Fuzzy Logic Control of a Series-Connected Two Five-Phase Synchronous Magnet Permanent Machines (PMSM) Supplied from a Single Inverter

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July 16, 2021

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ABSTRACT. *This paper is based on the study of fuzzy logic control independent of series-connected two five-phase permanent magnet synchronous machine (PMSM) supplied by a single inverter. A fuzzy logic-based speed controller has been constructed and used to drive the two-motor in this work. The two-motor system, inverter system, and the fuzzy controller models are implemented and tested using Matlab / Simulink facilities. The obtained results show the validity of the model to control the speed under different operating conditions. We observed that an appropriate transposition of the phase order allows an independent control of two machines.*

KEY WORDS: five-phase permanent magnet synchronous machines (PMSM), Fuzzy logic control, series-connected, two-motor, vector control.

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1. Introduction

In recent years, there has been a great evolution of modern power electronics technology and the development of control theory, Multi-phase machines (PMSM) were widely used, meant that the phases of the motor are more than three phases, such five-phase motor, six-phase motor, twelve phase motors, and so on [1-2], because they have offered multiple advantages. Such as splitting power and thus reducing the constraints on the components, besides decreasing the torque ripples and operating under fault conditions. Due to these advantages, multiphase motors are used in many sensitive applications such automobile electric traction, marine electric propulsion, wind turbines or for high power industrial electrical applications and aerospace applications more aircraft applications etc [3-4].

Controlling torques is critical in all multiphase machine. However, controlling effectively the torque dynamics requires more sophisticated control strategies [5-6]. The commonly used control is the vector control which allows the control of torque transients, the remaining degrees of freedom can be used to control other machines within a multimotor group. This constitutes the main idea behind the concept of series-connected multiphase multimotor drive systems Supplied from a Single Inverter, the control of each machine must be independent of others [7-8-10-11].

In [9], the author studies the Modeling and Vector Control of two five-phase synchronous magnet permanent machines (PMSM) connected in series and using a classic PI controller. However, the main disadvantage of using a PI controller is that its performance degrades under external disturbances and machine parameter variations.

To overcome the main disadvantages, the fuzzy logic controllers suitable for the speed control of series-connected five-phase two PMSM has been presented [8].

The fuzzy logic controller (FLC) is not based on a mathematical model [12, 13], is widely used to solve problems under uncertain and vague environments, have been successfully applied in many control applications, especially for speed control of servo motor drives such as induction motors speed drive and PMSM.

The purpose of this paper is to investigate independent Control of Series-Connected Two Five-Phase PMSM supplied from a single five- leg inverter using fuzzy logic control.

2. Modeling of the two five-phase PMSM connected in series:

The studied system consists of two permanent magnet synchronous machines (PMSM) five-phase, generally without loss. This system is shown in fig. 1, with an illustration of the connection of the five-phase stator windings of the two machines in series, translated by the transposition of the phases of the two stators. The purpose of the phase transposition is to produce a magnetomotive force (mmf) in the first machine and to produce an mmf whose distribution is opposite to the first in the second machine and vice versa [3-9].

The phases of the inverter are indicated in Figure. 1 with capital letters A, B, C, D, E. While the phases of two machines are indicated in lowercase letters a, b, c, d, e; with an offset of $\alpha = 2\pi/5$.

