A NOVEL CONCEPT FOR MULTIMACHINE DRIVE SYSTEM WITH SINGLE INVERTER SUPPLY

Abdelkader DJAHBAR[*], Benyounès MAZARI[**]
[*]Department of Electrical Engineering, Faculty of Electrical Engineering,
University of Chlef, Chlef 02000, Algeria
[**] Development of Electric Drives Laboratory L.D.E.E, Department of Electrical Engineering,
Faculty of Electrical and Electronics Engineering,
University of Sciences and Technology (USTO), Oran, Algeria
E-mail: a_djahbar@yahoo.fr

ABSTRACT

The interest in multiphase machines for high performance applications has been growing in recent years due to their potential advantages over three-phase machines.

One of the possibilities of taking advantage of the additional degrees of freedom that exist in multiphase machines is the series connection of several multiphase machines, with the supply coming from a single multiphase inverter.

This paper discusses the possibility of connecting in series the stator windings of a six-phase and three-phase induction machines in an appropriate manner. This enables full decoupling of the dynamics of the two machines by means of vector control. Mathematical derivations and simulation proof of independent vector control, achievable with this system, are provided for the series connection of six-phase induction machine and a three-phase induction machine. The existence of the independent control of the machines is fully verified both in torque and speed mode using indirect rotor-flux oriented control principles.

Keywords: *Multiphase induction machine, multimotor drive, vector control.*

1. INTRODUCTION

Multiphase machines offer a number of advantages when compared to three-phase machines. The most important ones are the possibility of achieving a higher torque density through injection of higher stator current harmonics and utilisation of higher spatial field harmonics, fail-safe operation in redundancy mode, and reduction of the required per-phase inverter rating for the same output power [1], [2]. It should be noted that the first two advantages of multiphase machines will not exist in the multiphase multimotor drive system elaborated in this paper. This is so since the additional degrees of freedom, which exist in multiphase-machines and can be used to increase torque density and for fail-safe operation, will be used here for the control of other machines of the multimotor group. The basic idea behind the concept presented in the paper relies on the fact that, regardless of the number of phases, only two stator currents are required for decoupled dynamic flux and torque control (vector control) of an *n*-phase ac machine. This means that the remaining currents can be used to control the other machines, provided that the stator windings of all the machines are connected in series. However, in order to enable decoupled flux/torque control of one machine from all the other machines in the group, it is necessary that flux/torque producing currents of one machine do not produce a rotating field in all the other machines. This requires introduction of an appropriate phase transposition in the series connection of stator windings. The concept of the multiphase multimotor drive system developed in detail in this paper was for the first time proposed in [3], where the idea was introduced for a two-motor five-phase drive using the notion of an *n* dimensional space for an *n*-phase machine. An entirely different approach, based on the general theory of electrical machines [4], [5], is adopted here. The rules for establishing the necessary connection diagram within a multimotor group are developed by analysing the properties of the decoupling (Clark's) transformation matrix. The flux/torque producing currents of one machine do not produce flux and torque in the other machines when the appropriate phase transposition is introduced in the series connection.

2. MODELLING OF THE TWO-MOTOR DRIVE

The two-motor drive system under consideration is shown in Fig.1. It consists of a six-phase source, one six-phase and one three-phase ac machine. The two machines are connected in series according to the diagram in Fig.1. The six-phase machine has the spacial displacement between any two consecutive stator phases equal to 60° (i.e. $\alpha=2\pi/6$). The type of machine is induction machine since the connection of fig.1 can used with both induction and synchronous (all type) machines. The only requirement is that the mmf distribution in the air-gap is sinusoidal [3], [6]. Both machines are taken here as induction machines for the modelling purposes.

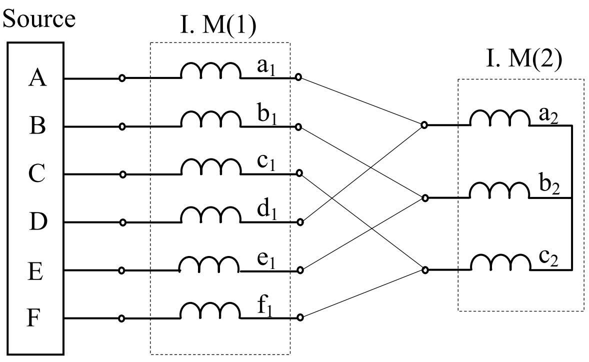

Fig. 1 A six-phase series-connected two-motor drive.

