is to be described further on.

The required phase transposition follows directly from the decoupling transformation matrix, given in (8). Let the source phase sequence be identified with A, B, C, D and E and let the phases of the stator windings of the two five-phase machines have phase sequence 1, 2, 3, 4, 5 which corresponds to the spatial ordering of the phases. According to the transformation matrix, phases '1' of the two machines will be connected directly in series (the first column). The phase transposition for phase '1' is therefore 0 degrees. However, phase '2' of the first machine will be connected to phase '3' of the second machine. The phase transposition moving from one machine to the other is α and the phase step is 1. This follows from the second column of the transformation matrix (8) that contains cosine and sine terms with spatial displacements equal to α and 2α. In a similar manner phase '3' of the first machine (spatial displacement of 2α) is connected to the phase '5' of the second machine. The phase transposition is 2α, and the phase step is 2. This follows from the third column of the transformation matrix. Further, phase '4' of the first machine needs to be connected to the phase '7' of the second machine; since the machine is five-phase, resetting takes place and phase '4' is connected to phase '2' (7 – 5 = 2) of the second machine. The phase step is equal to 3 and phases are transposed by 3α. This corresponds to the fourth column in the transformation matrix, where terms with 3α and 6α appear. For phase '5' of the first machine the phase transposition will equal 4α and phase step will be 4, so that phase '5' gets connected to phase '9', or after resetting, to phase '4' (9 – 5 = 4). On the basis of these considerations it is possible to construct a connection table, shown in Table I. The corresponding connection diagram is given in Fig. 2 (with the change from machine's phase order symbols 1, 2, 3, 4, 5 to a, b, c, d, e).

In order to verify the concept, a steady state operation with ideal sinusoidal currents is examined first. Let us assume that the

Table I: Connectivity matrix for the five-phase case.

	A	B	C	D	E
M1	1	2	3	4	5
M2	1	3	5	2	4

machine 1 is supplied for the purposes of torque and flux production with ideal sinusoidal currents of RMS value and angular frequency equal to I_1, ω_1. Similarly, machine 2 is supplied with a flux and torque producing set of currents of RMS value and frequency I_2, ω_2. According to the connection diagram in Fig. 2, source currents are simultaneously corresponding phase currents for machine 1:

$$\begin{aligned}
i_A &= i_{a1} = \sqrt{2}I_1 \sin(\omega_1 t) + \sqrt{2}I_2 \sin(\omega_2 t) \\
i_B &= i_{b1} = \sqrt{2}I_1 \sin(\omega_1 t - \alpha) + \sqrt{2}I_2 \sin(\omega_2 t - 2\alpha) \\
i_C &= i_{c1} = \sqrt{2}I_1 \sin(\omega_1 t - 2\alpha) + \sqrt{2}I_2 \sin(\omega_2 t - 4\alpha) \\
i_D &= i_{d1} = \sqrt{2}I_1 \sin(\omega_1 t - 3\alpha) + \sqrt{2}I_2 \sin(\omega_2 t - \alpha) \\
i_E &= i_{e1} = \sqrt{2}I_1 \sin(\omega_1 t - 4\alpha) + \sqrt{2}I_2 \sin(\omega_2 t - 3\alpha)
\end{aligned} \tag{17}$$

The machine 2 is connected to the source via the "phase transposition", so that the machine is supplied with the following currents:

$$\begin{aligned}
i_{a2} &= i_A = \sqrt{2}I_1 \sin(\omega_1 t) + \sqrt{2}I_2 \sin(\omega_2 t) \\
i_{b2} &= i_D = \sqrt{2}I_1 \sin(\omega_1 t - 3\alpha) + \sqrt{2}I_2 \sin(\omega_2 t - \alpha) \\
i_{c2} &= i_B = \sqrt{2}I_1 \sin(\omega_1 t - \alpha) + \sqrt{2}I_2 \sin(\omega_2 t - 2\alpha) \\
i_{d2} &= i_E = \sqrt{2}I_1 \sin(\omega_1 t - 4\alpha) + \sqrt{2}I_2 \sin(\omega_2 t - 3\alpha) \\
i_{e2} &= i_C = \sqrt{2}I_1 \sin(\omega_1 t - 2\alpha) + \sqrt{2}I_2 \sin(\omega_2 t - 4\alpha)
\end{aligned} \tag{18}$$

Application of the transformation matrix (8) on stator currents of the two machines given with (17)-(18) produces results summarised in Table II. From Table II it is evident that, due to phase transposition in the series connection of the two machines, flux/torque producing currents of machine 1 produce α–β current components in machine 1, while they produce x-y current components in machine 2, and vice versa. It therefore follows that the currents of the second machine create a resultant mmf of overall zero value in any instant in time in machine 1, and vice versa. Hence it becomes possible to independently control the two five-phase machines while supplying them form a single five-phase inverter.

