

A six-phase series-connected two-motor drive with decoupled dynamic control supplied by a three-level six-phase inverter

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Abstract - *This paper presents independent vector control of six-phase two-motor drive machine series-connected fed by a three-level six-phase inverter. Via appropriate phase transposition during the series connection of the stator windings, the fully decoupled control of the two machines is possible. The control system multi machines classic based on vector control with conventional inverters comprise various problems are related to low power quality, pressure on motor bearing, etc. However, decoupling control of a series- six-phase two-motor drive machine by a three-level six-phase inverter is developed. A simulations results clearly shows the possibility of independent vector control of the two machines, although a single three-level six-phase inverter is used as the supply.*

Résumé - *Cet article présente la commande vectorielle indépendante d'une machine d'entraînement à deux moteurs et à six phases, connectée en série et alimentée par un onduleur à trois niveaux à six phases. Grâce à une transposition de phase appropriée lors du raccordement en série des enroulements statoriques, la commande entièrement découplée des deux machines est possible. Le système de commande multi-machines classique basé sur la commande vectorielle avec des onduleurs conventionnels comporte différents problèmes liés à la faible qualité de puissance, à la pression sur les paliers du moteur, etc. Cependant, la commande de découplage d'une machine d'entraînement à deux moteurs à six phases en série par un onduleur à trois niveaux et six phases est développée. Les résultats d'une simulation montrent clairement la possibilité d'un contrôle vectoriel indépendant des deux machines, bien qu'un seul onduleur six phases à trois niveaux soit utilisé comme alimentation.*

Keywords: Multiphase machines - Six-phase - Vector control - Three-level six-phase inverter.

1. INTRODUCTION

The multiphase systems have more advantages compared to the three phase systems like high output power rating, low torque pulsations and stable speed response [1]. The major advantages of using a multiphase machine instead of a standard three-phase machine were discussed [2]. At present multiphase drive, systems have gained increasing demand owing to their better performance and stable operation even when load fluctuations occur [3, 4].

Multiphase machines have gained attention in numerous fields of applications such as Aircraft, ship propulsion, petrochemical and automobiles, where high reliability is required [5, 6]. Multi-motor variable speed drive system has theoretical research and application significance in the fields of ship traction and More-Electric-Aircraft [7].

However, the disadvantages of traditional multi-motor variable speed drive system greatly limit its application. To improve the performance of multi -motor variable speed drive system, it is necessary to solve the problem of independent operation of motors in multi-motor system supplied from a single inverter.

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An additional possibility, opened up by the use of multiphase machines, is independent control of a set of series-connected motors, supplied from a single VSI. In an appropriate phase transposition is necessary when connecting the machines in series.

This logic is applicable to all machines having number of phase greater than or equal to five. A lot of works have been presented with diverse control diagrams of multi-phases machines is independent control of a group of series-connected machines [7, 8].

These control diagrams are usually based on vector control notion with conventional two-level voltage source inverter. with the conventional inverters comprise various problems are related to low power quality, immense voltage stresses, common mode noise, pressure on motor bearing, etc.

These problems are overcome by increasing the number phases and levels instead of conventional inverters, called as multi level inverters [9, 10]. In this approach, we focus in particular on the modeling and the decoupling control of a series-connected two five-phase PMSM supplied by a three-level six-phase Voltage source inverter.

The rest of the paper is arranged as follows. In section 2, the three level five-phase NPC inverter scheme is presented. Section 3 gives the system modeling. In section 4 we present the vector control strategy of two five-phase motor connected series supplied by a three-level inverter. Session 5 shows the simulation results. Finally, the main conclusions of the work are drawn.

2. THREE LEVEL SIX-PHASE NPC INVERTER SCHEME

Multilevel inverters are increasingly being used in high-power medium-voltage applications due to their superior performance compared to two-level inverters. Different types of multilevel inverter topologies were presented [11, 12].

A k level NPC-MLI inverter contains of $(k-1)$ capacitors on DC bus link, $2(k-1)$ power switching vector devices per phase and $2(k-2)$ variable clamping diodes per phase.