According to the connection diagram of Fig.1, source phase to neutral voltages are determined with:

$$[V^s] = \begin{bmatrix} v_A \\ v_B \\ v_C \\ v_D \\ v_E \\ v_F \end{bmatrix} = \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{bs2} \\ v_{cs1} + v_{cs2} \\ v_{ds1} + v_{as2} \\ v_{es1} + v_{bs2} \\ v_{fs1} + v_{cs2} \end{bmatrix} \tag{1}$$

Where indices 1 and 2 identify the two machines in Fig.1. Relationship between source currents and individual stator phase currents of the two motors is governed with:

$$\begin{aligned} [I^s] &= \begin{bmatrix} i_A & i_B & i_C & i_D & i_E & i_F \end{bmatrix}^t \\ &= \begin{bmatrix} i_{as1} & i_{bs1} & i_{cs1} & i_{ds1} & i_{es1} & i_{fs1} \end{bmatrix}^t \\ &= [I_{s1}] \end{aligned} \tag{2}$$

$$[I_{s2}] = \begin{bmatrix} i_{as2} \\ i_{bs2} \\ i_{cs2} \end{bmatrix} = \begin{bmatrix} i_A + i_D \\ i_B + i_E \\ i_C + i_F \end{bmatrix} \tag{3}$$

The electrical sub-system's model of the drive in Fig.1 is of the 15th order. It can be given in matrix form with:

$$[V] = [RI] + \frac{d[LI]}{dt} \tag{4}$$

Matrix equation of the voltage equilibrium (4) can be further given as :

$$\begin{bmatrix} [V^s] \\ [0] \\ [0] \end{bmatrix} = \begin{bmatrix} [R_{seq}] & [0] & [0] \\ [0] & [R_{r1}] & [0] \\ [0] & [0] & [R_{r2}] \end{bmatrix} \begin{bmatrix} [I^S] \\ [I_{r1}] \\ [I_{r2}] \end{bmatrix} + \frac{d}{dt} \left\{ \begin{bmatrix} [L_{seq}] & [L_{sr1}] & [L'_{sr2}] \\ [L_{rs1}] & [L_{r1}] & [0] \\ [L'_{rs2}] & [0] & [L_{r2}] \end{bmatrix} \begin{bmatrix} [I^S] \\ [I_{r1}] \\ [I_{r2}] \end{bmatrix} \right\} \tag{5}$$

Where

$$[R_{seq}] = [R_{s1}] + \begin{bmatrix} [R_{s2}] & [R_{s2}] \\ [R_{s2}] & [R_{s2}] \end{bmatrix}$$

$$[L_{seq}] = [L_{s1}] + \begin{bmatrix} [L_{s2}] & [L_{s2}] \\ [L_{s2}] & [L_{s2}] \end{bmatrix}$$

$$[L'_{sr2}] = \begin{bmatrix} [L_{sr2}] & [L_{sr2}] \end{bmatrix}^t$$

$$[L'_{rs2}] = \begin{bmatrix} [L_{rs2}] & [L_{rs2}] \end{bmatrix} = \begin{bmatrix} [L_{sr2}]^t & [L_{sr2}]^t \end{bmatrix}$$

Application of the transformations matrix (7) and (8) in conjunction with the first row of (5) lead to the decoupled model of the six-phase two-motor drive system.

Source voltage equations that include equations of the two stator windings connected in series can be given as:

$$\begin{aligned} V_\alpha^s &= R_{s1} i_\alpha^s + L_{s1} \frac{di_\alpha^s}{dt} + L_{m1} \frac{d}{dt}(\cos(\theta_1) i_{r\alpha1} - \sin(\theta_1) i_{r\beta1}) \\ V_\beta^s &= R_{s1} i_\beta^s + L_{s1} \frac{di_\beta^s}{dt} + L_{m1} \frac{d}{dt}(\sin(\theta_1) i_{r\alpha1} + \cos(\theta_1) i_{r\beta1}) \\ V_x^s &= R_{s1} i_x^s + L_{ls1} \frac{di_x^s}{dt} + 2R_{s2} i_x^s + 2L_{s2} \frac{di_x^s}{dt} + \\ &\quad + \sqrt{2}\left[L_{m2} \frac{d}{dt}(\cos(\theta_2) i_{r\alpha2} - \sin(\theta_2) i_{r\beta2} \right] \\ V_y^s &= R_{s1} i_y^s + L_{ls1} \frac{di_y^s}{dt} + 2R_{s2} i_y^s + 2L_{s2} \frac{di_y^s}{dt} + \\ &\quad + \sqrt{2}\left[L_{m2} \frac{d}{dt}(\sin(\theta_2) i_{r\alpha2} + \cos(\theta_2) i_{r\beta2} \right] \\ V_{o+}^s &= R_{s1} i_{o+}^s + L_{ls1} \frac{di_{o+}^s}{dt} + 2\left[R_{s2} i_{o+}^s + L_{ls2} \frac{di_{o+}^s}{dt} \right] \\ V_{o-}^s &= R_{s1} i_{o-}^s + L_{ls1} \frac{di_{o-}^s}{dt} \end{aligned} \tag{6}$$

