Decoupling control of a series-connected two five-phase PMSM supplied by a three-level five-level inverter

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(reçu le 15 Mars 2018 - accepté le 30 Mars 2018)

Abstract - *This paper presents independent vector control of two five-phase permanent magnet synchronous machines, 'PMSMs' series-connected fed by a three-level five-phase inverter. Fully decoupled control of both machines is possible via an appropriate phase transposition while connecting the stator windings serial. 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. In this paper, decoupling control of a series-connected two five-phase PMSM powered by a three-level five-phase inverter is presented. Simulations results are presented and discussed for the whole system.*

Résumé - *Cet article présente le contrôle vectoriel indépendant de deux machines synchrones à aimants permanents à cinq phases, 'PMSMs' connectées en série alimentées par un onduleur penta phase à trois niveaux. La commande entièrement découplée des deux machines est possible via une transposition de phase appropriée tout en connectant les enroulements du stator en série. Le système de contrôle multi-machines classique basé sur le contrôle vectoriel avec des onduleurs classiques comprend divers problèmes liés à la faible qualité de puissance, la pression sur le palier du moteur, etc. Dans cet article, le contrôle de découplage de deux PMSM à cinq phases alimentées par un onduleur à cinq phases à trois niveaux est présenté. Les résultats des simulations sont présentés et discutés pour l'ensemble du système.*

Keywords: Multi-machine - Permanent magnet synchronous machines (PMSMs) - Series-connected - Decoupling control - Five-phase PMSM - Three-level five-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

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drive system, it is necessary to solve the problem of independent operation of motors in multi-motor system supplied from a single inverter.

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 [7-9], 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-phase machines is independent control of a group of series-connected machines [9-11]. 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 [12, 13].

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 five-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 FIVE-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 [14, 15].

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.

The figure 1 demonstrates the five-phase 3 levels NPC inverter scheme [16].

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

In figure 2, the drive system is composed by two five-phase PMSM connected in series. The two motors are supplied by a three-level five-phase inverter. The five-phase machine has the spatial displacement between any two consecutive stator phases equal to 72° (i.e. $\alpha = 2\pi/5$).

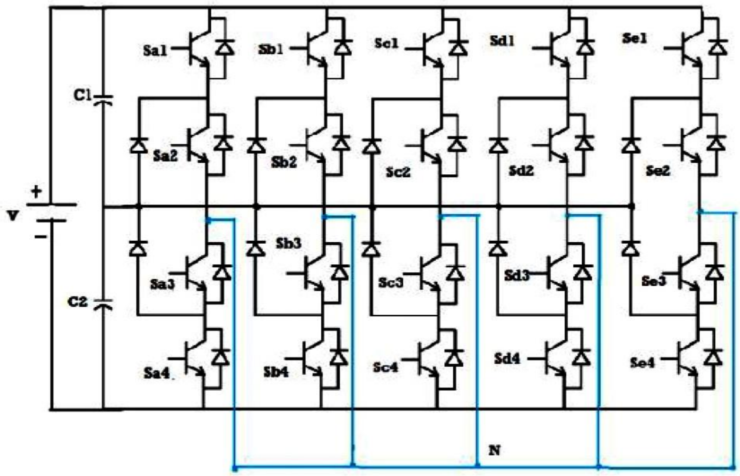

Fig. 1: Three level five-phase NPC-inverter

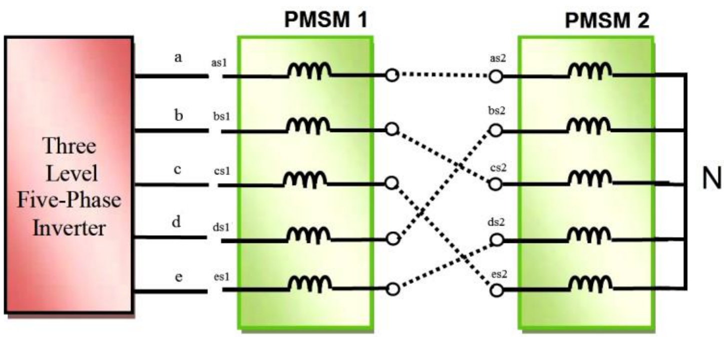

Fig.2: Two five-phase PMSM supplied by a three-level five- phaseinverter

Phase variable model of two five-phase PMSM connected in series according to figure 2 is developed in state space form as follows [17]:

$$\begin{aligned} v_a &= v_{as1} + v_{as2} \\ v_b &= v_{bs1} + v_{cs2} \\ v_c &= v_{cs1} + v_{es2} \\ v_d &= v_{ds1} + v_{bs2} \\ v_e &= v_{es1} + v_{ds2k} \end{aligned} \quad \text{and} \quad \begin{aligned} i_a &= i_{as1} + i_{as2} \\ i_b &= i_{bs1} + i_{cs2} \\ i_c &= i_{cs1} + i_{es2} \\ i_d &= i_{ds1} + i_{bs2} \\ i_e &= i_{es1} + i_{ds2} \end{aligned} \tag{1}$$

The Clark’s decoupling transformation matrix in power invariant form is [7-17]:

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

The new variables are defined as:

$$[f]_{\alpha\beta} = [C][f]_{abcdef}, \quad f = v, i \tag{3}$$

In order to simplify the phase-domain model, the decoupling transformation is applied. The new variables are defined as:

$$v_{\alpha\beta}^{inv} = C v^{inv}, \quad i_{\alpha\beta}^{inv} = C i^{inv} \tag{4}$$

The inverter/stator voltage equations are:

$$\begin{aligned}
v_{\alpha}^{inv} &= (R_{s1}+R_{s2}) i_{\alpha}^{inv} + (L_{sl1}+5/2m_{s1}) \frac{d}{d} i_{\alpha}^{inv} + L_{sl2} \frac{d}{d} i_{\alpha}^{inv} - \sqrt{5/2}\, w_1 \phi_{f1} \sin(\theta_1) \\
v_{\beta}^{inv} &= (R_{s1}+R_{s2}) i_{\beta}^{inv} + (L_{sl1}+5/2m_{s1}) \frac{d}{d} i_{\beta}^{inv} + L_{sl2} \frac{d}{d} i_{\beta}^{inv} + \sqrt{5/2}\, w_1 \phi_{f1} \sin(\theta_1) \\
v_{x}^{inv} &= (R_{s1}+R_{s2}) i_{x}^{inv} + (L_{sl2}+5/2m_{s2}) \frac{d}{d} i_{x}^{inv} + L_{sl1} \frac{d}{d} i_{x}^{inv} - \sqrt{5/2}\, w_2 \phi_{f2} \sin(\theta_2) \\
v_{y}^{inv} &= (R_{s1}+R_{s2}) i_{y}^{inv} + (L_{sl2}+5/2m_{s2}) \frac{d}{d} i_{y}^{inv} + L_{sl1} \frac{d}{d} i_{y}^{inv} - \sqrt{5/2}\, w_2 \phi_{f2} \sin(\theta_2)
\end{aligned} \tag{5}$$

For the model in space $(d-q)$ and $(x-y)$, rotational transformation matrix is applied D for voltage of the inverter.

$$D = \sqrt{\frac{2}{5}} \begin{bmatrix} \cos(\theta) & \sin(\theta) & - \\ \sin(\theta) & \cos(\theta) & - \\ - & - & [I]^{3*3} \end{bmatrix} \tag{6}$$

Torque equations of the two machines are:

$$\begin{cases} T_{e1} = p_1 \left((L_d - L_q) i_d^{inv} i_q^{inv} + \sqrt{\frac{5}{2}} \phi_{f1} i_q^{inv} \right) \\ T_{e2} = p_2 \left((L_x - L_y) i_x^{inv} i_y^{inv} + \sqrt{\frac{5}{2}} \phi_{f2} i_y^{inv} \right) \end{cases} \tag{7}$$

On the other hand, the mechanical equation of the machine is:

$$\begin{cases} J_{m1} \frac{dw_1}{dt} = p_1 T_{e1} - p_1 T_{r1} - f_{m1} w_1 \\ J_{m2} \frac{dw_2}{dt} = p_2 T_{e2} - p_2 T_{r2} - f_{m2} w_2 \end{cases} \tag{8}$$

4. INDEPENDENT CONTROL OF THE TWO FIVE- PHASE PMSM CONNECTED IN SERIES

As can be seen to equations (5) and (7), that flux/torque producing stator currents of the five-phase PMSM1 are the source (α, β) current components, while the flux/torque producing stator currents of the second machine PMSM2 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 three-level five-phase inverter.