The capacitors used in 3 level inverter are C_1 and C_2 , which divides the DC bus voltage split into 3 level 14. Each capacitor divides voltage as $V_{dc}/2$ volts and voltage pressure will be inadequate to one capacitor level throughout clamping diodes. Figure 1 demonstrates the six-phase 3 levels NPC inverter scheme.

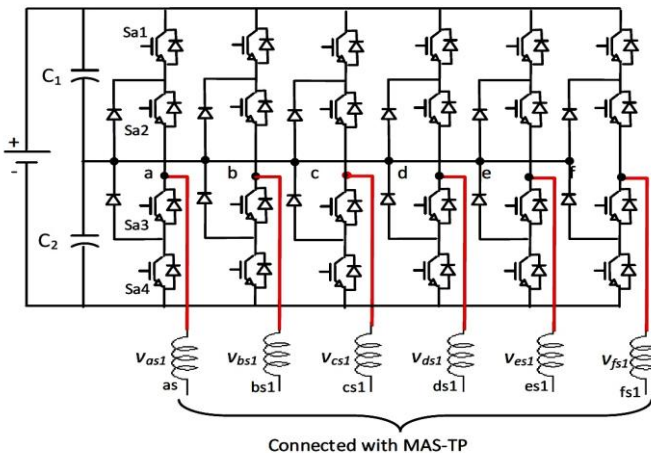


Fig. 1: Three level six-phase NPC-inverter

3. MODELLING OF THE SERIES-CONNECTED SIX-PHASE TWO-MOTOR

The drive system is composed by two induction machines. The first one is a symmetrical six-phase induction motor I.M (1) which its windings are series connected with that of a second three-phase induction motor M (2).

The two motors are supplied by a single power converter which is a six-phase Voltage Source Inverter (VSI). Figure 1 presents the connecting and supplying schematic of the two motors and the converter. The six-phase machine has the spatial displacement between any two consecutive stator phases equal to 60° (i.e. $\alpha = 2\pi/6$). Only phases 1, 3 and 5 are used by the second machine I.M (2), this phases are electrically displaced to each other by an angle of $2\pi/3$.

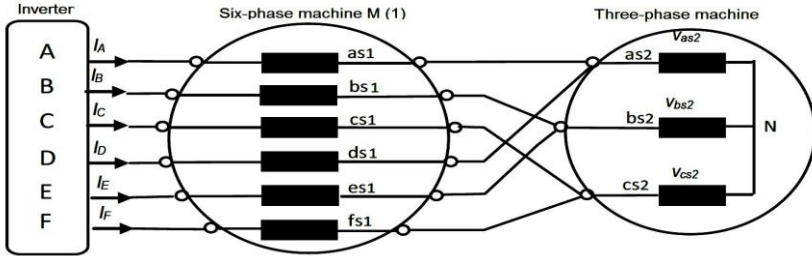


Fig. 2: Diagram of connection of a hexaphase machine with a three-phase machine in series

According to figure. 2, the stator and rotor voltages of the two machines can be written as follows:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \\ V_E \\ V_F \end{bmatrix} = \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{bs2} \\ v_{cs1} + v_{cs2} \\ v_{ds1} + v_{ds2} \\ v_{es1} + v_{es2} \\ v_{fs1} + v_{fs2} \end{bmatrix} \tag{1}$$

The relationship between the current source and the stator currents of each machine are given as follows:

$$\begin{aligned} [i_s] &= [I_A \ I_B \ I_C \ I_D \ I_E \ I_F] \\ &= [I_{as1} \ I_{bs1} \ I_{cs1} \ I_{ds1} \ I_{es1} \ I_{fs1}] \\ &= [i_{s1}] \end{aligned} \tag{2}$$

$$[i_{s2}] = \begin{bmatrix} i_{as2} \\ i_{bs2} \\ i_{cs2} \end{bmatrix} = \begin{bmatrix} I_A + I_D \\ I_B + I_E \\ I_C + I_F \end{bmatrix} \tag{3}$$

The electrical equations

$$\begin{cases} [V_{sk}] = [R_{sk}] \cdot [i_{sk}] + \frac{d}{dt} [\phi_{sk}] \\ [0] = [R_{rk}] \cdot [i_{rk}] + \frac{d}{dt} [\phi_{rk}] \end{cases} \tag{4}$$