When a single five-phase machine is supplied from an inverter, stator current harmonics of the order 10 $n \pm 1$ (n = 0, 1, 2…) contribute to the torque and therefore appear in α–β stator current components. On the other hand, harmonics of the order 5 $n \pm 2$ (n = 1, 3, 5….) do not contribute to the air-gap flux and torque production and they therefore appear in x-y current components. When the two five-phase machines are connected in series as in Fig. 2, the flux/torque producing currents (α–β) of one machine behave as x-y current components for the other machine due to the phase transposition, and vice versa. In simple terms, flux/torque producing currents of one machine have a 'wrong' phase sequence for the other machine (thanks to the phase transposition), which does not correspond to the spatial sequence of phases in that machine, so that no air-gap flux and torque are produced by these currents.

One particularly interesting situation arises if the two machines are identical and they operate under exactly the same operating conditions (i.e. with the same RMS currents $I_1 = I_2 = I$ and the same frequency $\omega_1 = \omega_2 = \omega$). Depending on the phase relationship between flux/torque producing currents of the two machines a steady state may result in which any one of the five inverter phase currents has an instantaneous value equal to zero at all times[1] (note that due to phase transposition this may happen with only one inverter current). This situation simultaneously corresponds to the fault condition with an open-circuited phase. Although one could expect that the drive operation and control should be disturbed under these conditions, this is not the case. It can be shown that the relationships of Table II remain to hold true, meaning that the drive operation is not affected. This is so since in the proposed five-phase two-motor drive system only four degrees of freedom are utilised. The fifth is redundant, meaning that there is one degree of redundancy that remains for utilisation in safety critical applications, in the case of failure of one inverter leg. More detailed considerations are given in Appendix 1.

Vector control of the two-motor five-phase drive system

The basic indirect vector controller is of the same structure for an induction machine, regardless of the number of phases on the stator. An indirect vector controller for a five-phase induction machine is shown in Fig. 3. Operation in the constant flux region (base speed region) only is assumed and the vector controller is the same for the two machines. Phase current references for the two machines are obtained using co-ordinate transformation, in the same manner as it is done for a three-phase machine:

$$\begin{aligned}
i^*_{a1} &= \sqrt{\frac{2}{5}}[i^*_{ds1}\cos\phi_{r1} - i^*_{qs1}\sin\phi_{r1}] \\
i^*_{a2} &= \sqrt{\frac{2}{5}}[i^*_{ds2}\cos\phi_{r2} - i^*_{qs2}\sin\phi_{r2}] \\
i^*_{b1} &= \sqrt{\frac{2}{5}}[i^*_{ds1}\cos(\phi_{r1}-\alpha) - i^*_{qs1}\sin(\phi_{r1}-\alpha)] \\
i^*_{b2} &= \sqrt{\frac{2}{5}}[i^*_{ds2}\cos(\phi_{r2}-\alpha) - i^*_{qs2}\sin(\phi_{r2}-\alpha)] \\
i^*_{c1} &= \sqrt{\frac{2}{5}}[i^*_{ds1}\cos(\phi_{r1}-2\alpha) - i^*_{qs1}\sin(\phi_{r1}-2\alpha)] \\
i^*_{c2} &= \sqrt{\frac{2}{5}}[i^*_{ds2}\cos(\phi_{r2}-2\alpha) - i^*_{qs2}\sin(\phi_{r2}-2\alpha)] \\
i^*_{d1} &= \sqrt{\frac{2}{5}}[i^*_{ds1}\cos(\phi_{r1}-3\alpha) - i^*_{qs1}\sin(\phi_{r1}-3\alpha)] \\
i^*_{d2} &= \sqrt{\frac{2}{5}}[i^*_{ds2}\cos(\phi_{r2}-3\alpha) - i^*_{qs2}\sin(\phi_{r2}-3\alpha)] \\
i^*_{e1} &= \sqrt{\frac{2}{5}}[i^*_{ds1}\cos(\phi_{r1}-4\alpha) - i^*_{qs1}\sin(\phi_{r1}-4\alpha)] \\
i^*_{e2} &= \sqrt{\frac{2}{5}}[i^*_{ds2}\cos(\phi_{r2}-4\alpha) - i^*_{qs2}\sin(\phi_{r2}-4\alpha)]
\end{aligned} \tag{19}$$

1 This issue was raised by Prof. R.D.Lorenz during the discussion of the paper at EPE 2003, to whom the authors are indebted for highlighting a potential problem.