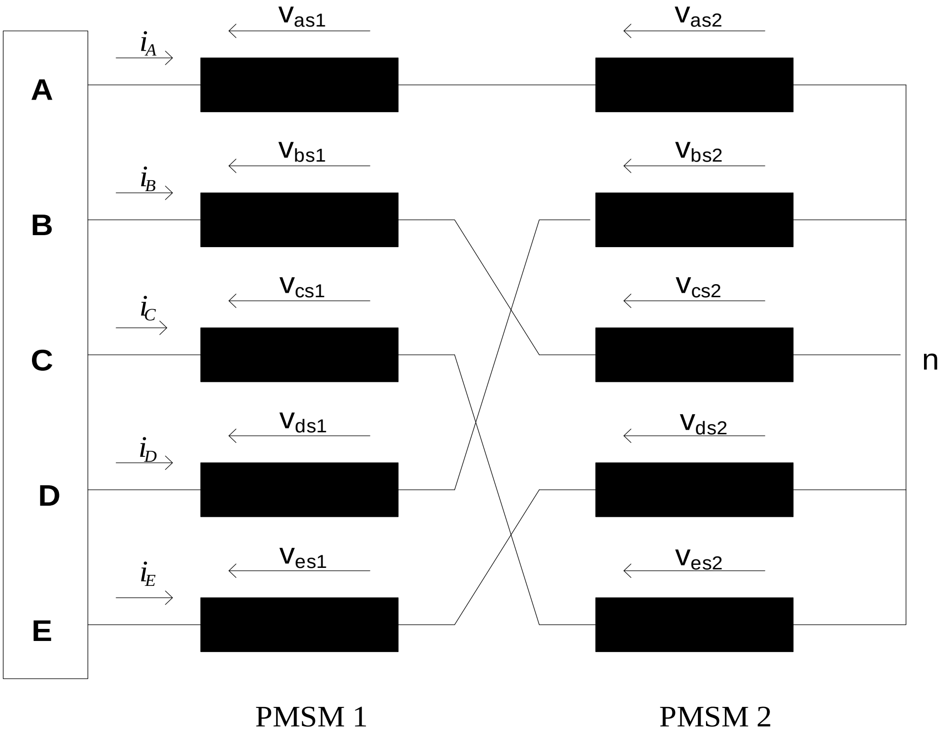


Figure 1. *Representation of two five-phase PMSM connected in series*

According to the connection diagram in Figure.1, where the phase voltages of the two machines are defined, voltages of the phase-neutral inverter (A, B, C, D, E at neutral point n) given with [5-9]:

$$v_A = v_{as1} + v_{as2} \quad v_B = v_{bs1} + v_{cs2} \qquad v_C = v_{cs1} + v_{es2} \tag{1}$$

$$v_D = v_{ds1} + v_{bs2} \quad v_E = v_{es1} + v_{ds2}$$

The relationship between the output currents of the inverter and the phase currents of two machines are given with:

$$i_A = i_{as1} = i_{as2} \quad i_B = i_{bs1} = i_{cs2} \quad i_C = i_{cs1} = i_{es2} \tag{2}$$

$$i_D = i_{ds1} = i_{bs2} \quad i_E = i_{es1} = i_{ds2}$$

It is assumed for modeling that all the standard assumptions of the general theory of electric machines are applicable [9], including that relating to the sinusoidal distribution of the resulting field in the machine.

The relationship between the original phase variables and the new variables $(\alpha\beta xyo)$ is given by:

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

Where $[C]$ is the invariant power transformation matrix:

$$[C_5] = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) \\ 0 & \sin(\alpha) & \sin(2\,\alpha) & \sin(\,3\alpha) & \sin(4\,\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha)\,N & \cos(8\alpha) \\ 0 & \sin(2\,\alpha) & \sin(\,4\alpha) & \sin(6\,\alpha) & \sin(8\,\alpha) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \qquad (3)$$

By applying this matrix to the vector of the inverter voltages we will have:

$$\begin{bmatrix} v_\alpha^{INV} \\ v_\beta^{INV} \\ v_x^{INV} \\ v_y^{INV} \\ v_o^{INV} \end{bmatrix} = [C]\begin{bmatrix} v_A \\ v_B \\ v_C \\ v_D \\ v_E \end{bmatrix} \qquad (4)$$

By using this matrix for the relation (1) will find the tensions of each machine in this reference:

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

The relation between the output currents of the inverter and the currents $\alpha - \beta, x - y$ of the two Machines is obtained using (3) and (2):

$$\begin{aligned} i_\alpha^{INV} &= i_{\propto 1} = i_{x2} \\ i_\beta^{INV} &= i_{\beta 1} = -i_{y2} \\ i_x^{INV} &= i_{x1} = i_{\propto 2} \\ i_y^{INV} &= i_{y1} = i_{\beta 2} \end{aligned} \qquad (6)$$