<u>For the machine 1</u>

$$
\begin{aligned}
v_d^{inv} &= (R_{s1}+R_{s2})i_d^{inv} + \left(L_{s1}+5/2m_{sl1}\right)\frac{d}{dt}i_d^{inv} + L_{s2}\frac{d}{dt}i_d^{inv} - w_1\left(L_{s1}+5/2m_{sl1}\right)i_q^{inv} \\
v_q^{inv} &= (R_{s1}+R_{s2})i_q^{inv} + \left(L_{s1}+5/2m_{sl1}\right)\frac{d}{dt}i_q^{inv} + L_{s2}\frac{d}{dt}i_q^{inv} - w_1\left(L_{s1}+5/2m_{sl1}\right)i_d^{inv} + \sqrt{\frac{5}{2}}w_1\phi_{f1}
\end{aligned}
\tag{9}
$$

<u>For the machine 2</u>

$$
\begin{aligned}
v_x^{inv} &= (R_{s1}+R_{s2})i_x^{inv} + \left(L_{s1}+5/2m_{sl2}\right)\frac{d}{dt}i_x^{inv} + L_{s1}\frac{d}{dt}i_x^{inv} - w_1\left(L_{s2}+5/2m_{sl2}\right)i_y^{inv} \\
v_y^{inv} &= (R_{s1}+R_{s2})i_y^{inv} + \left(L_{s1}+5/2m_{sl2}\right)\frac{d}{dt}i_y^{inv} + L_{s1}\frac{d}{dt}i_y^{inv} - w_2\left(L_{s2}+5/2m_{sl2}\right)i_x^{inv} + \sqrt{\frac{5}{2}}w_2\phi_{f2}
\end{aligned}
\tag{10}
$$

Among the control strategies, one that is often used is to maintain the components i_d^{inv} and i_x^{inv} null. We control torques only by i_q^{inv} and i_y^{inv} as shown in figure 3.

The overall voltage references are then formed on the wiring diagram of figure 2 where as [11]:

$$
\begin{bmatrix} v_a^* \\ v_b^* \\ v_c^* \\ v_d^* \\ v_e^* \end{bmatrix} = \begin{bmatrix} v_{as1}^* + v_{as2}^* \\ v_{bs1}^* + v_{cs2}^* \\ v_{cs1}^* + v_{es2}^* \\ v_{ds1}^* + v_{bs2}^* \\ v_{es1}^* + v_{ds2}^* \end{bmatrix}
\tag{11}
$$

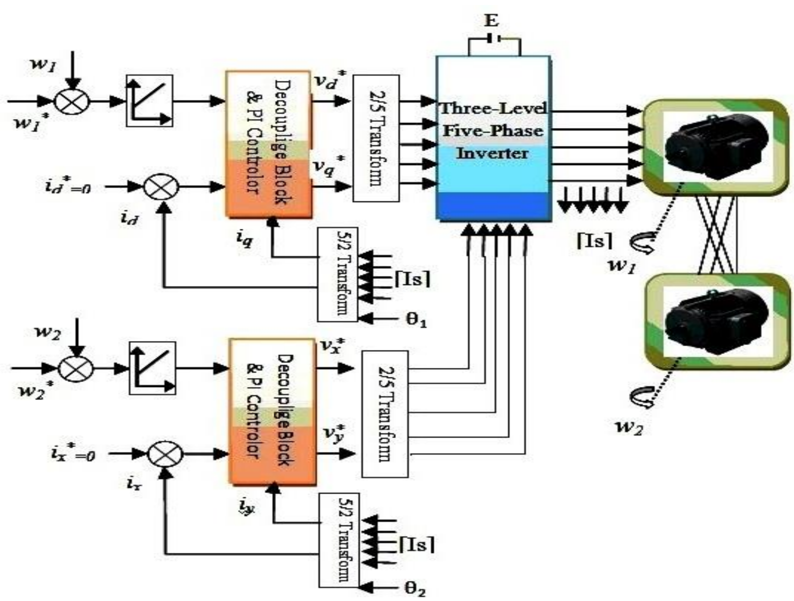

Fig. 3: Block diagram of the independent control of series-connected two five phase PMSM

