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Decoupled Control of a Multi-Machines System Fed by a Single Multilevel Inverter Six-Phase

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Abstract: The use of multiphase motors offers an additional possibility of independent control of a set of series-connected motors that are supplied from a single inverter.This paper presents independent vector control of six-phase two-motor drive machine series-connected fed by a seven-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 seven-level six-phase inverter is developed. A simulations result clearly shows the possibility of independent vector control of the two machines, although a single seven-level six-phase inverter is used as the supply.

Keywords: Multiphase machines, Six-phase, Vector control, Seven-level six-phase inverter

Introduction

Recently, researchers are interested in machines with a number of phases greater than three. These machines are often called «multiphase machines». Multi-phase machines have following advantages over three-phase machines: The application of these machines is an effective solution to the problem of high power under supply voltage restriction circumstances. Power segmentation, reducing torque ripple and increasing ripple frequency, significantly improving low-speed performance; by reducing vibration and noise, the reliability of the drive system is greatly improved with increased number of phases. A lot of works have been presented with diverse control diagrams of multi–phase machines is independent control of a group of series-connected machines.

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.

Multilevel power conversion was rest introduced more than two decades ago. The general concept involves utilizing a higher number of active semiconductor switches to perform the power conversion in small voltage steps. Multilevel inverters are promising; they have nearly sinusoidal outputvoltage waveforms, output current with better harmonic pro le, less stressing of electronic components owing to decreased voltages, switching losses that are lower than those of conventional two-level inverters, a smaller size, and lower EMI, all of which make them cheaper, lighter, and more compact. This paper studies the seven levels inverter NPC structure applied in multi-machines system, we focus in particular on the modeling and the decoupling control of a series-connected two six-phase and three-phase machines supplied by a seven-level six-phase Voltage source inverter.

Seven Lever 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. The seven-level hexaphase inverter studies and consists of six arms and four sources of voltage contained. Each arm has eight switches, six in series and the other two in parallel, plus two diodes. The structure chosen in this study is that of the five-level NPC-structured six-phase voltage inverter, represented by the figure 1:

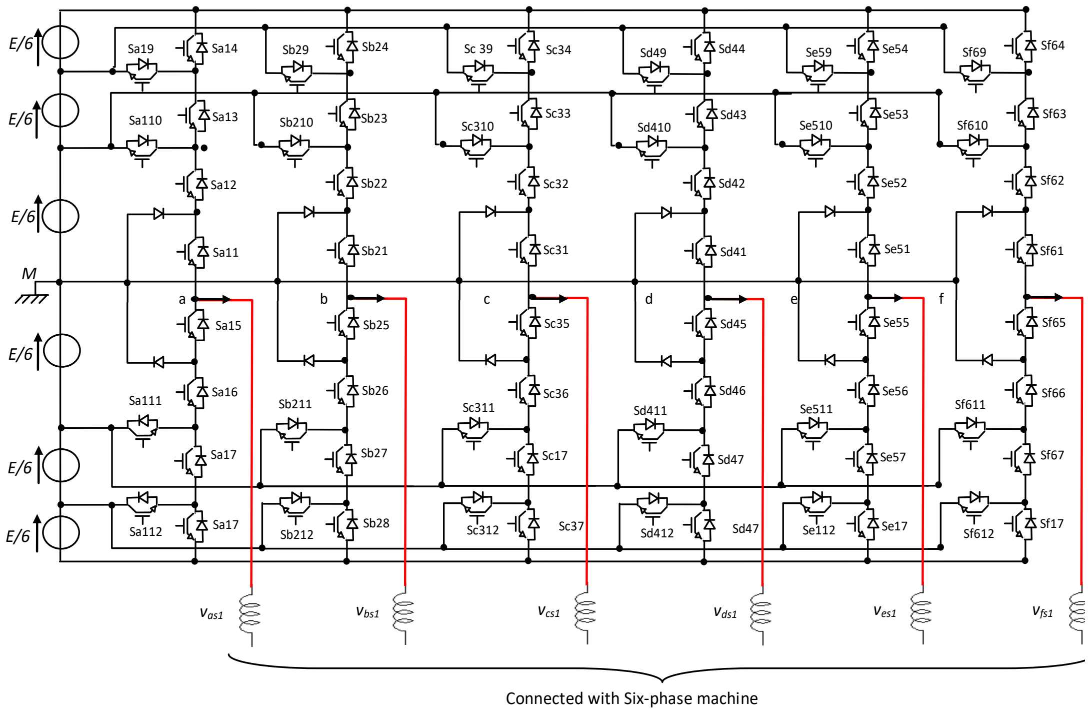

Figure 1. Seven level six-phase NPC-inverter

The switching states of the proposed seven-level SC-based inverter current flowing paths in different output voltage levels are presented in Table 1.

