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Vector control of two five phase machines synchronous with permanent magnet connected in series application to the rail traction

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***Abstract* —The Systems Multi-machines /multi -converters (MMS) have recently been developed for many applications industry that some machines are driven by the inverters. This class of system offers a reduction of design time, costs and the optimization of the volume of embedded systems.**
The objective of this work is to order, model and characterize the behavior of a training system multimachines composed of two five phase synchronous permanent magnet motors connected in series and powered by a five phase inverter applied to the rail traction (bogie of a locomotive BB 36000) In view of the design of its command.

***Keywords*— synchronous machine, Multi-machine Multi-inverter, five-phase, vector control, Railway traction**.

I. INTRODUCTION

Thanks to the advances in technology and the means of calculating the powerful, it is possible to consider the variable speed applications in an efficient manner where the association of electrical machines and of static converters are more and more applications in embedded systems (ships, submarines, vehicles, aircraft...etc.), where the gain in space and weight requires a very particular attention. An example of the systems of drives, which combine the advantages offered by the use of machinery multiphasées, of the electronic power and the means of calculation, is the system monoconvertisseur multimachines which allows you to order in a way completely decoupled several electrical machines whose windings are connected in series.
The traction systems electric railway are complex, they have electrical couplings, magnetic and mechanical solid. These couplings impose a number of constraints that complicate the modeling and analysis of these systems. Multi Machine / System Multi-converter systems (MMS) used to meet the industrial requirements such as the optimization of the system volume and weight. Several configurations are developed and analyzed in order to guarantee the stability of operation when a mechanical disturbance or electric appears.
In this approach, we focus in particular on the modeling and the independent control of the two five phase synchronous permanent magnet motors connected in series.

II. Description and modeling of the system:

The use of a structure composed of two engines powered by a single static converter, allows one hand to reduce the number of components of power and control, and on the other hand, to establish a command for the entirety of the bogie of traction. In this study the overall system consists of two five phase motor synchronous with permanent magnet connected in series. Therefore many configurations are possible. The first consists of a continuous floor which supplies several three-phase inverters mounted in parallel, or each inverter supplies a three phase motors. The control of each engine is independent via its inverter and its control algorithm. The second configuration consists of a single converter, which moreover supplies in parallel several Engines. For this structure, the engines must have the same speed of rotation and suffer the same load torque.

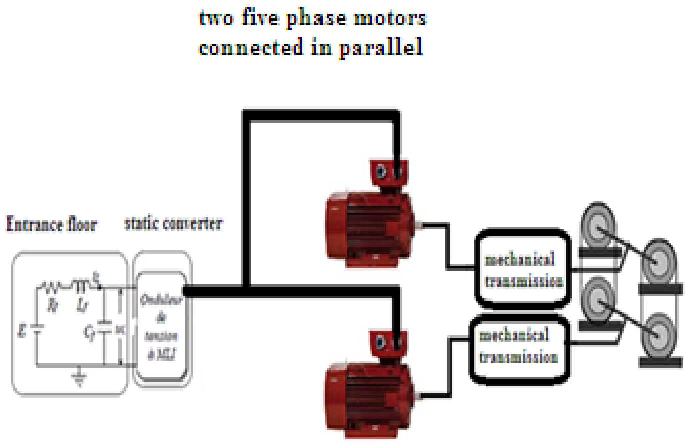

Fig .(01): Block diagram with a command structure of the configuration parallel for the chain of rail traction.

A new structure of propulsion is proposed. It consists of a inverter to seven levels of voltage to pulse width modulation, feeding in series with the two five phase motors.

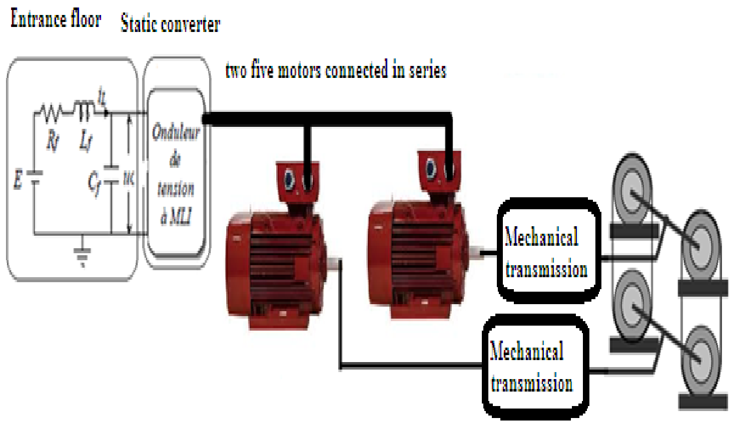

Fig (02): Block diagram with a command structure proposed for the chain of rail traction.