$$[T_6] = \sqrt{\frac{2}{6}} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha & \cos 5\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha & \sin 5\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \cos 8\alpha & \cos 10\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \sin 8\alpha & \sin 10\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \tag{7}$$

$$[T_3] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \cos 2\alpha & \cos 4\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{8}$$

where

$$\begin{bmatrix} V_\alpha^s \\ V_\beta^s \\ V_x^s \\ V_y^s \\ V_{o+}^s \\ V_{o-}^s \end{bmatrix} = [T_6] \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{bs2} \\ v_{cs1} + v_{cs2} \\ v_{ds1} + v_{as2} \\ v_{es1} + v_{bs2} \\ v_{fs1} + v_{cs2} \end{bmatrix} = \begin{bmatrix} V_{s\alpha1} \\ V_{s\beta1} \\ V_{sx1} + \sqrt{2} V_{s\alpha2} \\ V_{sy1} + \sqrt{2} V_{s\beta2} \\ V_{so+} \\ V_{so-} \end{bmatrix} \tag{9}$$

and

$$\begin{cases} i_\alpha^s = i_{s\alpha1} \\ i_\beta^s = i_{s\beta1} \end{cases} ; \quad \begin{cases} i_x^s = i_{sx1} = i_{s\alpha2} / \sqrt{2} \\ i_y^s = i_{sy1} = i_{s\beta2} / \sqrt{2} \end{cases} ; \quad \begin{cases} i_{o+}^s = i_{so+1} \\ i_{o-}^s = i_{so-1} \end{cases}$$

The torques equation takes the form:

$$\begin{cases} T_{e1} = p_1 L_{m1} \left(i_{rd1} i_q^s - i_d^s i_{rq1} \right) \\ T_{e2} = \sqrt{2} p_2 L_{m2} \left(i_{rd2} i_y^s - i_x^s i_{rq2} \right) \end{cases} \tag{10}$$