Table 1. Switching States of the proposed 7-level inverter

Switching states of the converter												Level of V_{ao}
S_{a1}	S_{a2}	S_{a3}	S_{a4}	S_{a5}	S_{a6}	S_{a7}	S_{a8}	S_{a9}	S_{a10}	S_{a11}	S_{a12}	
1	1	1	1	1	1	0	0	0	0	0	0	E/2
0	1	1	1	1	1	1	0	0	0	0	0	E/3
0	0	1	1	1	1	1	1	0	0	0	0	E/6
0	0	0	1	1	1	1	1	1	0	0	0	0
0	0	0	0	1	1	1	1	1	1	0	1	-E/2
0	0	0	0	0	1	1	1	1	1	1	0	-E/3
0	0	0	0	0	0	1	1	1	1	1	1	-E/6

Modeling 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.M1 which its windings are series connected with that of a second three-phase induction motor I.M2. The two motors are supplied by a single power converter which is a 7-level six-phase Voltage Source Inverter (VSI). Figure 2. presents the connecting and suppling 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.M2, this phases are electrically displaced to each other by and angle of $2\pi/3$.

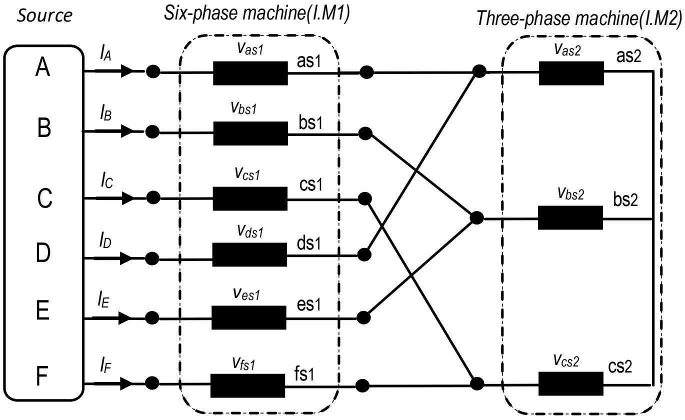

Figure 2. Diagram of connection of a tow-machine in series

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

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

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

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

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

The electrical equations:

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

where :

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

Knowing that k = 1 for the I.M1 and k = 2 for the I.M2

with:

$$\left[R_{seq}\right]=\left[R_{s1}\right]+\begin{bmatrix}[R_{s2}] & [R_{s2}]\\ [R_{s2}] & [R_{s2}]\end{bmatrix} \quad ; \quad \left[L_{seq}\right]=\left[L_{s1}\right]+\begin{bmatrix}[L_{s2}] & [L_{s2}]\\ [L_{s2}] & [L_{s2}]\end{bmatrix}$$

Modeling of Multi-Machine System (MSCS) into Three Subspaces (α,β), (X,Y), (O+,O-)

The original six dimensional systems of the SMMC can be decomposed into three orthogonal subspaces, (α, β), (x, y) and (o+, o-), using the following transformation $X_{\alpha\beta o}= [T_6(\alpha)]^{-1}.X_{abc}$ and $X_{dqo} = [T_6(\alpha)]^{-1}\ X_{\alpha\beta o}$
Where: X represents stator currents, stator flux, stator voltages in MSCS. The matrix $[T_6(\alpha)]$ is given by:

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

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

$$\left[\rho(\theta)\right]=\begin{bmatrix}\begin{bmatrix}\cos(\theta o & -\sin(\theta i\\ -\sin(\theta i & \cos(\theta o\end{bmatrix} & [0]_{2\times 4}\\ [0]_{4\times 2} & [I]_{4\times 4}\end{bmatrix} \quad (8)$$

where:

$$\begin{cases}[T_6]^{-1}\left[\varphi_{s,abcdef}\right]=\left[\varphi_{s\alpha}\quad \varphi_{s\beta}\quad \varphi_{sx}\quad \varphi_{sy}\quad \varphi_{so^+}\quad \varphi_{so^-}\right]^T\\ [T_6]^{-1}\left[i_{s,abcdef}\right]=\left[i_{s\alpha}\quad i_{s\beta}\quad i_{sx}\quad i_{sy}\quad i_{so^+}\quad i_{so^-}\right]^T\end{cases} \quad (9)$$