Table II: Stator current components in series connected motors in steady state

Current components	M1	M2
α	$\sqrt{5}I_1 \sin\omega_1 t$	$\sqrt{5}I_2 \sin\omega_2 t$
β	$-\sqrt{5}I_1 \cos\omega_1 t$	$-\sqrt{5}I_2 \cos\omega_2 t$
x1	$\sqrt{5}I_2 \sin\omega_2 t$	$\sqrt{5}I_1 \sin\omega_1 t$
y1	$-\sqrt{5}I_2 \cos\omega_2 t$	$\sqrt{5}I_1 \cos\omega_1 t$
0	0	0

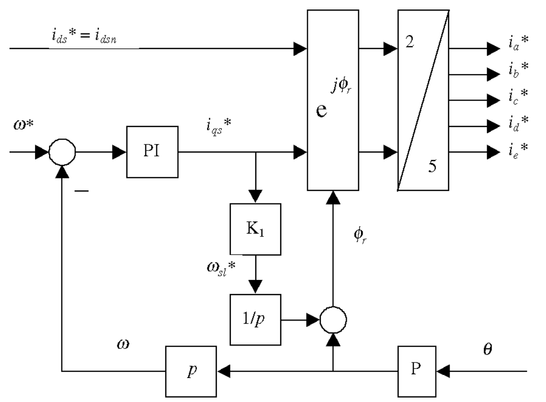


Fig. 3: Indirect vector controller for the five phase induction machine $K_1 = 1/(T_r i^*_{ds})$.

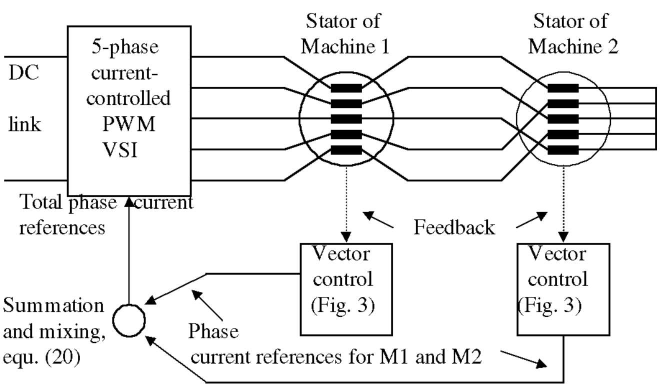


Fig. 4: Vector control scheme for a five-phase two-motor drive system

Overall inverter current references are then formed respecting the connection diagram of Fig. 2, so that:

$$
\begin{aligned}
&i^*_A = i^*_{a1} + i^*_{a2} && i^*_B = i^*_{b1} + i^*_{c2} \\
&i^*_C = i^*_{c1} + i^*_{e2} && i^*_D = i^*_{d1} + i^*_{b2} \\
&i^*_E = i^*_{e1} + i^*_{d2}
\end{aligned}
\tag{20}
$$

Either hysteresis current control or ramp comparison control can be applied in order to get desired currents at the inverter output. An illustration of the complete drive control system is given in Fig. 4.

Simulation verification

The proposed two-motor five-phase drive system is verified by simulation (motor data are given in Appendix 2; the two motors are the same). Current-controlled VSI is treated as an ideal current source, so that the source current references given with (20) are the inputs into the induction machine models. Operation in the torque mode is examined first. The motor model applied at this stage is the one in terms of phase variables, given with (1)-(7). The application of the phase-variable model represents the ultimate proof of the concept, since general theory of electrical machines is not utilised for the machine representation. Due to the assumed ideal current feeding stator currents for the two machines are known and are used to calculate current derivatives. Stator voltage equations are used to reconstruct the machines' phase voltages and subsequently determine the source phase voltages according to

$$
\begin{aligned}
&v_A = v_{as1} + v_{as2} && v_B = v_{bs1} + v_{cs2} \\
&v_C = v_{cs1} + v_{es2} && v_D = v_{ds1} + v_{bs2} \\
&v_E = v_{es1} + v_{ds2}
\end{aligned}
\tag{21}
$$