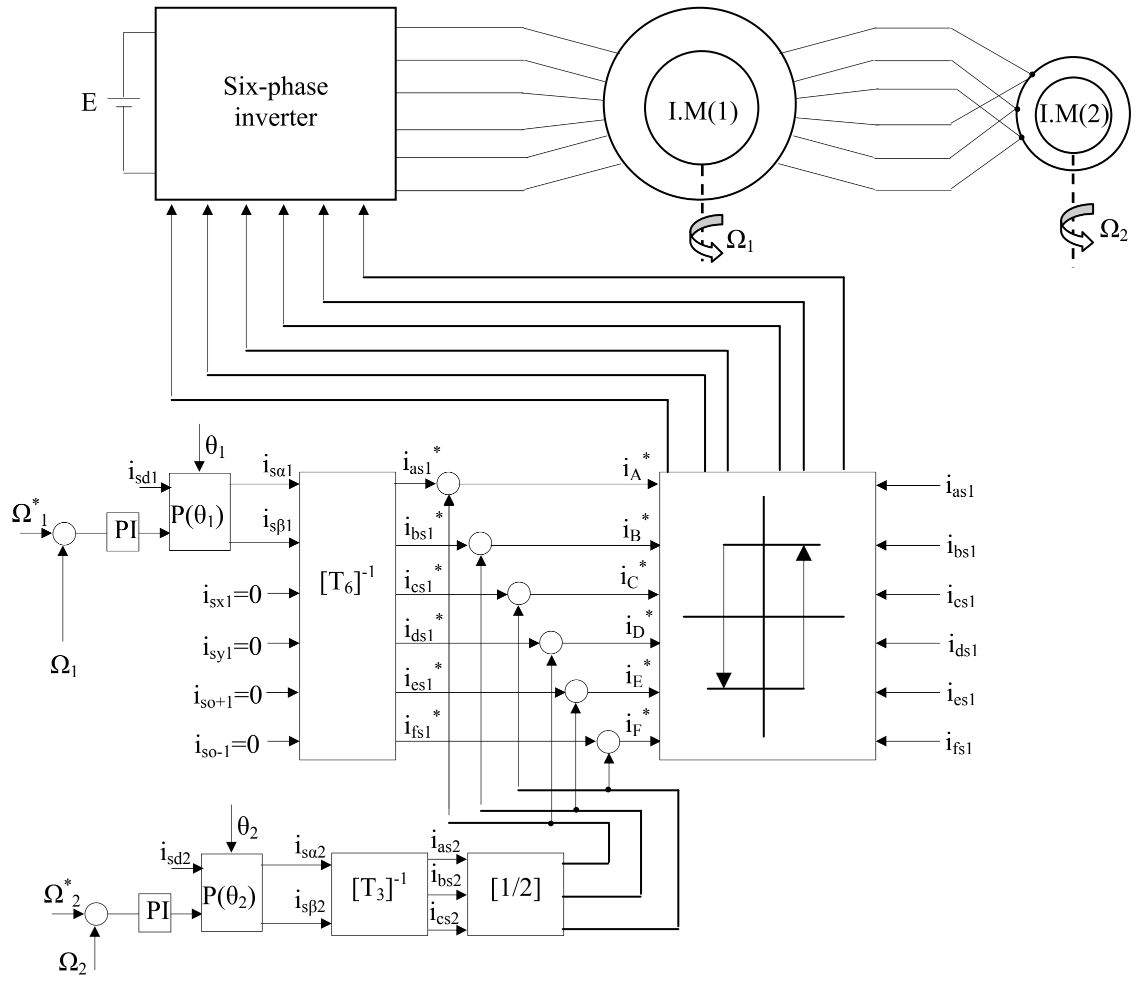

Fig. 2 Indirect rotor flux oriented controller for the two-motor drive.

According to (6)-(10), flux/torque producing stator currents of the six-phase machine are the source α-β current components, while the flux/torque producing stator currents of the three-phase machine are the source x-y current components. This indicates the possibility of independent vector control of two machines.

3. VECTOR CONTROL OF THE TWO-MOTOR DRIVE

As the model (6)–(10) indicates, the two series-connected machines can be controlled independently using rotor-flux-oriented control principles. Flux and torque of the six-phase machine are controllable by inverter d-q axis current components, while flux and torque of the three-phase machine can be controlled using inverter x-y current components. Indirect (feedforward) rotor-flux-oriented control is considered and current control in the stationary reference frame is assumed and exercised upon the inverter phase currents [7]-[11].

4. ROTOR TIME CONSTANT ESTIMATION

On-line estimation of the time constant T_{ri} (i=1,2) is realized using a model reference adaptive corrector approach . As depicted in fig. 3, the adaptation scheme is based on the inferential variables F^* and F^{est} representing the gap between T_{ri} and T_{ri}^{est} respectively.

The reference variable F^* is determined using the same dynamic model of the machine used for the computation of flux oriented control action. The estimated variable F^{est} is estimated based on the measured data of the current and tensions of the machines. Time constant estimation is the same for both machines and the one presented is for six phase machine.

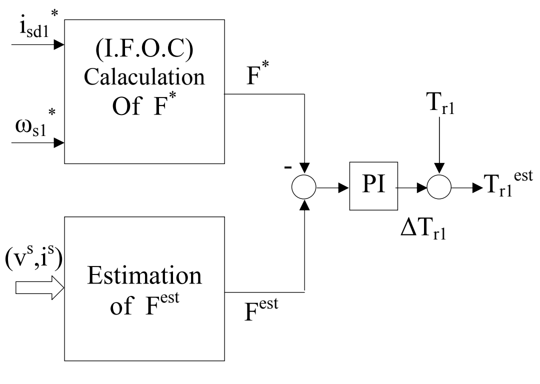

Fig. 3 Model Reference Adaptive Corrector scheme for estimation of time constant (I.F.O.C: Indirect Field Oriented Control).

The estimation algorithm is based on the calculation of the reactive power at steady state:

$$Q_{r1} = v_{sq1} i_{sd1} - v_{sd1} i_{sq1} \tag{11}$$

The Reference Model is represented by the function F* [8]:

$$F_1^* = \frac{L_{m1}}{L_{r1}} \left(\frac{d\phi_{rd1}}{dt} i_{sq1} - w_{s1} \phi_{rd1} i_{sd1} \right) \tag{12}$$

F^{est} could be expressed function of the rotor fluxes as follows :

$$\hat{F}_1 = \frac{L_{m1}}{L_{r1}} \frac{d\phi_{rd1}}{dt} i_{sq1} - \frac{L_{m1}}{L_{r1}} \frac{d\phi_{rq1}}{dt} i_{sd1} - \frac{L_{m1}}{L_{r1}} w_{s1} (\phi_{rq1} i_{sq1} + \phi_{rd1} i_{sd1}) \tag{13}$$

With :

$$\Delta F_1 = \hat{F}_1 - F_1^* = w_{s1} w_{sl(1)}^2 \frac{\phi_{rd1}^2}{L_{r1}} \Delta T_{r1} \frac{T_{r1} + \hat{T}_{r1}}{1 + (w_{sl(1)} \hat{T}_{r1})^2} \tag{14}$$

It can be noticed that the estimation algorithm depends also on the rotor inductance. Since we are interested only in studying the effect Tr_1 variations, we will assume that the rotor inductance is known and constant.