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

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:

Sub-system (α, β):

$$\begin{cases}V_{s\alpha}=R_{s1}i_{s\alpha 1}+L_{s1}\dfrac{di_{s\alpha 1}}{dt}+M_1\dfrac{di_{r\alpha 1}}{dt}\\ V_{s\beta}=R_{s1}i_{s\beta 1}+L_{s1}\dfrac{di_{s\beta 1}}{dt}+M_1\dfrac{di_{r\beta 1}}{dt}\end{cases} \quad (10)$$

Sub-system (x, y):

$$\begin{cases}V_{sx}=R_{eq}i_{sx1}+(l_{s1}+2L_{s2})\dfrac{di_{sx1}}{dt}+\sqrt{2}M_2\dfrac{di_{r\alpha 2}}{dt}\\ V_{sy}=R_{eq}i_{sy1}+(l_{s1}+2L_{s2})\dfrac{di_{sy1}}{dt}+\sqrt{2}M_2\dfrac{di_{r\beta 2}}{dt}\end{cases} \quad (11)$$

Sub-system (O^+, O^-):

$$\begin{cases} V_{so+} = R_{eq} i_{so+1} + (l_{s1} + 2L_{s2}) \dfrac{di_{so+1}}{dt} \\ V_{so-} = R_{eq} i_{so-1} + l_{s1} \dfrac{di_{so-1}}{dt} \end{cases} \tag{12}$$

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

$$\begin{cases} 0 = R_{r1} i_{r\alpha 1} + L_{m1} \dfrac{di_{s\alpha 1}}{dt} + L_{r1} \dfrac{di_{r\alpha 1}}{dt} + \omega_{r1} (L_{m1} i_{s\beta 1} + L_{r1} i_{r\beta 1}) \\ 0 = R_{r1} i_{r\beta 1} + L_{m1} \dfrac{di_{s\beta 1}}{dt} + L_{r1} \dfrac{di_{r\beta 1}}{dt} + \omega_{r1} (L_{m1} i_{s\alpha 1} + L_{r1} i_{r\alpha 1}) \end{cases} \tag{13}$$

$$\begin{cases} 0 = R_{r2} i_{r\alpha 2} + \sqrt{2} L_{m2} \dfrac{di_{sx1}}{dt} + L_{r2} \dfrac{di_{r\alpha 2}}{dt} + \omega_{r2} (\sqrt{2} L_{m2} i_{sy1} + L_{r2} i_{r\beta 2}) \\ 0 = R_{r2} i_{r\beta 2} + \sqrt{2} L_{m2} \dfrac{di_{sy1}}{dt} + L_{r2} \dfrac{di_{r\beta 2}}{dt} - \omega_{r2} (\sqrt{2} L_{m2} i_{sx1} + L_{r2} i_{r\alpha 2}) \end{cases} \tag{14}$$

with:

$$\begin{cases} L_{s1} = l_{s1} + \dfrac{3}{2} L_{ms1} \\ M_1 = \dfrac{3}{\sqrt{2}} L_{sr1} \\ L_{r1} = l_{r1} + \dfrac{3}{2} L_{mr1} \end{cases} \quad \begin{cases} L_{s2} = l_{s2} + \dfrac{3}{2} L_{ms2} \\ M_2 = \dfrac{3}{\sqrt{2}} M_{sr2} \\ L_{r2} = l_{r2} + \dfrac{3}{2} L_{mr2} \end{cases} \tag{15}$$

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

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sx} \\ v_{sy} \\ v_{so+} \\ v_{so-} \end{bmatrix} = [T_6] \begin{bmatrix} v_{sa1} + v_{sa2} \\ v_{sb1} + v_{sb2} \\ v_{sc1} + v_{sc2} \\ v_{sd1} + v_{sa2} \\ v_{se1} + v_{sb2} \\ v_{sf1} + v_{sc2} \end{bmatrix} = \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sx1} + \sqrt{2} v_{s\alpha 2} \\ v_{sy1} + \sqrt{2} v_{s\beta 2} \\ v_{so+} \\ v_{so-} \end{bmatrix} \tag{16}$$

and

$$\begin{cases} i_{s\alpha} = i_{s\alpha 1} \\ i_{s\beta} = i_{s\beta 1} \end{cases} ; \quad \begin{cases} i_x = i_{sx1} = \dfrac{i_{s\alpha 2}}{\sqrt{2}} \\ i_y = i_{sy1} = \dfrac{i_{s\beta 2}}{\sqrt{2}} \end{cases} ; \begin{cases} i_{o+} = i_{so+1} \\ i_{o-} = i_{so-1} \end{cases} \tag{17}$$