Different profiles of the rotor flux reference (stator d-axis current reference) are applied at first to excite the machines. Once when the rated rotor flux in both machines has been established, torque command is at first applied and later removed for both machines, in a ramp-wise manner, in different time instants. Torque reference for the first machine equals twice the rated torque (16.67 Nm), while it is the rated torque (8.33 Nm) for the second machine. Fig. 5 shows the simulation results. As can be seen from Fig. 5, excitation of the two machines is independent and rotor flux attains desired rated value after the initial transient. Rotor flux remains undisturbed in both machines during subsequent torque transients, indicating that completely decoupled control has been achieved. Torque reference and actual torque for the two machines are indistinguishable one from the other. Moreover, application of the torque command to one of the machines does not have any impact on the torque in the other machine, and vice versa. Consequently, speed transients are smooth, with maximum allowed rate of change. Stator phase 'a' current references, calculated according to (19), are sinusoidal in any steady state operation. The stator phase 'a' voltages of the two machines are distorted due to the flow of flux/torque producing currents for both machines through all the phases of both machines. That is, x-y components of stator voltages exist and this is evident especially for IM2 which operates at a lower final steady state speed.

Source phase voltages, obtained using (21), are shown in Fig. 6, while Fig. 7 depicts source currents, calculated according to (20). Results are given for the first two phases. High level of distortion is evident in both source currents and source voltages. The flow of flux/torque producing currents of one machine through the stator winding of the other machine, and vice versa, is the main drawback of this drive system, as discussed shortly.

Further simulations are performed in the speed mode of operation. The two machines are now represented with the d-q model and are excited using the same rotor flux reference profile. Upon completion of the excitation transient, speed commands, equal to rated and one half of the rated, are applied in different time instants to the two machines (zero load torque), in a ramp-wise manner. Torque limit is set to twice the rated torque (16.67 Nm). Fig. 8 shows rotor flux reference and rotor flux magnitude, torque response, corresponding speed responses, and the stator phase 'a' current references for the two machines. Once more, fully decou-

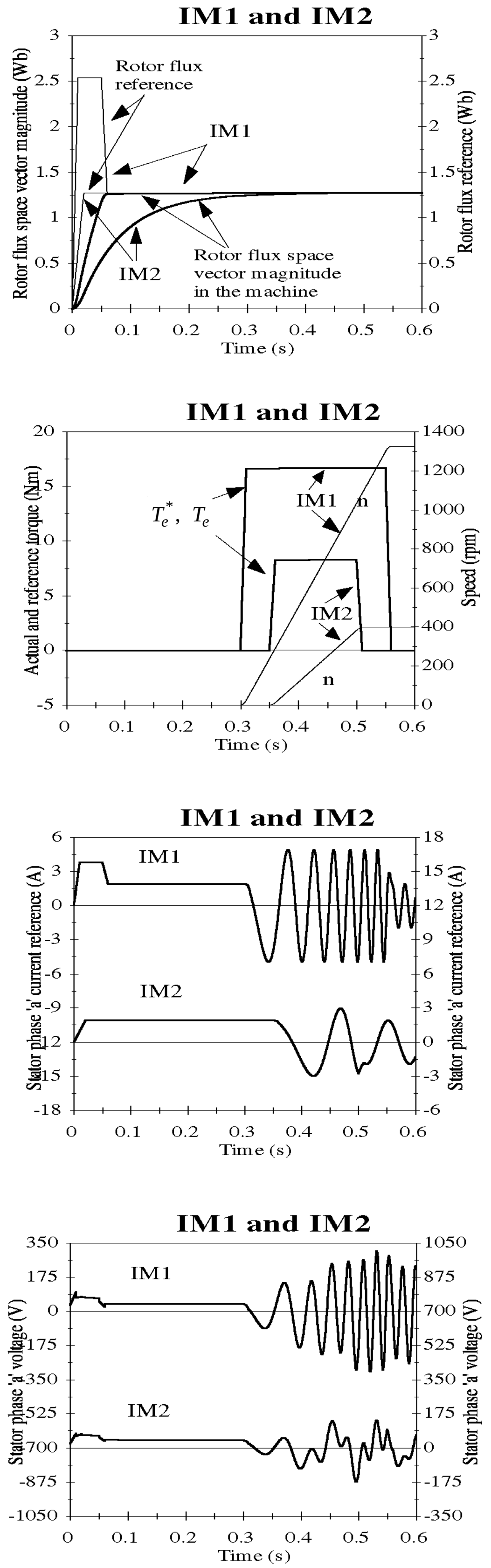


Fig. 5: Torque mode of operation of a five-phase two-motor drive: rotor flux reference and rotor flux magnitude; torque reference, torque response and speed response; stator phase 'a' current reference; stator phase 'a' voltage.