III.modeling of two five phase motors synchronous with permanent magnet connected in series:

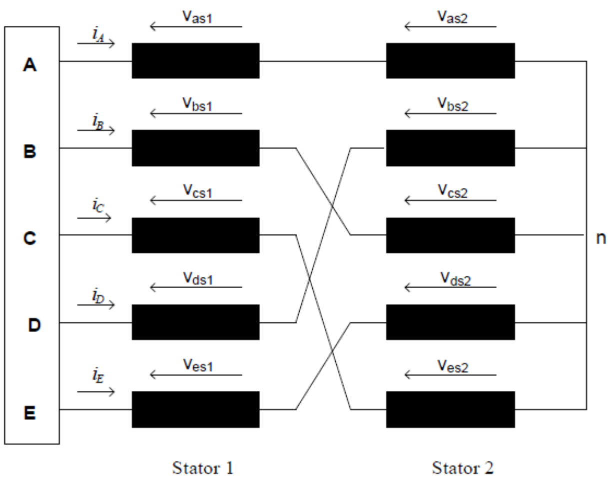

Fig .(03): description of two five phase motor connected in series.

According to the connection diagram of the fig(3), where the phase voltages of the two machines are defined, voltages of the inverter phase-neutral (A, B, C, D, E to NEUTRAL (N) and the relationship between the output current of the ups and currents of the phases of the two machines are provided with:

$$[V_s]=\begin{bmatrix} v_A \\ v_B \\ v_C \\ v_D \\ v_E \end{bmatrix}=\begin{bmatrix} v_{as1}+v_{as2} \\ v_{bs1}+v_{cs2} \\ v_{cs1}+v_{es2} \\ v_{ds1}+v_{bs2} \\ v_{es1}+v_{ds2} \end{bmatrix} \quad (1)$$

$$\begin{aligned} i_A &= i_{as1} = i_{as2} \\ i_B &= i_{bs1} = i_{cs2} \\ i_C &= i_{cs1} = i_{es2} \\ i_D &= i_{ds1} = i_{bs2} \\ i_E &= i_{es1} = i_{ds2} \end{aligned} \quad (2)$$

The two machines of Fig (3) are assumed to be of the same parameters, the electrical circuit of the model of the fig (3) it can be represented as a matrix form (quantities not linear) by:

$$[V_{\text{ABCDE}}] = [R_s][I_{\text{ABCDE}}] + \frac{d}{dt}[\Phi_{\text{ABCDE}}] \quad (3)$$

III.1.Transformation of decoupling of Clark:

The relationship between the original variables of the phases and the new variables (αβxyo) is given by:

$$f(\alpha\beta)' = [C] f(ABCDE) \quad (4)$$

Where [C] is the transformation matrix to invariant Power:

$$[C_s]^t = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) \\ 0 & \sin(\alpha) & \sin(2\alpha) & \sin(3\alpha) & \sin(4\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha) & \cos(8\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & \sin(6\alpha) & \sin(8\alpha) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

Applying this matrix tension vector inverter there will:

$$\begin{bmatrix} v_\alpha^{inv} \\ v_\beta^{inv} \\ v_x^{inv} \\ v_y^{inv} \\ v_o^{inv} \end{bmatrix} = [C]\begin{bmatrix} v_A \\ v_B \\ v_C \\ v_D \\ v_E \end{bmatrix}$$

Using this matrix to the relation (1), The tensions of each machine in this mark:

$$\begin{bmatrix} v_\alpha^{inv} \\ v_\beta^{inv} \\ v_x^{inv} \\ v_y^{inv} \\ v_o^{inv} \end{bmatrix} = [C]\begin{bmatrix} v_{as1}+v_{as2} \\ v_{bs1}+v_{cs2} \\ v_{cs1}+v_{es2} \\ v_{ds1}+v_{bs2} \\ v_{es1}+v_{ds2} \end{bmatrix} = \begin{bmatrix} v_{\alpha s1}+v_{xs2} \\ v_{\beta s1}+v_{ys2} \\ v_{xs1}+v_{\alpha s2} \\ v_{ys1}+v_{\beta s2} \\ 0 \end{bmatrix} \quad (5)$$