Torque equations of the two machines are:

$$\begin{cases} T_{em1} = P_1 M_1 (i_{rd} \, 1_{isq1} - i_{sd} i_{rq1}) \\ T_{em2} = P_2 M_2 (i_{rd2} i_{sy1} - i_{sx} i_{rq2}) \end{cases} \tag{18}$$

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.

Vector Control of the Two-Motor Drive

With the transformation (8), the components of the plane (α, β) to equations (10)-(14) can be expressed in the (d, q) plane. The two series-connected machines can be controlled independently using rotor-flux oriented control principles (Figure 3).

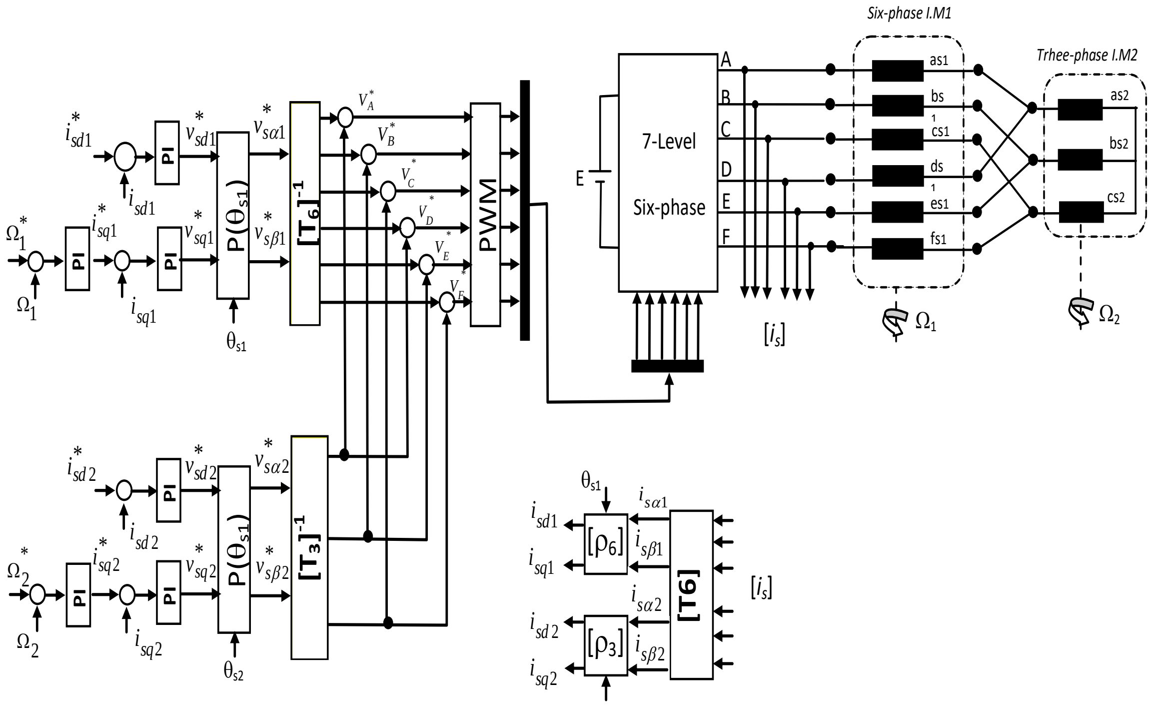

Figure 3. Indirect rotor flux oriented controller for the two-motor drive

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. Fig. 4 shows the operation of the two-machine drive system for many different speeds references with no load at starting up phase. At steady state condition, the two machines are loaded simultaneously or not by their nominal loads. At the beginning, the first machine is running at 20 rad/s; at t=0.5 s, it is accelerated to 50 rad/s, after that, its direction of rotation is reversed to -50 rad/s at t=2s and then stopped at t=3.5s. For the second machine the speed reference is set at 40 rad/s, 100 rad/s,-60 rad/s , and -40 rad/s at t=0 s, 1 s, 2.5 s, 3.5 s, respectively.It is clear too that the start of six phase machine (I.M1) did not have an impact on the speed or on the electromagnetic torque of the three phase machine (I.M2).