Where:

$$\begin{cases} [\varphi_{sk}] = [L_{ssk}] \cdot [i_{sk}] + [M_{srs}] \cdot [i_{rk}] \\ [\varphi_{rk}] = [L_{rrk}] \cdot [i_{rk}] + [M_{rsk}] \cdot [i_{sk}] \end{cases} \tag{5}$$

Knowing that $k = 1$ for the M (1) and $k = 2$ for the M (2)

With:

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

4. MODEL OF THE SMMC IN THE REFERENCE FRAME $(\alpha, \beta), (X, Y), (O+, O-)$

The original six dimensional systems of the SMMC can be decomposed into three orthogonal subspaces, $(\alpha, \beta), (X, Y)$, and $(O+, O-)$, using the following transformation $X_{\alpha\beta o} = [T_6(\alpha)]^{-1} \cdot X_{abc}$ and $X_{dqo} = [T_6(\alpha)]^{-1} \cdot X_{\alpha\beta o}$.

Where: X represents stator currents, stator flux, stator voltages in MSCS.

The matrix $[T_6(\alpha)]$ is given by:

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

$$[T_3(\alpha)] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \cos 2\alpha & \cos 4\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{7}$$

$$[\rho(\theta)] = \begin{pmatrix} \begin{bmatrix} \cos(\theta_0) & -\sin(\theta_0) \\ -\sin(\theta_0) & \cos(\theta_0) \end{bmatrix} & [0]_{2 \times 4} \\ [0]_{4 \times 2} & [I]_{4 \times 4} \end{pmatrix} \tag{8}$$

$$\begin{cases} [T_6]^{-1} [\varphi_{s,abcdef}] = [\varphi_{s\alpha} & \varphi_{s\beta} & \varphi_{sx} & \varphi_{sy} & \varphi_{so+} & \varphi_{so-}]^T \\ [T_6]^{-1} [i_{s,abcdef}] = [i_{s\alpha} & i_{s\beta} & i_{sx} & i_{sy} & i_{so+} & i_{so-}]^T \end{cases} \tag{9}$$

$$\begin{cases} [T_6]^{-1} [\varphi_r] = [0 & 0 & 0]^T \\ [T_6]^{-1} [i_r] = [i_{r\alpha} & i_{r\beta} & i_{o+}]^T \end{cases}$$

Application of the transformations matrix (6) and (7) in conjunction with the first row of (4) 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:

- Subsystem (α, β)

$$\begin{cases} V_{s\alpha} = R_{s1} \cdot i_{s\alpha1} + L_{s1} \cdot \frac{di_{s\alpha1}}{dt} + M_1 \cdot \frac{di_{r\alpha1}}{dt} \\ V_{s\beta} = R_{s1} \cdot i_{s\beta1} + L_{s1} \cdot \frac{di_{s\beta1}}{dt} + M_1 \cdot \frac{di_{r\beta1}}{dt} \end{cases} \quad (10)$$

- Subsystem (X, Y)

$$\begin{cases} V_{sx} = R_{eq} \cdot i_{sx1} + (I_{s1} + 2L_{s2}) \cdot \frac{di_{sx1}}{dt} + \sqrt{2} M_2 \cdot \frac{di_{r\alpha2}}{dt} \\ V_{sy} = R_{eq} \cdot i_{sy1} + (I_{s1} + 2L_{s2}) \cdot \frac{di_{sy1}}{dt} + \sqrt{2} M_2 \cdot \frac{di_{r\beta2}}{dt} \end{cases} \quad (11)$$

- Subsystem ($O+, O-$)

$$\begin{cases} V_{so+} = R_{eq} \cdot i_{so+1} + (I_{s1} + 2L_{s2}) \cdot \frac{di_{so+1}}{dt} \\ V_{so-} = R_{eq} \cdot i_{so-1} + I_{s1} \cdot \frac{di_{so-1}}{dt} \end{cases} \quad (12)$$