5. SIMULATION RESULTS AND DISCUSSIONS

Different simulation results demonstrating the decoupling and independent control of the two machines connected in series are shown in figures 4 to 6. The following simulations are performed using two identical five-phase PMSM. The Parameters of the machine are given in appendix.

The whole system is simulated using the Matlab / Simulink software. Many simulation tests are performed in order to verify the independence of the control of the two machines.

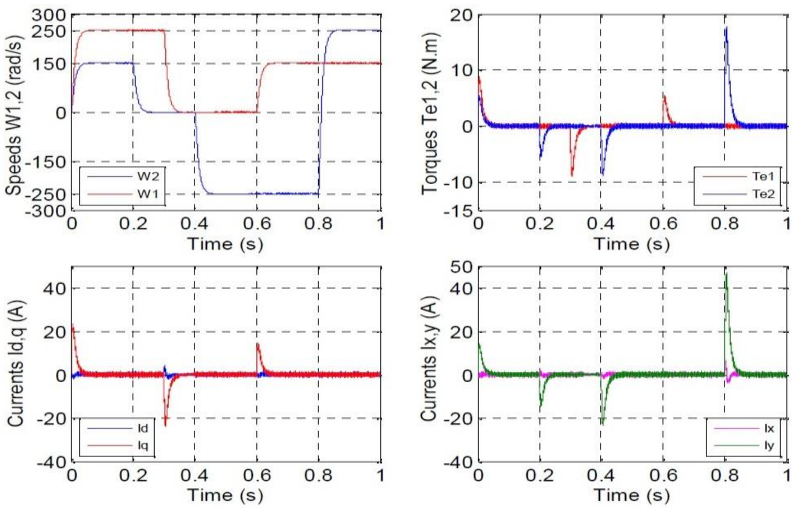

Fig. 4: Dynamic responses of series-connected two five-phase PMSMs system fed by a three-level five-phase inverter at different reference speeds values

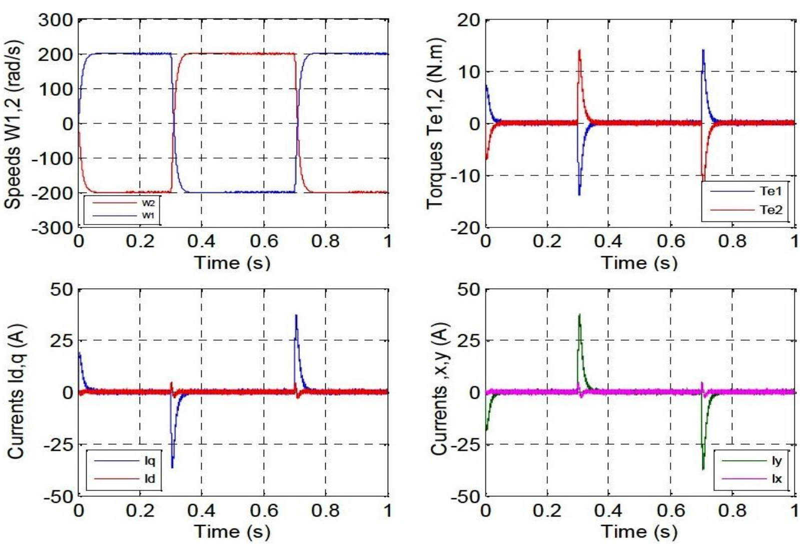

Fig. 5: Dynamic responses of series-connected two five-phase PMSMs system fed by a three-level five-phase inverter: when the two motors are operating in the opposite directions