The relationship between the output current of the ups and currents α-β, x-y of the two machines is:

$$\begin{aligned} i_\alpha^{INV} &= i_{\alpha 1} = i_{X2} \\ i_\beta^{INV} &= i_{\beta 1} = -i_{Y2} \\ i_X^{INV} &= i_{X1} = i_{\alpha 2} \\ i_Y^{INV} &= i_{Y1} = i_{\beta 2} \end{aligned} \quad (6)$$

As the sub-Space α-β is orthogonal to the sub- space X-Y, it follows that the specific method of the serial connection used in the Fig (3) will allow the vector command independent of the two machines.

$$[V_{\text{ABCDE}}] = [R_s][I_{\text{ABCDE}}] + \frac{d}{dt}([L_s][i_{ABCDE}] + [\Phi_{\text{aimant}}] \quad (7)$$

The component of order zero for the converter can also be well neglected. The Electromagnetic part of the drive system can then be represented with eight equations of the first order. The four equations of the converter are as follows:

$$
\begin{aligned}
v_\alpha^{INV} &= (R_{s1}+R_{s2})i_\alpha^{INV} + (l_{s1}+\frac{5}{2}m_{s1})\frac{d}{dt}i_\alpha^{INV} + l_{s2}\frac{d}{dt}i_\alpha^{INV} - \sqrt{\frac{5}{2}}\omega_1\phi_{f1}\sin(\theta_1) \\
v_\beta^{INV} &= (R_{s1}+R_{s2})i_\beta^{INV} + (l_{sl1}+2m_{s2})\frac{d}{dt}i_\beta^{INV} + l_{s2}\frac{d}{dt}i_\beta^{INV} + \sqrt{\frac{5}{2}\omega_1\phi_{f1}\cos(\theta_1)} \\
v_x^{INV} &= (R_{s1}+R_{s2})i_X^{INV} + l_{s1}\frac{d}{dt}i_x^{INV} + (l_{s2}+\frac{5}{2}m_{s2})\frac{d}{dt}i_x^{INV} - \sqrt{\frac{5}{2}}\omega_2\phi_{f2}\sin(\theta_2) \\
v_y^{INV} &= (R_{s1}+R_{s2})i_y^{INV} + l_{s1}\frac{d}{dt}i_y^{INV} + (l_{s2}-\frac{5}{2}m_{s2})\frac{d}{dt}i_y^{INV} + \sqrt{\frac{5}{2}}\omega_2\phi_{f2}\cos(\theta_2)
\end{aligned}
\tag{8}
$$

III.2 Model in a rotary index:

In order to express all sizes in a single frame, the stator variables are projected into a rotating reference frame (d, q) shifted by φ with respect to the fixed coordinate system (α, β), this transformation is calculated from the matrix D rotation as:

$$
D=\begin{bmatrix} \cos(\theta) & \sin(\theta) & \cdot \\ \sin(\theta) & \cos(\theta) & \cdot \\ \cdot & \cdot & [I]3*3 \end{bmatrix} \tag{9}
$$

In terms of the different components of the tensions of stator d-q of two machines:

$$
\begin{aligned}
v_d^{INV} &= v_{ds1} + v_{xs2} \\
v_q^{INV} &= v_{qs1} + v_{ds2} \\
v_x^{INV} &= v_{xs1} + v_{ys2} \\
v_y^{INV} &= v_{ys1} + v_{qs2}
\end{aligned}
\tag{10}
$$

Couple relations between the two series-connected machines are given in terms of current components of the inverter:

$$
\begin{aligned}
C_{e1} &= p((L_d - L_q)i_d^{INV}\, i_q^{INV} + \sqrt{\frac{5}{2}}\phi_{f1} i_q^{INV}) \\
C_{e2} &= p((L_x - L_y)i_x^{INV}\, i_Y^{INV} + \sqrt{\frac{5}{2}}\phi_{f2} i_y^{INV})
\end{aligned}
\tag{11}
$$

IV. Vector control of two five phase motor connected in series:

To a voltage supply via a voltage-controlled inverter, the reference voltages are created by adding the reference voltages of each machine are:

For the machine 1:

$$
v_d^{INV}=(R_{s1}+R_{s2})i_d^{INV}+(l_{s1}+\frac{5}{2}m_{s1})\frac{d}{dt}i_d^{INV}+l_{s2}\frac{d}{dt}i_d^{INV}-\omega_1(l_{s1}+\frac{5}{2}m_{s1})i_q^{INV}
$$

$$
v_q^{INV}=(R_{s1}+R_{s2})i_d^{INV}+(l_{sl1}+\frac{5}{2}m_{s1})\frac{d}{dt}i_q^{INV}+l_{s2}\frac{d}{dt}i_q^{INV}+\omega_1(l_{s1}+\frac{5}{2}m_{s1})i_d^{INV}+\sqrt{\frac{5}{2}}\omega_1\phi_{f1}
$$

For the machine 2:

$$
v_x^{INV}=(R_{s1}+R_{s2})i_X^{INV}+l_{s1}\frac{d}{dt}i_x^{INV}+(l_{s2}+\frac{5}{2}m_{s2})\frac{d}{dt}i_x^{INV}-\omega_2(l_{s2}+\frac{5}{2}m_{s2})i_y^{INV}
$$

$$
v_y^{INV}=(R_{s1}+R_{s2})i_y^{INV}+l_{s1}\frac{d}{dt}i_y^{INV}+(l_{s2}-\frac{5}{2}m_{s2})\frac{d}{dt}i_y^{INV}+\omega_2(l_{s2}+\frac{5}{2}m_{s2})i_x^{INV}+\sqrt{\frac{5}{2}}\omega_2\phi_{f2}
$$

Couple relations between the two series-connected machines are given in terms of current components of the inverter:

$$
\begin{aligned}
C_{e1} &= p((L_d - L_q)i_d^{INV}\, i_q^{INV} + \sqrt{\frac{5}{2}}\phi_{f1} i_q^{INV}) \\
C_{e2} &= p((L_x - L_y)i_x^{INV}\, i_Y^{INV} + \sqrt{\frac{5}{2}}\phi_{f2} i_y^{INV})
\end{aligned}
\tag{12}
$$

Both equations are completely independent, so we can control each machine with two and vector control using a single inverter.
The couple first machine controlled by the two currents (id, iq) and. for the second machine torque controlled by both current (ix, iy) .Among control strategies, one that is often used is to maintain I_D component and zero i_x. We control couples only by i_q i_y and currents. Thus rule speeds by i_y and i_y component.
The overall voltage references are then formed on the wiring diagram of fig (3), where as:

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

Use of the matrix with the equation gives:

$$
\begin{aligned}
i_\alpha^{INV} &= i_{\alpha 1} = i_{X2} \\
i_\beta^{INV} &= i_{\beta 1} = -i_{Y2} \\
i_X^{INV} &= i_{X1} = i_{\alpha 2} \\
i_Y^{INV} &= i_{Y1} = i_{\beta 2}
\end{aligned}
$$

A system illustration of the vector control of two five phase motors is given in fig.(04)

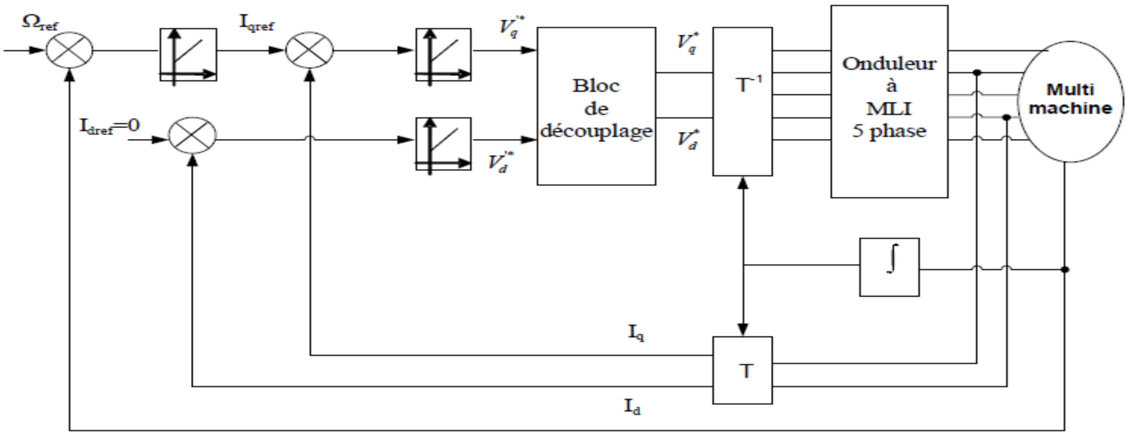

Fig. (04): Block diagram of vector control two five phase motors connected in series.