The zero-order component for the inverter can be neglected as well. The four equations of the inverter are as follows:

$$v_\alpha^{INV} = (R_{s1} + R_{s2})i_\alpha^{INV} + \left(l_{s1} + \frac{5}{2}m_{s1}\right)\frac{d}{dt}i_\alpha^{INV} + l_{s2}\frac{d}{dt}i_\alpha^{INV} - \sqrt{\frac{5}{2}}\omega_1\phi_{f1}\sin(\theta_1)$$

$$v_\beta^{INV} = (R_{s1} + R_{s2})i_\beta^{INV} + \left(l_{s1} + \frac{5}{2}m_{s1}\right)\frac{d}{dt}i_\beta^{INV} + l_{s2}\frac{d}{dt}i_\beta^{INV} + \sqrt{\frac{5}{2}}\omega_1\phi_{f1}\cos(\theta_1) \qquad (7)$$

$$v_x^{INV} = (R_{s1} + R_{s2})i_x^{INV} + l_{s1}\frac{d}{dt}i_x^{INV} + \left(l_{s2} + \frac{5}{2}m_{s2}\right)\frac{d}{dt}i_x^{INV} - \sqrt{\frac{5}{2}}\omega_2\phi_{f2}\sin(\theta_2)$$

$$v_y^{INV} = (R_{s1} + R_{s2})i_y^{INV} + l_{s1}\frac{d}{dt}i_y^{INV} + \left(l_{s2} - \frac{5}{2}m_{s2}\right)\frac{d}{dt}i_y^{INV} + \sqrt{\frac{5}{2}}\omega_2\phi_{f2}\cos(\theta_2)$$

φ_{f1} φ_{f2} : Total flux due to the magnets and which closes on the stator 1 and stator 2.

The torque and mechanical expressions of the two machines connected in series are given by:

$$\begin{cases} T_{e1} = p\sqrt{\frac{5}{2}}\phi_{f1}\left(-i_{\alpha}^{INV}\sin(\theta_1) + i_{\beta}^{INV}\cos(\theta_1)\right) \\ J_1\frac{d\Omega_1}{dt} + f_1\Omega_1 = T_{e1} - T_{L1} \end{cases} \qquad (8)$$

$$\begin{cases} T_{e2} = p\sqrt{\frac{5}{2}}\phi_{f2}\left(-i_{x}^{INV}\sin(\theta_2) + i_{y}^{INV}\cos(\theta_2)\right) \\ J_2\frac{d\Omega_2}{dt} + f_2\Omega_2 = T_{e2} - T_{L2} \end{cases} \qquad (9)$$

3. The independent vector control of series-connected two five phase PMSM:

The objective is to accomplish the independent control of all the polyphase machines in the group while using a single power inverter. The stator windings of the polyphase machines can be connected in series thus allowing the independent vector control of each machine, although the multi-motor drive complete system is fed from a polyphase power inverter [5-8-9].

The two equations are completely independent, so we can control each machine with two vector controls and using a single power inverter [9].

The first machine:

$$\begin{cases} v_d^{INV} = \left((R_{s1}+R_{s2}) + P\left(l_{s1}+\frac{5}{2}m_{s1}+l_{s2}\right)\right)i_d^{INV} - \omega_1(l_{s1}+\frac{5}{2}m_{s1})i_q^{INV} \\ v_q^{INV} = \left((R_{s1}+R_{s2}) + P\left(l_{s1}+\frac{5}{2}m_{s1}+l_{s2}\right)\right)i_q^{INV} + \omega_1(l_{s1}+\frac{5}{2}m_{s1})i_d^{INV} + \sqrt{\frac{5}{2}}\omega_1\phi_{f1} \end{cases} \qquad 10$$

The second machine:

$$\begin{cases} v_x^{INV} = \left((R_{s1}+R_{s2}) + P\left(l_{s2}+\frac{5}{2}m_{s2}+l_{s1}\right)\right)i_x^{INV} - \omega_2(l_{s2}+\frac{5}{2}m_{s2})i_y^{INV} \\ v_y^{INV} = \left((R_{s1}+R_{s2}) + P\left(l_{s2}+\frac{5}{2}m_{s2}+l_{s1}\right)\right)i_y^{INV} + \omega_2(l_{s2}+\frac{5}{2}m_{s2})i_x^{INV} + \sqrt{\frac{5}{2}}\omega_2\phi_{f2} \end{cases} \qquad (11)$$

The first machine torque controlled by the two currents $\left(I_d^{INV}\ ,\ I_q^{INV}\right)$ and for the second machine the torque controlled by the two currents $\left(I_x^{INV}\ ,\ I_y^{INV}\right)$. Among the control strategies, we often use the one which consists in maintaining the component I_d^{INV} and I_x^{INV} zero. We control the torques only by the currents I_q^{INV} and I_y^{INV} . The speeds are thus regulated by the component I_q^{INV} and I_y^{INV} as shown in Figure 2 [3-9].