5. SIMULATION RESULTS

First, in order to test the performance of the adaptation scheme, simulation under full nominal load with six phase and three phase machines rotating respectively at 1500 rpm and 750 rpm are performed. The results of dynamic behaviour of the estimated time constants Tr1 and T_{r2} after 50% change of the rotor resistance at t=1 s and t=1.5 s respectively are depicted in figure 4. The simulation results show that the estimated time constants converged to the correct values.

Next, different cases of simulation results demonstrating the decoupling and independent control of the two machines connected in series are shown in figures 5-10.

Case1: The three-phase induction machine is started at t=1.5 s after the acceleration transient time expired the speed settled at 500 rpm while the I.M(1) speed is maintained constant equal to 1000 rpm. Fig. 5 shows the speeds, torques and currents per phase. As can be noticed, I.M(1)'s speed and electromagnetic torque are not affected by the starting operation of the I.M(2).

Case 2: The three-phase induction machine is rotated at constant speed equal to 500 rpm while the I.M(1) is started at t = 1.5 s to settle at speed of 1000 rpm at the end of acceleration transient time (Fig.6). As can be noticed, the speed and torque of the I.M(2) are not affected by the acceleration period of the I.M(1).

Case 3: Effect of the change rotation direction one of the machines on system performance is investigated. Figs.(7), (8) shows the results when the speed of I.M(1) is changed from + 1000 rpm to -1000 rpm at t = 1.5s while the other I.M(2) direction is kept unchanged and vise versa (i.e. the direction of the I.M(2) is changed from +500 to -500 rpm while that of I.M(1) is kept unchanged). Simulation results show that the decoupled control is preserved and the characteristics of both machines are unaffected.

Finally, time constant variation effect on the indirect vector control of the multimachines is investigated with and without the adaptation scheme. We noticed that the time constant variation affect the decoupling flux/torque, however the other machine decoupling flux/torque of is unaffected. To overcome this problem, the time constants T_{r1} and T_{r2} of both machines are estimated on-line using the adaptation scheme described above. Dynamic behaviour of the fluxes and torques of the system subjected to variation of time.

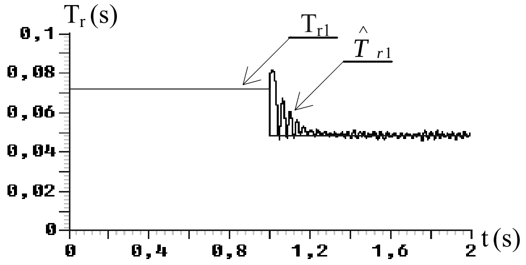

Fig. 4(a) Estimated time constant after 50 % change of the rotor resistance R_{r1} at t =1 s.

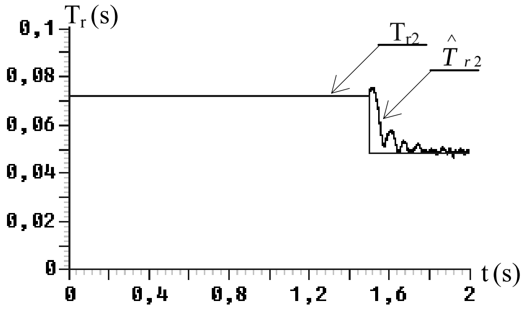

Fig. 4(b) Estimated time constant after 50 % change of the rotor resistance R_{r2} at t =1.5 s.