V. Simulation results:

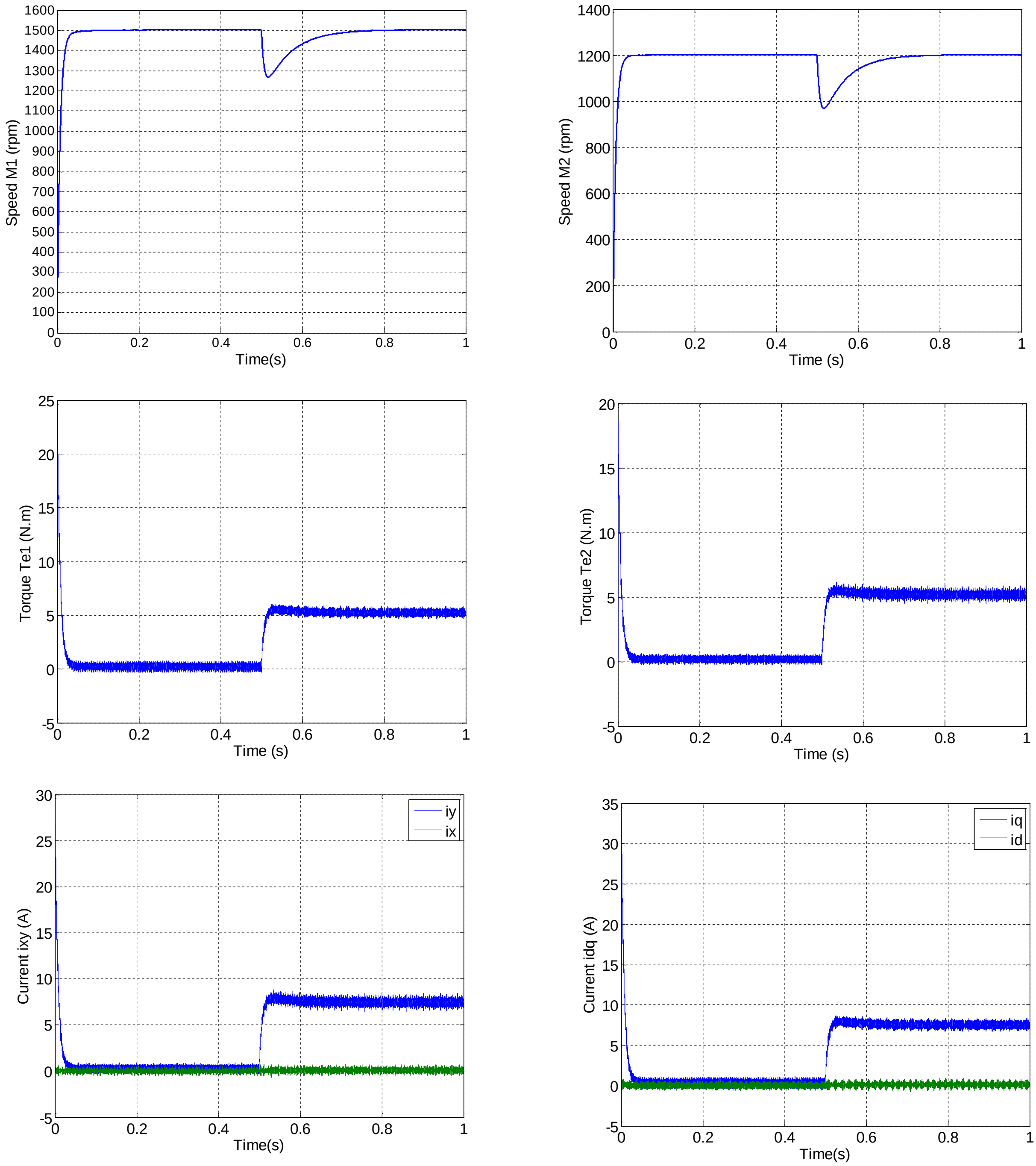

Fig.(05): Responses of the PMSM connected in series with a load of 05 Nm at 0.5s and a step change of two speed order (1500 rpm and 1200 rpm)