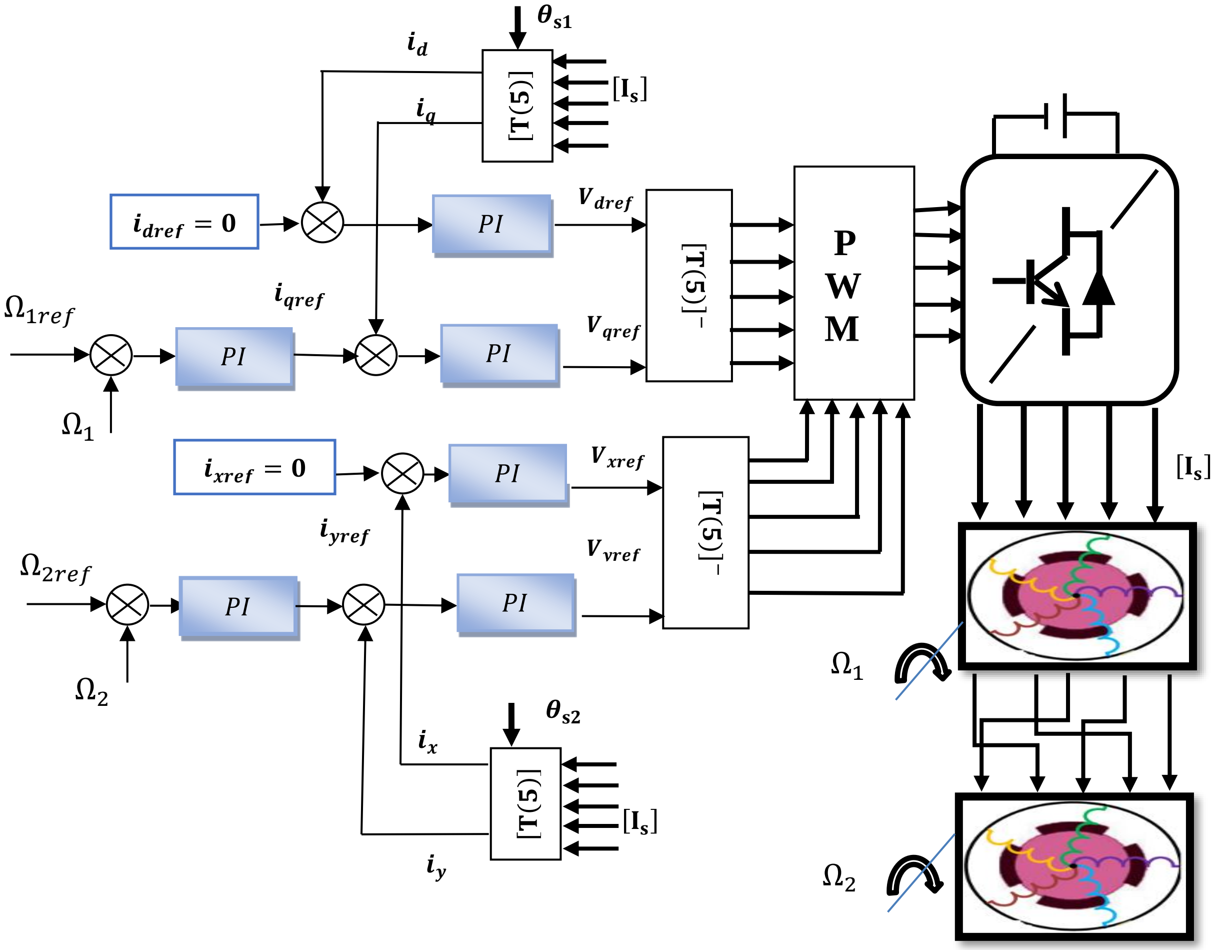


Figure 2. *vector control for the two five phase PMSM connected in series.*

4. Control by the Fuzzy Logic:

The fuzzy control system approaches the flexibility of human reasoning to some level; he achieves excellent performance without the requirement for a mathematical model of the system, just by incorporating experts' knowledge. Fuzzy control, in general, is a model-free strategy that does not rely on the model of the system under control. Because obtaining a mathematical model of the system can be a difficult process, model-free approaches make controller design easier [14-15].