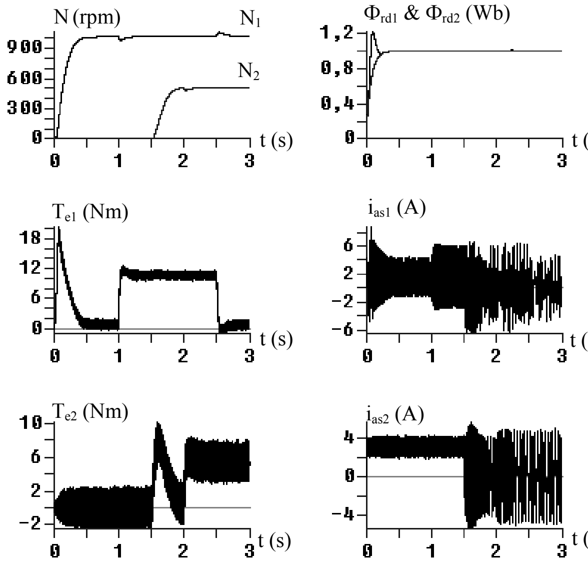

Fig. 5 Performance of indirect vector controlled system: Acceleration of I.M(2) from 0 to 500 rpm.

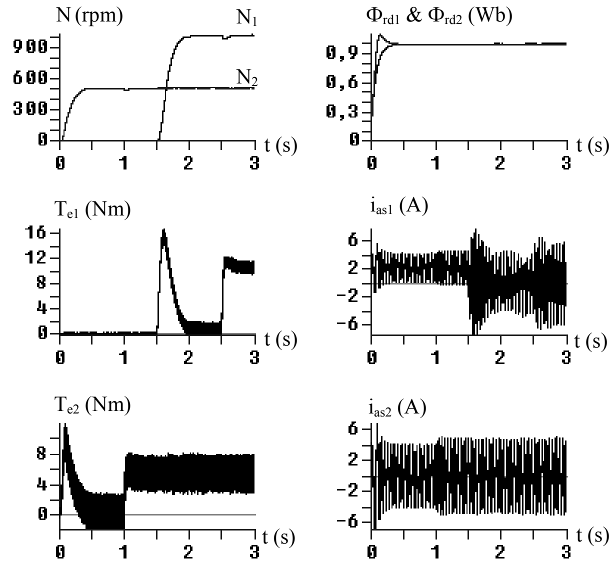

Fig. 6 Performance of indirect vector controlled system: Acceleration of I.M(1) from 0 to 1000 rpm.

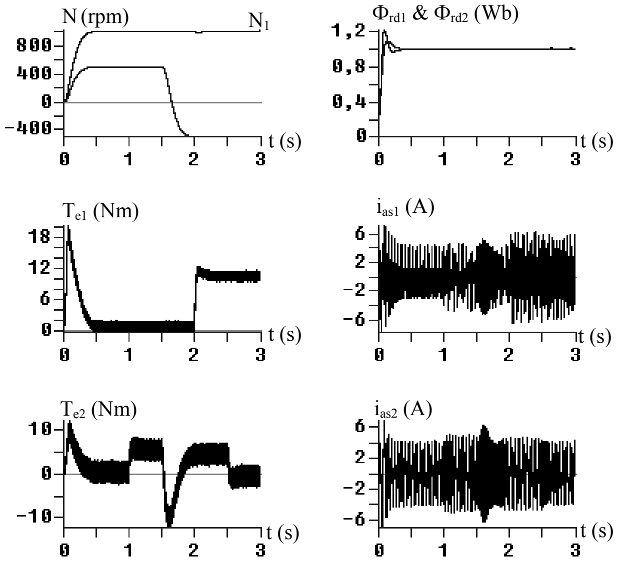

Fig. 7 Performance of indirect vector controlled system: The I.M(2) reverses from 500 to -500 rpm.

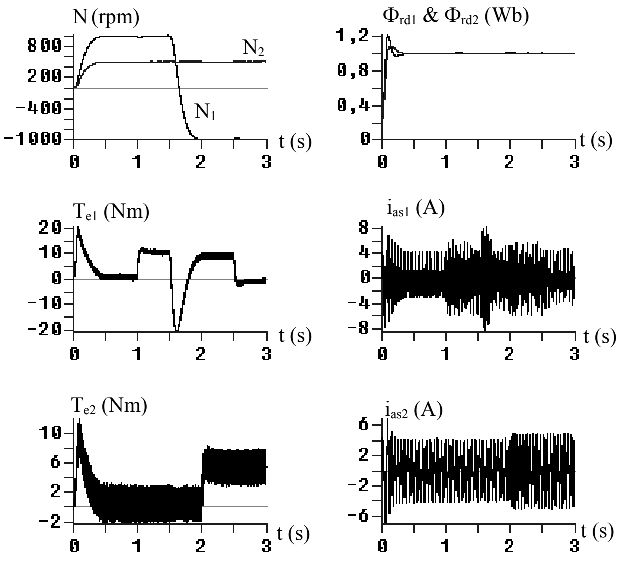

Fig. 8 Performance of indirect vector controlled system: The I.M(1) reverses from: 1000 to -1000 rpm.