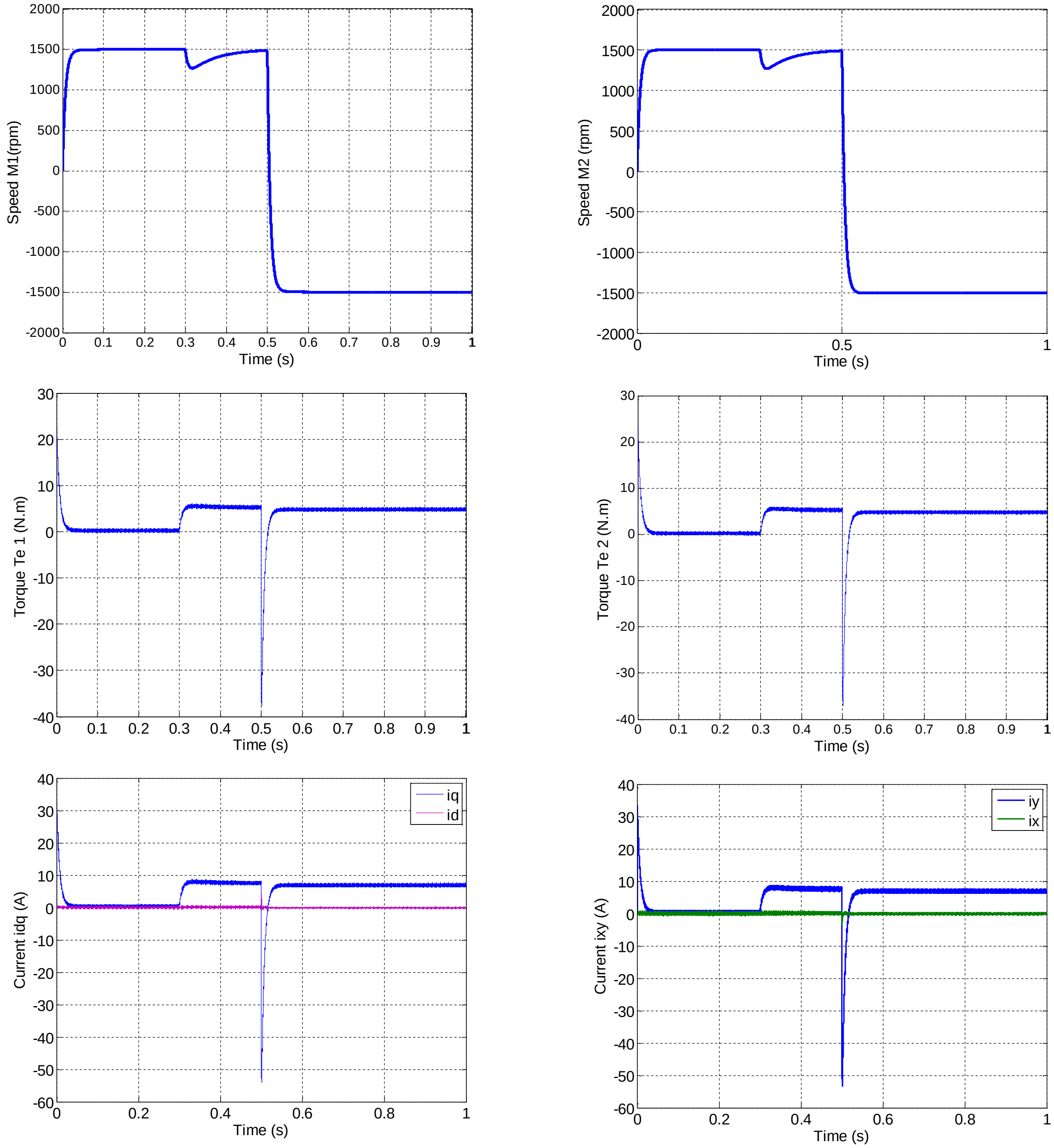

Fig.(06): responses of the PMSM connected in series with a load of 05 Nm and a step change of the reference speed from 1500 rpm to -1500 rpm at t=0.5 s

Tab .1: Five phase PMSM Parameters

R_s	L_d	L_q	j	p	φ_f	f_r
3.6 ohm	0.0021 H	0.0021 H	0.0011 kg/m^2	2	0.12 web	0

VI. Conclusion:

In this approach, we tested in simulation vector control applied to two five phase synchronous machines permanent magnets connected in series powered by a phase voltage inverter five phase. 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 independent vector control two machines gave good results and helped to decouple control flow and torque for both machines. This allowed controlling several machines in series and with different types of polyphase machines.

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