Fuzzification, fuzzy inference engine, rule base, and defuzzification are the four essential components of a fuzzy logic controller, as shown in Figure3. Inputs are fuzzified, then outputs are generated using a rule basis and inference system, and the fuzzy outputs are defuzzified and applied to the primary control system. Error of inputs from their references and error deviations in any time interval are chosen as inputs. Mamdani type fuzzy logic control is considered here.

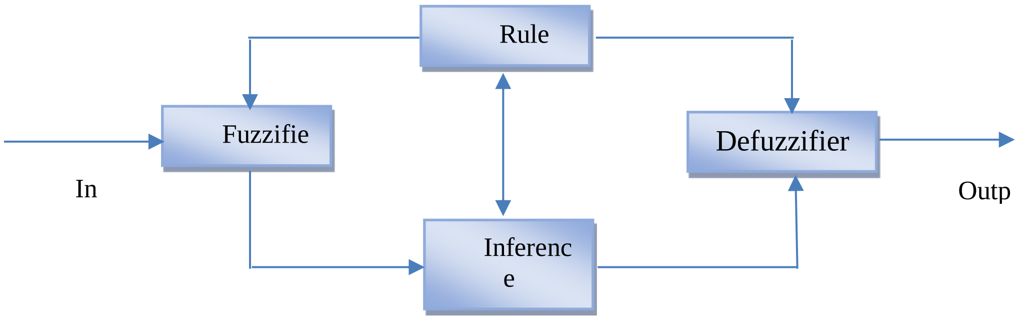


Figure 3. *Structure of fuzzy logic controller*

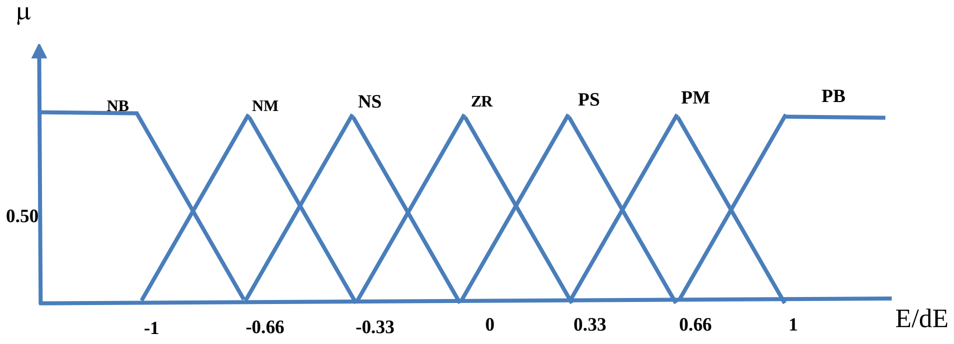


Figure 4. *Membership functions of input/output variables: speed and current.*

In this study, seven terms are assigned in Table I: NL, negative large; NM, negative medium; NS, negative small; ZE, zero; PS, positive small; PM, positive medium; and PL, positive large. Each fuzzy variable is a member of the subsets with a degree of membership μ varying between 0 and 1 (Figure 4). The rules have been written in matrix (Table I). Each rule is expressed in the form as:

R1 : If **E** is NL and **dE** is PL then μ is ZR
R2 : If **E** is NM and **dE** is PL then μ _is PS
R49 : If **E** is PL and **dE** is NL then μ is ZR

Table 1. The rule base for controlling the speed and the current

		E						
		NL	**NM**	**NS**	**ZR**	**PS**	**PM**	**PL**
dE	**PL**	ZR	PS	PM	PL	PL	PL	PL
	PM	NS	ZR	PS	PM	PL	PL	PL
	PS	NM	NS	ZR	PS	PM	PL	PL
	ZE	NL	NM	NS	ZR	PS	PM	PS
	NS	NL	NL	NM	NS	ZR	PS	PM
	NM	NL	NL	NL	NM	NS	ZR	PS
	NL	NL	NL	NL	NL	NM	NS	ZR

The same steps used for the conception of the speed controller will be repeated for the currents controller, only we have:

The first machine:

Input error E : instead of being equal to $E = \Omega_{1ref} - \Omega_1$, it will be equal with $\boldsymbol{E} = \boldsymbol{i}_{\boldsymbol{dref}} - \boldsymbol{i}_{\boldsymbol{d}}$ for the first fuzzy controller of current ids and $\boldsymbol{E} = \boldsymbol{i}_{\boldsymbol{qref}} - \boldsymbol{i}_{\boldsymbol{q}}$ for the second fuzzy controller of current iqs ;

The output of the fuzzy controller is $\boldsymbol{V}_{\boldsymbol{ds}}$ for the $\boldsymbol{i}_{\boldsymbol{ds}}$ current controller and $\boldsymbol{V}_{\boldsymbol{qs}}$ for the $\boldsymbol{i}_{\boldsymbol{qs}}$ current controller.