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 Ω1 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 Fig. 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.

Conclusion

The paper examines a six-phase series-connected two-motor drive system, powered by a five-level six-phase inverter. Modeling and simulation of the two machine-drives and independent vector control of the two machines has been considered. The transposition of two machines has al lowed 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.

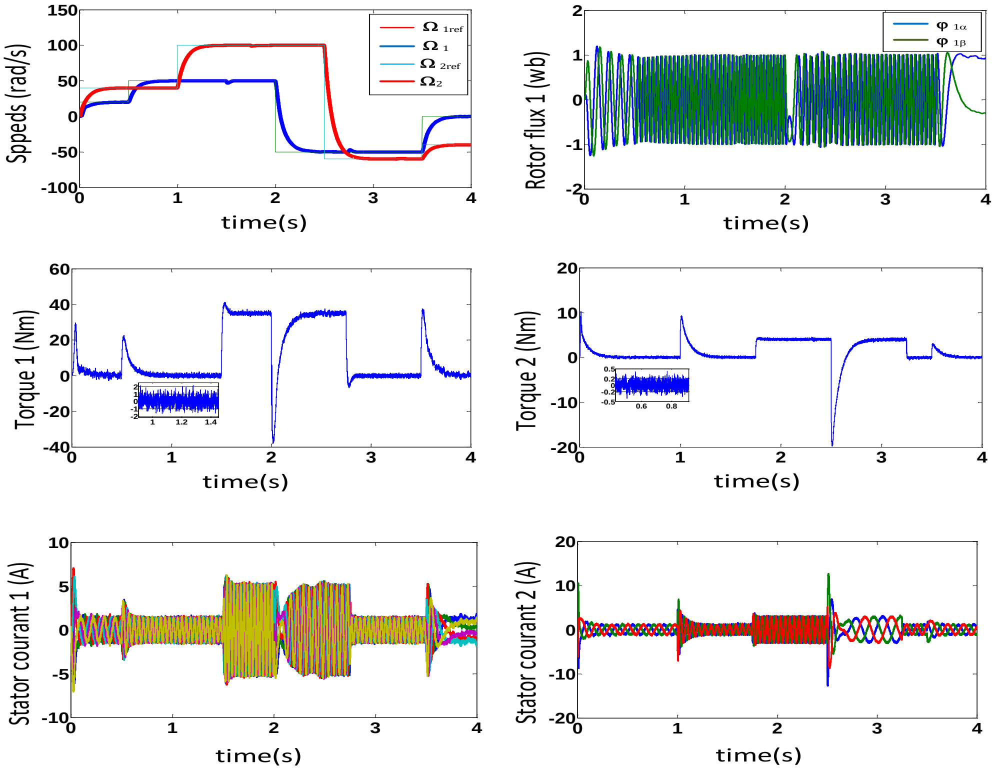

Figure 4. Dynamic responses of series-connected two six-phase system fed by a 7-level six-phase inverter at different reference speeds values.