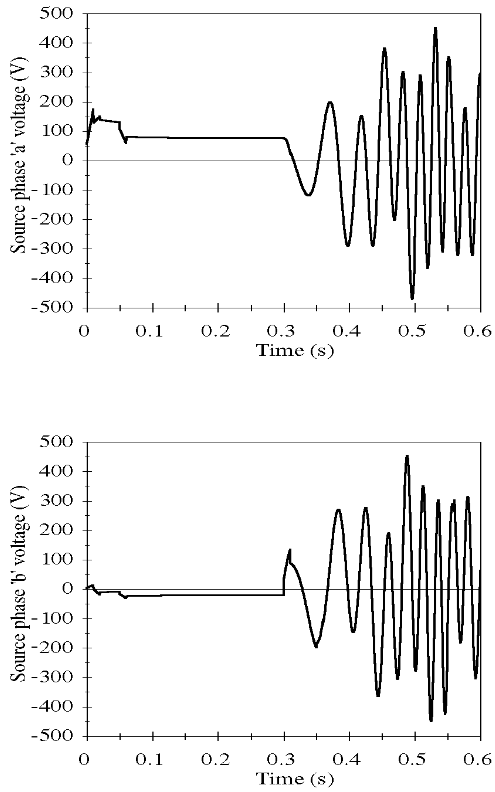


Fig. 6: Source phase voltages (phases A and B)

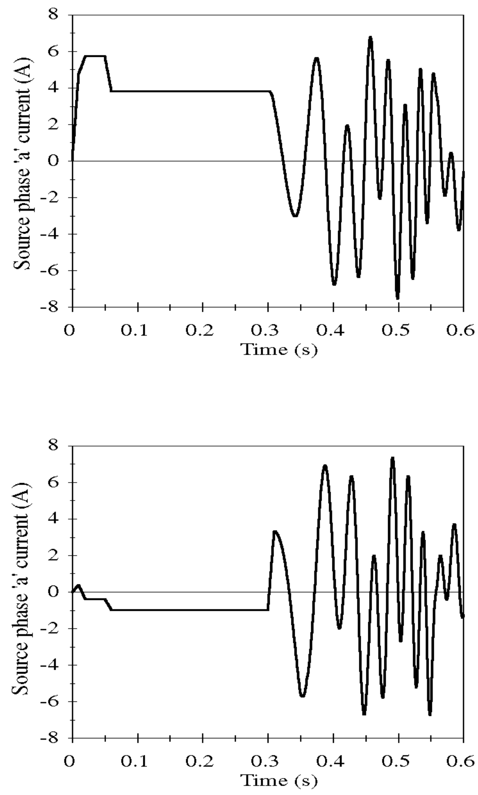


Fig. 7: Source currents (phases A and B)