Rotor voltage equations of six-phase machine and three-phase machine are:

$$\begin{cases} 0 = R_{r1} \cdot i_{r\alpha1} + L_{m1} \cdot \frac{di_{s\alpha1}}{dt} + L_{r1} \cdot \frac{di_{r\alpha1}}{dt} + \omega_{r1} (L_{m1} \cdot i_{s\beta1} + L_{r1} \cdot i_{r\beta1}) \\ 0 = R_{r1} \cdot i_{r\beta1} + L_{m1} \cdot \frac{di_{s\beta1}}{dt} + L_{r1} \cdot \frac{di_{r\beta1}}{dt} + \omega_{r1} (L_{m1} \cdot i_{s\alpha1} + L_{r1} \cdot i_{r\alpha1}) \end{cases} \quad (13)$$

$$\begin{cases} 0 = R_{r2} \cdot i_{r\alpha2} + \sqrt{2} L_{m2} \cdot \frac{di_{sx1}}{dt} + L_{r2} \cdot \frac{di_{r\alpha2}}{dt} + \omega_{r2} (\sqrt{2} L_{m2} \cdot i_{sy1} + L_{r2} \cdot i_{r\beta2}) \\ 0 = R_{r2} \cdot i_{s\beta2} + \sqrt{2} L_{m2} \cdot \frac{di_{sy1}}{dt} + L_{r2} \cdot \frac{di_{r\beta2}}{dt} - \omega_{r2} (\sqrt{2} L_{m2} \cdot i_{sx1} + L_{r2} \cdot i_{r\alpha2}) \end{cases} \quad (14)$$

With:

$$\begin{cases} L_{s1} = l_{s1} + 3/2 L_{msl} \\ M_1 = 3/\sqrt{2} L_{sr1} \\ L_{r1} = l_{r1} + 3/2 L_{msl} \end{cases} ; \begin{cases} L_{s2} = l_{s2} + 3/2 L_{ms2} \\ M_2 = 3/\sqrt{2} M_{sr2} \\ L_{r2} = l_{r2} + 3/2 L_{mr2} \end{cases} \quad (15)$$

Application of (6) in conjunction with (1) yields:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sx} \\ v_{sy} \\ v_{so+} \\ v_{so-} \end{bmatrix} = [T_6] \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{bs2} \\ v_{cs1} + v_{cs2} \\ v_{sd1} + v_{sa2} \\ v_{se1} + v_{sb2} \\ v_{sf1} + v_{sc2} \end{bmatrix} = \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sx1} + \sqrt{2} v_{s\alpha2} \\ v_{sy1} + \sqrt{2} v_{s\beta2} \\ v_{so+} \\ v_{so-} \end{bmatrix} \quad (16)$$

and

$$\begin{cases} i_{s\alpha} = i_{s\alpha1} \\ i_{s\beta} = i_{s\beta1} \end{cases} ; \begin{cases} i_x = i_{sx1} = i_{s\alpha2} / \sqrt{2} \\ i_y = i_{sy1} = i_{s\beta2} / \sqrt{2} \end{cases} ; \begin{cases} i_{o+} = i_{so+1} \\ i_{o-} = i_{so-1} \end{cases} \quad (17)$$

Torque equations of the two machines are:

$$\begin{cases} T_{em1} = P_1 M_1 (i_{rd1} i_{sq1} - i_{sd} I_{rq1}) \\ T_{em2} = P_2 M_2 (i_{rd2} i_{sy1} - i_{sx} I_{rq2}) \end{cases} \quad (18)$$

As can be seen to equations (10) - (14) and (18), that 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. It therefore follows that independent vector control of the two machines can be realized with a single six-phase inverter.