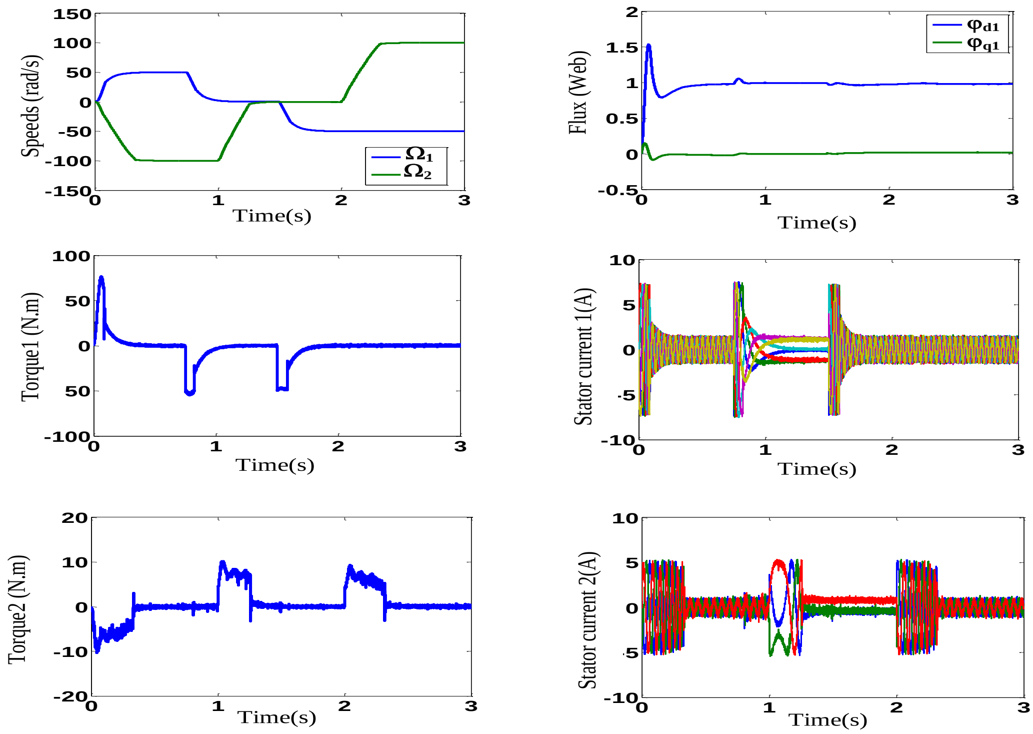

Figure 5. Dynamic responses of series-connected two six-phase system fed by a 7-level six-phase inverter: when the two motors are operating in the opposite directions.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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References

Bessaad, T., Taleb, R., Bachir, B. & Mellakhi, A. (2015). Modélisation et commande d'un système Multi machines alimentées par un seul convertisseur. *Revue des Energies Renouvelables*, *19*(1), 127 – 136.

Cui, Y., & Kavasseri, R. (2015). A particle filter for dynamic state estimation in multi-machine systems with detailed models. *IEEE Transactions on Power Systems*, *30*(6), 1-9.

Gheraia H., Berkouk E.M., & Manesse G. (2001). Modelling and control of a seven level NPC voltage source inverter, application to high power induction machine drive. *The European Physical Journal, 15*, 105-115.

Iqbal, A., & Levi, E. (2004). Modeling of a six-phase series-connected two motor drive system. *in Proc. Int. Conf. on Electrical Machines ICEM.* Krakow, Poland

Jyothi1, B. & Rao, M.V.G. (2017). Performance analysis of 3-level 5-phase multilevel inverter topologies. *International Journal of Electrical and Computer Engineering*, *7*(4), 1696 – 1705.

Kim, H., Shin, K., Englebretson, S., Frankand, N., & Arshad, W. (2013). Application areasof Multiphase Machines. *IEEE Conference on Electric Machines & Drives, Chicago*, *IL, USA*, 172 – 179.

Levi, E. (2008). Multiphase electric machines for variable-speed applications. *IEEE Conference on Industrial Electronics*, *55*(5), 1893 - 1909.

Levi, E., Jones, M., & Vukosavic, S.N. (2004). A novel concept of a multiphase, multi-motor vector controlled drive system supplied from a single voltage source inverter. *IEEE Trans. on Power Electronics*, 19(2), 320-335.

Levi, E., Jones, M., Vukosavic, S.N. (2005). A six-phase series-connected two-motor drive with decoupled dynamic control. *IEEE Trans. on Industry Applications*, *41*(4), 1056-1066.

Mohapatra, K. K., Baiju, M. R., & Gopakumar, K. (2004). Independent speed control of two six-phase induction motors using a single six-phase inverter. *EPE J.*, *14*(3) 49–62.

Odeh, C. I., Obeand, E. S., & Ojo, O. (2016). Topology for cascaded multilevel inverter', *IET Power Electronics*, *9(*5), 921 - 929,

Poh Chiang, L., Donald, G. H., Yusuke, F., & Thomas Lipo, A. (2004). A reduced common mode hysteresis current regulation strategy for multilevel inverters. *IEEE Transactions on Power Electronics*, *19*(1), pp. 192-200.

Ranjan, A., Bhatnagar, P., Sahu, L.K., & Jain, S.(2016). Multilevel inverter topologies with Reduced Device Count: A Review. *IEEE Power Electronics Society*, *31*(1), 135-151,

Saleh, M.A. (2013). *Development of control techniques for direct AC/AC matrix converter fed multiphase multi-motor drive system*. (Doctoral dissertation). Victoria University, Melbourne, Australia,

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