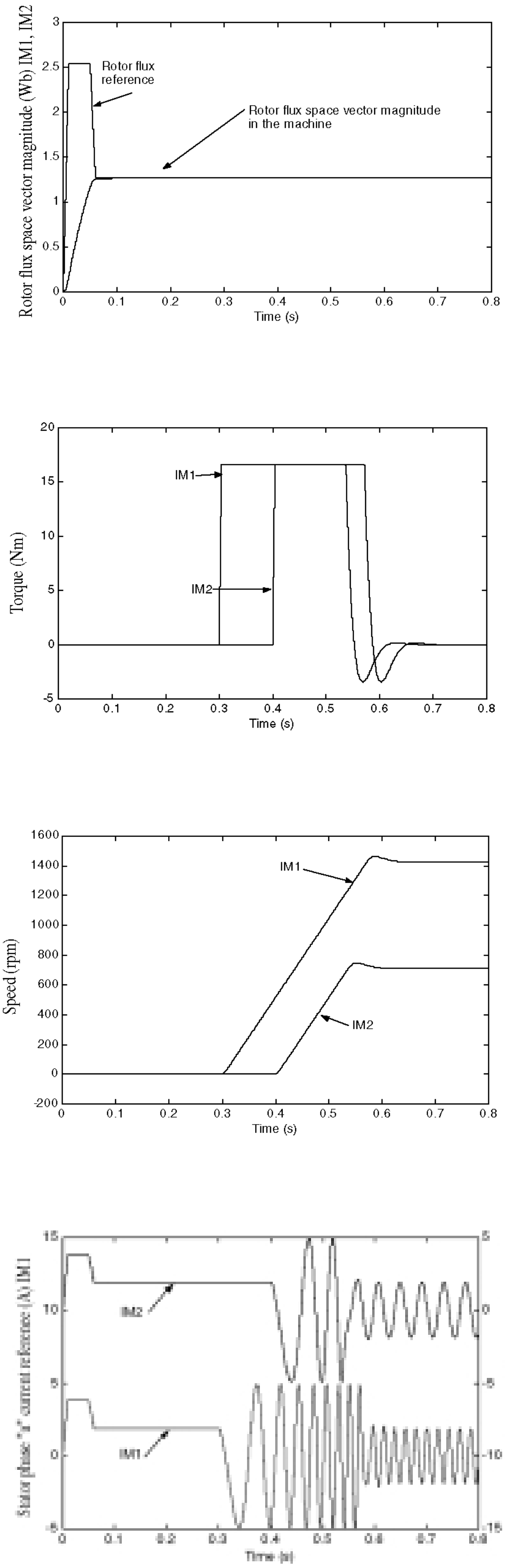


Fig. 8: Speed mode of operation: rotor flux reference and rotor flux magnitude, torque response, speed response, and stator phase ‘a’ current references.

pled rotor flux and torque control results for the both machines, confirming again that the applied phase transposition in the series connection of stator windings enables complete decoupling of the vector control of the two machines.

Discussion

Shortcomings of the two-motor series-connected drive are addressed first. As already noted, the flow of flux/torque producing currents of one machine through the stator winding of the other machine, and vice versa, is the main drawback of this drive system. Clearly, such a situation will lead to an increased amount of stator copper losses in both machines, therefore reducing the overall efficiency of the drive system (rotor copper losses will however not be affected). Determination of the additional amount of the stator winding losses depends on the machine ratings and operating conditions. For simplicity, it is assumed that the two machines are identical and operate with the same load (i.e. current) and at the same speed (i.e. frequency). In other words, situation described with (17) (for $I_1 = I_2 = I$, $\omega_1 = \omega_2 = \omega$) and (A1) is considered. Using either (17) or (A1), it can be easily shown that the amount of stator winding loss will double in each machine in this series connection, compared to the case when a single five-phase machine operates under the same conditions. It should be noted however, that distribution of the additional stator winding loss is uneven among the phases (for example, if (17) applies then phase 'a' losses of both machines will quadruple, while if (A1) applies there will be no losses at all in phase 'a' of both machines).

The second shortcoming is the voltage drop produced by x-y stator current components in both machines, which will impact on the voltage rating of the inverter semiconductors. This means that the voltage rating will have to be higher (but only slightly, since these voltage drops appear across stator leakage impedance and are therefore rather small) than twice the rating for a single five-phase motor drive. Current rating of the inverter will have to correspond to the sum of current ratings of the two machines.

The main advantage of the system is that five rather than six inverter legs are required, since smaller number of components means higher reliability and easier manufacturing. However, there are other advantages as well. First of all, a single DSP can be used to realise control of both machines. Next, braking energy of one machine can be directly used for motoring of the other machine, so that regenerative braking is realised without the need for an active front-end rectifier. Energy saving which results in this way may be considerable in drives with frequent reversals and braking, and may outweigh the loss in efficiency due to the increase in stator winding losses. Finally, the connection automatically solves one of the problems experienced with multi-phase motor drives, namely the flow of large stator current harmonics that do not contribute to flux and torque production (i.e. x-y current components) [29]. With the series connection active impedance of one machine (α-β impedance) is placed in series to the stator leakage impedance (x-y impedance) of the other machine, and vice versa, so that low order stator current harmonics are significantly attenuated (practically eliminated).

Conclusion

The paper develops a novel concept for a two-motor drive system, which enables independent control of a set of AC machines supplied from a single current-controlled voltage source inverter. The number of connectable machines depends on the number of phases of the stator winding and is two in the five-phase case, covered in detail in the paper. The stator multiphase windings have to be connected in series with an appropriate phase transposition, in order to achieve the independent control of the two machines. The concept is developed in a systematic manner, using general theory of electrical machines, and is valid regardless of the type of the AC machine. This implies that different machine types can be used within the same drive system without any difficulty (for example, an induction motor and a synchronous motor).

The two-motor five-phase drive system is verified by simulation. Torque mode and speed mode of operation are examined and it is shown that completely decoupled and independent vector control of the two machines is possible with the proposed series connection. The major advantages and shortcomings of such a multi-drive system are discussed in detail.