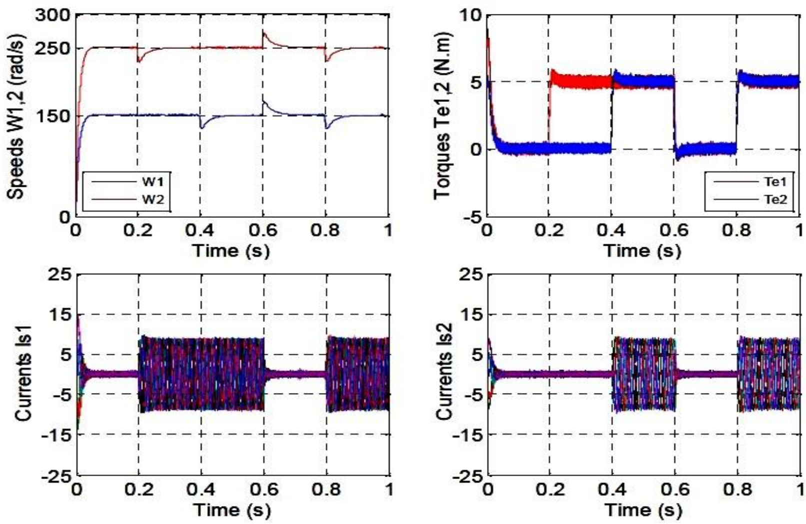

Fig. 6: Dynamic responses of series-connected two five-phase PMSMs system fed by a three-level five-phase inverter at different loading conditions

Figure 4 show then speeds, currents and torques of the unloaded two machines for many different speeds references. At the beginning, the first machine the speed reference is set at 250 rad/s, 0 rad/s and 150 rad/s at $t = 0s$, 0.3 s, 0.6 s, respectively.

For the second machine the speed reference is set at 150 rad/s, 0 rad/s, -250 rad/s and 250 rad/s at $t = 0s$, 0.2 s, 0.4 s, 0.8 s, respectively. The pace of speed perfectly follows its reference which is reached very quickly with an acceptable response time. The response of the two components of the current shows decoupling introduced by vector control of two five phase 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.

Figure 6 shows the speeds and torques of the two-machine drive using a three-level five-phase inverter in the presence of load torques variations.

The reference of the first speed is fixed at 250 rad/s, while the speed reference of the second machine is fixed at 150 rad/s. Load torques are applied on the two machines at $t =$ [0.2 s, 0.6 s] and $t =$ [0.8 s, 1 s] (PSMS1), $t =$ [0.4 s, 0.6 s] and $t =$ [0.8 s, 1 s] (PMSM2), the load torque is kept equal to its value $T_r =$ 0.5 N.m.

From figure 6, it can be noticed that each machine speed follows closely its reference. The effect of the disturbance is quickly removed and the electromagnetic torque stabilizes at a value of 5 N.m. The current I_q is the image of the torque 1. The current I_y is the image of torque 2.

6. CONCLUSION

This paper presents simulation studies of series-connected twofive-phase PMSM powered by a three-level five-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 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 five-phase inverter.

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

APPENDIX A

A.1 List of symbols

Table 1: List of symbols

Symbol	Significance
v_{ds}, v_{qs}, i_{ds}, i_{qs}	d and q axis stator voltages and currents
v_{xs}, v_{ys}, i_{xs}, i_{ys}	x and y axis stator voltages and currents
R_s	Stator resistances,
L_s	Total inductance of stator,
L_{sl}	Leakage inductance of stator,
ms	Magnetizing inductance,
ϕ_p	main magnetic flux of the permanent
p	Number of pole pairs,
J_m	Inertia moment,
f_m	Viscous damping,
w_r	Rotational speed (rd/s),
T_r	Load torque,
T_e	Electromagnetic torque.

A.2 Machine parameters

Table 2: Parameters of five-phase PMSM

Parameters	Rated Value
Stator resistance, R_s	3.6 Ω
Stator inductance, L_s	0.0021 H
Rotor inductance, L_q	0.0021 H
Stator frequency, f	50 Hz
Number of pairs poles, p	2
Inertia moment, J_m	0.0011 kg/m^2
Viscous damping, f_m	0
Magnetic flux, ϕ_f	0.12 Web

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