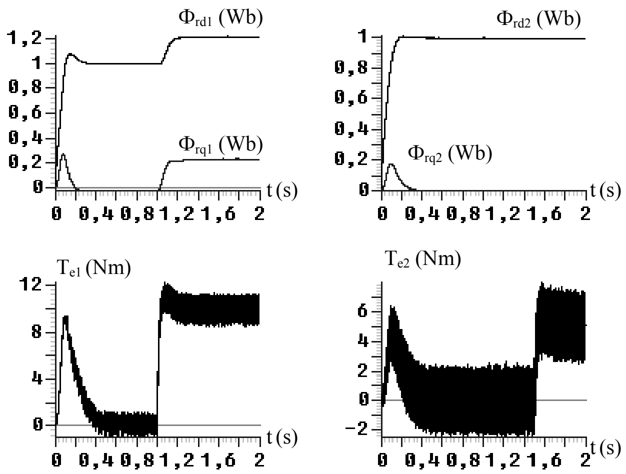

Fig. 9 (a) Sensitivity of indirect vector controlled system to T_{r1} variation (without updating of T_{r1}).

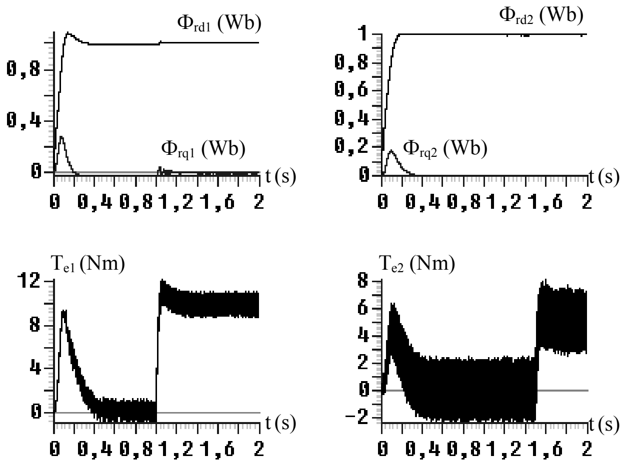

Fig. 9 (b) Sensitivity of indirect vector controlled system to T_{r1} variation (with updating of T_{r1}).

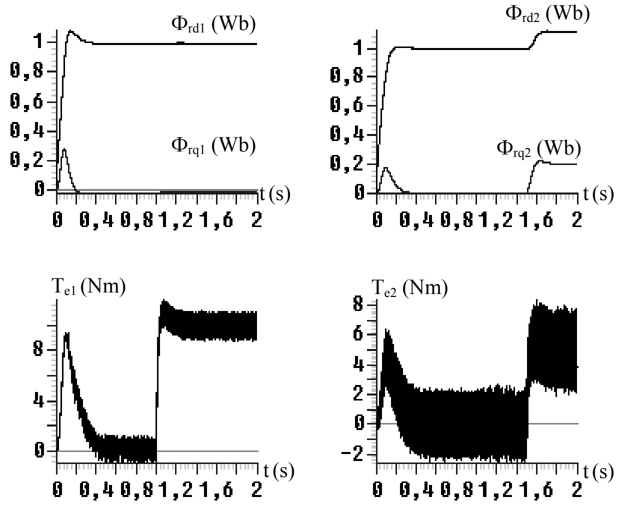

Fig. 10(a). Sensitivity of indirect vector controlled system to T_{r2} variation (without updating of T_{r2}).

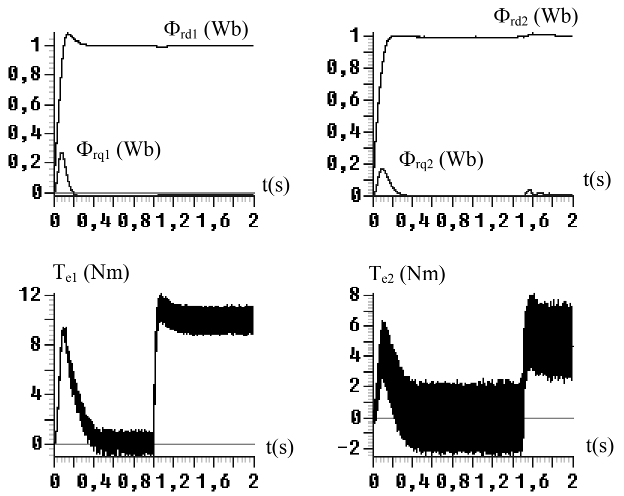

Fig. 10(b) Sensitivity of indirect vector controlled system to T_{r2} variation (with updating of T_{r2}).