5. VECTOR CONTROL OF THE TWO-MOTOR DRIVE

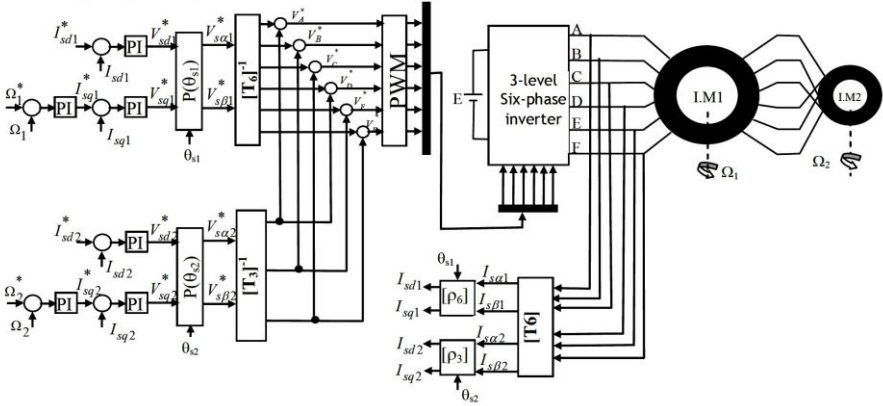


Fig. 3: Indirect rotor flux oriented controller for the two-motor drive

6. SIMULATION RESULTS

The simulation results of vector speed control of the two series connected machines in (MSCS) is developed in the Matlab, different simulation results demonstrating the decoupling and independent control of the two machines connected in series are shown in figures 4 and 5. The following simulations are performed using two machines.

Many simulation tests are performed in order to verify the independence of the control of the two machines.

Figure 4 show then speeds, currents, Flux and torques of the unloaded two machines for many different speeds references. At the beginning, the first machine the speed reference is set at 50 rad/s, 0 rad/s and 50 rad/s at 0, 0.75 s , 1.5 s, respectively. For the second machine the speed reference is set at 100 rad/s, 0 rad/s, 80 rad/s at 0 s, 1 s, 2 s respectively.

The pace of speed perfectly follows its reference which is reached quickly with an acceptable response time. The response of the two components of the current shows decoupling introduced by vector control of two machines.

As shown from figure 5, the starting and reversing transients of one machine do not have any tangible consequence on the operation of the second machine. The decoupled control is preserved and the characteristics of both machines are unaffected.

In the stating phase, the first machine is rotating at 50 rad/s; the other is running at the opposite speed. After that Ω_1 is kept at standstill, while the second machine, the speed reference is set at -100 rad/s, 0 rad/s and 100 rad/s at $t = 0s, 1s$ and $2s$ respectively. It can be seen in figure 5 that initiation of a speed transient for the three-phase machine has no impact on the behavior of the six-phase machine since neither the speed nor the stator-axis.