Appendix 1

Steady state operation with zero resulting current in one inverter phase

Consider a steady state in which flux/torque producing currents of both machines have the same RMS value and the same frequency and let the flux/torque producing currents for phases 'a' be in phase opposition. Under these conditions (17) becomes

$$\begin{aligned}
i_A &= \sqrt{2}I\sin(\omega t) + \sqrt{2}I\sin(\omega t - \pi) = 0 \\
i_B &= \sqrt{2}I\sin(\omega t - \alpha) + \sqrt{2}I\sin(\omega t - 2\alpha - \pi) \\
&= 2I\sqrt{1+\cos(3\alpha/2)}\,\sin(\omega t - \alpha/4) \\
i_C &= \sqrt{2}I\sin(\omega t - 2\alpha) + \sqrt{2}I\sin(\omega t - 4\alpha - \pi) \\
&= 2I\sqrt{1+\cos(\alpha/2)}\,\sin(\omega t - 7\alpha/4) \\
i_D &= \sqrt{2}I\sin(\omega t - 3\alpha) + \sqrt{2}I\sin(\omega t - \alpha - \pi) \\
&= 2I\sqrt{1+\cos(\alpha/2)}\,\sin(\omega t - 13\alpha/4) \\
i_E &= \sqrt{2}I\sin(\omega t - 4\alpha) + \sqrt{2}I\sin(\omega t - 3\alpha - \pi) \\
&= 2I\sqrt{1+\cos(3\alpha/2)}\,\sin(\omega t - 19\alpha/4)
\end{aligned} \tag{A1}$$

Application of the decoupling transformation (8), in complex form and with $\underline{a} = \exp(j\alpha) = \exp(j2\pi/5)$,

$$\begin{aligned}
\underline{i}_{\alpha\beta} &= \sqrt{2/5}\left(i_A + \underline{a}i_B + \underline{a}^2 i_C + \underline{a}^3 i_D + \underline{a}^4 i_E\right) \\
\underline{i}_{xy} &= \sqrt{2/5}\left(i_A + \underline{a}^2 i_B + \underline{a}^4 i_C + \underline{a}^6 i_D + \underline{a}^8 i_E\right)
\end{aligned} \tag{A2}$$

yields as the final result for inverter (motor 1) current components

$$\begin{aligned}
\underline{i}_{\alpha\beta} &= \sqrt{5}I\exp j(\omega t - \pi/2) \\
\underline{i}_{xy} &= \sqrt{5}I\exp j(\omega t + \pi/2)
\end{aligned} \tag{A3}$$

which is the same as in Table II, except for the signs (phases) of x-y components. Inverter phase currents and inverter (motor 1) current components are illustrated in Fig. A1. This particular situation is investigated by dynamic simulation as well (Fig. A2). The machines are at first excited and the same speed command, corresponding to 50 Hz electrical frequency is then applied. A time delay of 10 ms is introduced in the speed command application of IM2, resulting in a 180° phase shift of the IM2 flux/torque producing currents with respect to flux/torque producing currents of IM1. A load torque (50 % of the rated torque) is further applied, at the same time instant, to both machines. Results shown in Fig. A2 confirm undisturbed operation under these conditions, which yield zero inverter phase A current after the initial acceleration transient. Although the inverter phase A current is zero, full decoupled vector control of the two machines still results. This indicates that the two-motor series-connected five-phase motor drive possesses one degree of redundancy.