6. CONCLUSION

In this paper, extensive simulation studies of series-connected multimachine drive supplied by a single inverter is presented. Modelling and simulation of the two motors drive and independent indirect vector control of the two machines has been considered. The results obtained demonstrate the possibility for independent control of both machines suing a single inverter. The sensitivity of the decoupling algorithm to change in the machine time constant has been analyzed. The results show that the effect of time constant variation is significantly eliminated by updating the time constants on-line.

APPENDIX

Per-phase equivalent circuit parameters of the 50 Hz 6-phase induction motor:

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

Inertia and number of pole pairs: J=0.03 Kgm^2, p=2.
Rated-per phase voltage and current (RMS) : 220 V, 3.6A.

REFERENCES

[1] E.LEVI, M.JONES, S.N.VUKOSAVIC, " Even-phase multi-motor vector controlled drive with single inverter supply and series connection of stator windings," IEE Proc. – Electric Power Applications, vol. 150, no. 5, pp. 580-590, 2003.

[2] E.LEVI, M.JONES, S.N.VUKOSAVIC, " A novel concept of a multiphase, multi-motor vector controlled drive system supplied from a single voltage source inverter," IEEE Trans. on Power Electronics, vol. 19, no. 2, pp. 320-335, 2004.

[3] E.LEVI, M.JONES, S.N.VUKOSAVIC, " Operating principles of a novel multi-phase multi-motor vector controlled drive," IEEE Trans. on Energy Conversion, vol. 19, no.2 , pp. 508-5173, 2004.

[4] E.LEVI, M.JONES, S.N.VUKOSAVIC, " Vector control schemes for series-connected six-phase two-motor drive systems," IEE Proc. – Electric Power Applications, vol. 152, no. 2, pp. 226-238, 2005.

[5] E.LEVI, M.JONES, S.N.VUKOSAVIC, " A six-phase series-connected two-motor drive with decoupled dynamic control," IEEE Trans. on Industry Applications, vol. 41, no. 4, pp. 1056-1066, 2005.

[6] E.LEVI, M.JONES, S.N.VUKOSAVIC, " Vector-controlled multi-phase multi-motor drive systems with a single inverter supply," IEEE Electronics, vol. 7, no. 2, pp. 9-20, 2003.

[7] E.LEVI, M.JONES, S.N.VUKOSAVIC, "A five-phase two-machine vector controlled induction motor drive supplied from a single inverter," European Power Electronics & Drives Journal, vol. 14, no. 3, pp. 38-48, 2004.

[8] E.LEVI, M.JONES, " Vector control of a five-phase series-connected two-motor drive using synchronous current controllers," Electric Power Components and Systems, vol. 33, no. 4, pp. 411-430, 2005.

[9] E.LEVI, M.JONES, S.N.VUKOSAVIC, " A series-connected two-motor six-phase drive with induction and permanent magnet machines," IEEE Trans. on Energy Conversion, vol. 20, 2005

[10] E.LEVI, M.JONES, S.N.VUKOSAVIC, "Rotor flux oriented control of a symmetrical six-phase induction machine," Electric Power Systems Research, vol. 75, no. 2-3, pp. 142-152, 2005.

[11] A.IQBAL, S.VUKOSAVIC, E.LEVI, M.JONES, " Dynamics of a series-connected two-motor five-phase drive system with a single-inverter supply," IEEE Industry Applications Society Annual Meeting IAS, Hong Kong, Oct. 2005.

Recevied December 5, 2007, accepted August 22, 2008

BIOGRAPHIES

Abdelkader Djahbar was born in Chlef, Algeria, in 1970. He received the Master degree, with honor, in electrical engineering from the Polytechnical School of Algiers, Algeria In 1999, he joined the department of electrical engineering, university of chlef, where, from 2000 to 2005, he was a research assistant. His scientific work is related to electrical machines and drives and Power Electronics. He has authored more than 20 papers published in conference proceedings. His present research interests include nonlinear adaptive observer of induction machine, matrix converter and power quality.

Benyounés Mazari (1953) received the state engineer degree in electrical engineering in 1978 from the University of Sciences and Technology of Oran USTO Algeria, the M.Sc degree from the University of Colorado Boulder USA in 1981 and the Doctorat degree from the “Institut National Polytechnique de Lorraine” INPL Nancy France in 1992. Since 1982, he was at the USTO-Oran and from 1987-1992 he was on leave as a researcher at INPL (France). Since 1992 he was a Professor of electrical sciences at the same university. His area of research includes power electronics, traction drives and harmonics in power systems.