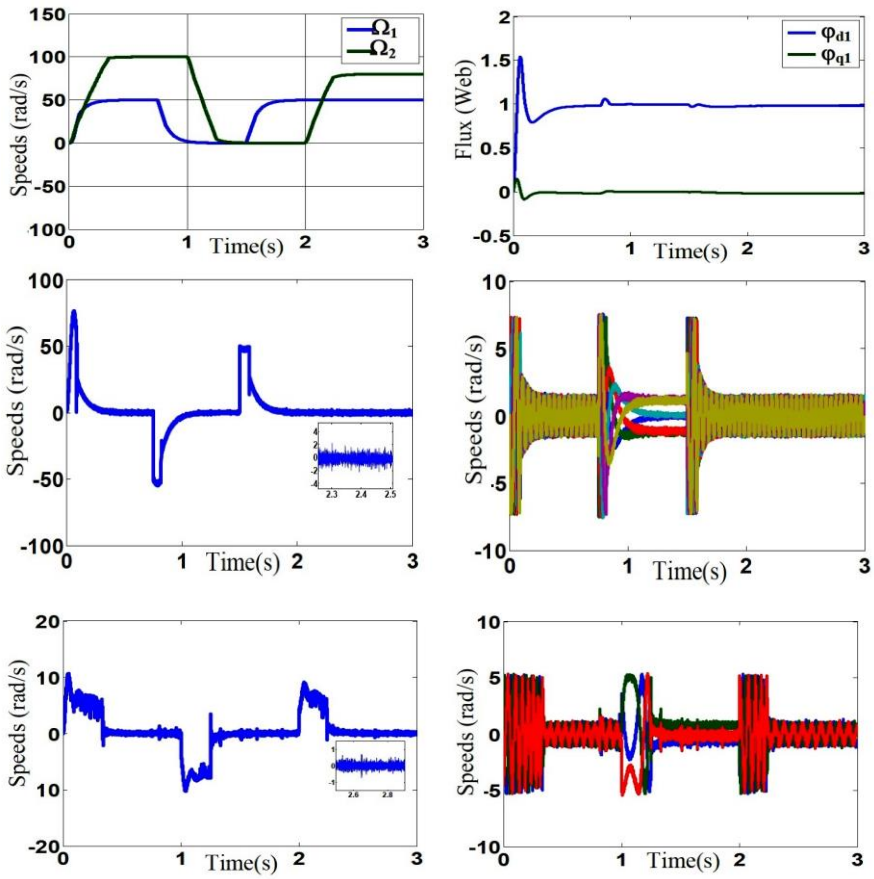
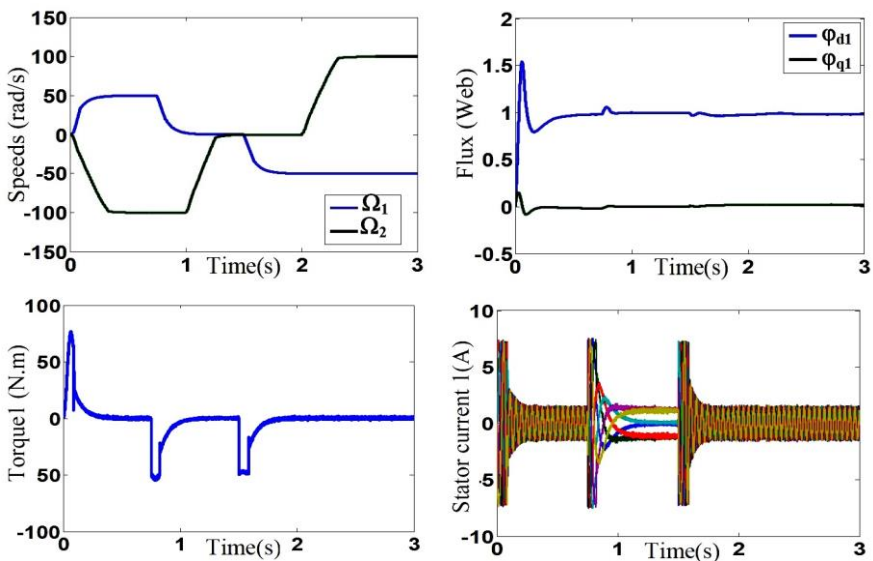


Fig. 4: Dynamic responses of series-connected two six-phase system fed by a three-level six-phase inverter at different reference speeds values



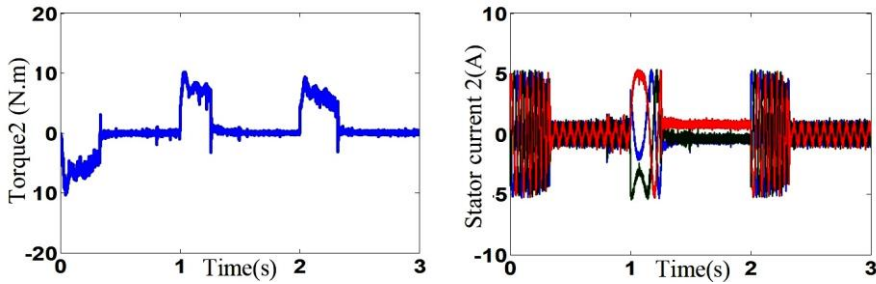


Fig. 5: Dynamic responses of series-connected two six-phase system fed by a three-level six-phase inverter: when the two motors are operating in the opposite directions

7. CONCLUSION

The paper examines a six-phase series-connected two-motor drive system, powered by a three-level six-phase inverter. Modelling and simulation of the two machine-drives and independent vector control of the two machines has been considered. The transposition of two machines has allowed us to have more degree of freedom on the axes of currents and so ordered two machines independently.

The control system multi-machines classic based on vector control with conventional inverters comprise various problems. These problems are overcome by increasing the number of level instead of conventional two-level six-phase inverter.

The independent vector control two machines gave good results and helped to decouple control flow and torque for both machines.

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