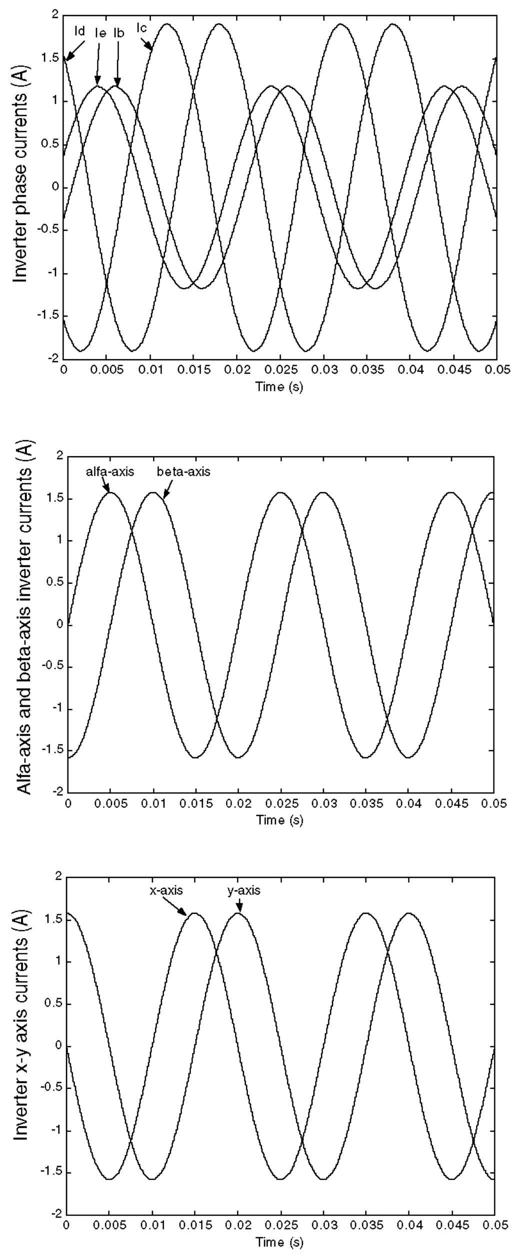


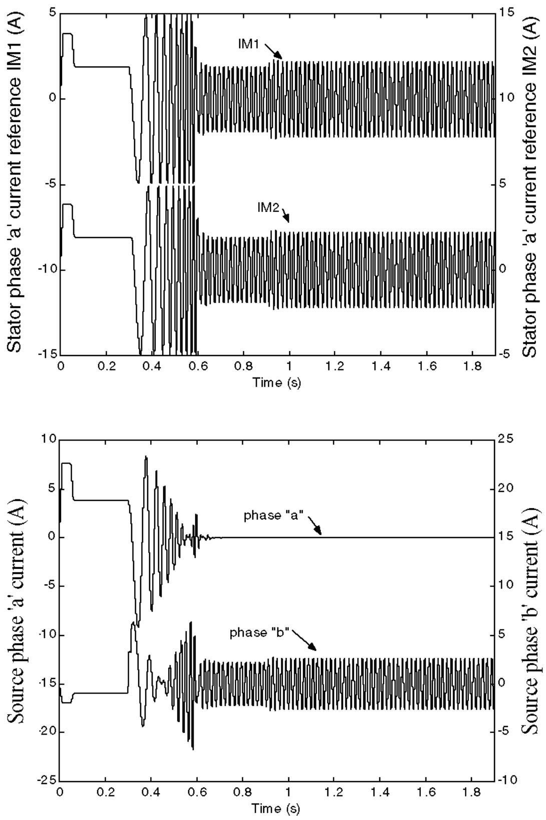
Fig. A1: Inverter currents of (A1) and associated α-β and x-y current components of (A3)

Appendix 2

Motor Data

Per-phase equivalent circuit parameters of the 4-pole, 50 Hz five-phase induction motor (J = 0.03 kgm²):

a)



b)

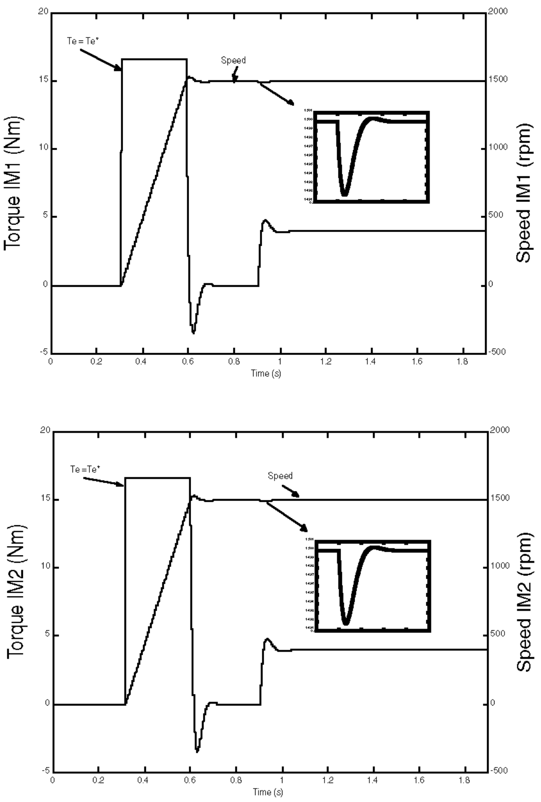


Fig. A2: Dynamics of the drive with motor flux/torque producing current cancellation in inverter phase A
a. Phase ‘a’ current references for the two machines and inverter current references for the first two phases
b. Torque and speed responses of the two machines

$R_s = 10\ \Omega$ $R_r = 6.3\ \Omega$ $L_{ls} = L_{lr} = 0.04$ H $L_m = 0.42$ H

Per-phase ratings of the five-phase induction motor: 220 V, 2.1 A, 1.667 Nm.

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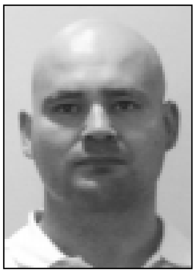

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