The second machine:

Input error E : instead of being equal to $E = \Omega_{2ref} - \Omega_2$, it will be equal with $\boldsymbol{E} = \boldsymbol{i}_{\boldsymbol{xref}} - \boldsymbol{i}_{\boldsymbol{x}}$ for the first fuzzy controller of current ids and $\boldsymbol{E} = \boldsymbol{i}_{\boldsymbol{yref}} - \boldsymbol{i}_{\boldsymbol{y}}$ for the second fuzzy controller of current iys ;

The output of the fuzzy controller is $\boldsymbol{V}_{\boldsymbol{xs}}$ for the $\boldsymbol{i}_{\boldsymbol{xs}}$ current controller and $\boldsymbol{V}_{\boldsymbol{ys}}$ for the $\boldsymbol{i}_{\boldsymbol{ys}}$ current controller.

5. Simulation results

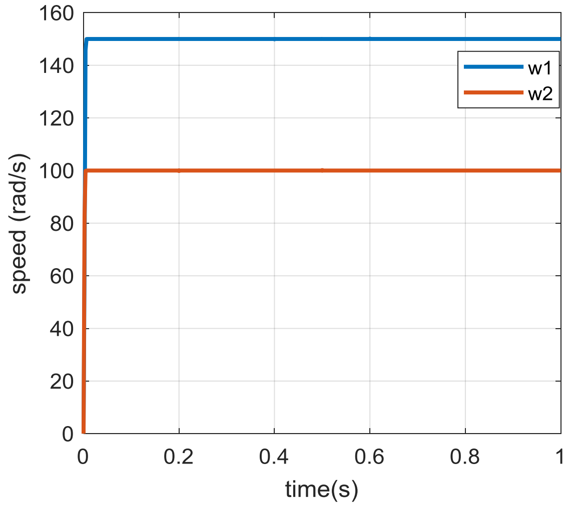
We have tested in simulation the fuzzy logic control of a series-connected two five-phase PMSM supplied by a Single inverter, with the application of two different speed as shown in the figure.

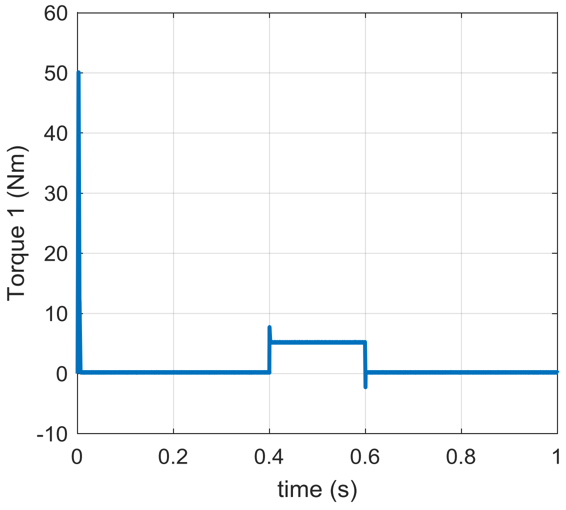
Where the first machine runs according to the speed 150 rad/s and for the second machine runs according to the speed of 100 rad/s,

The speed rate follows its reference value perfectly, which is reached very quickly with an acceptable response time. The effect of the disturbance is quickly eliminated, Load torques (T_{L1} = 5 Nm) is applied on the first machine at t=0.4s to t=0.6s t and Load torques (T_{L2} = 5 Nm) is applied on the second machine at t=0.2 s to t=0.5s

The response of the two current components clearly shows by the FLC control of two five-phase PMSMs in series-connected (the currents $I_d^{INV} et\ I_x^{INV}$ are zero).

The current I_q^{INV} is the image of the torque1. and the current I_y^{INV} is the image of the torque2.





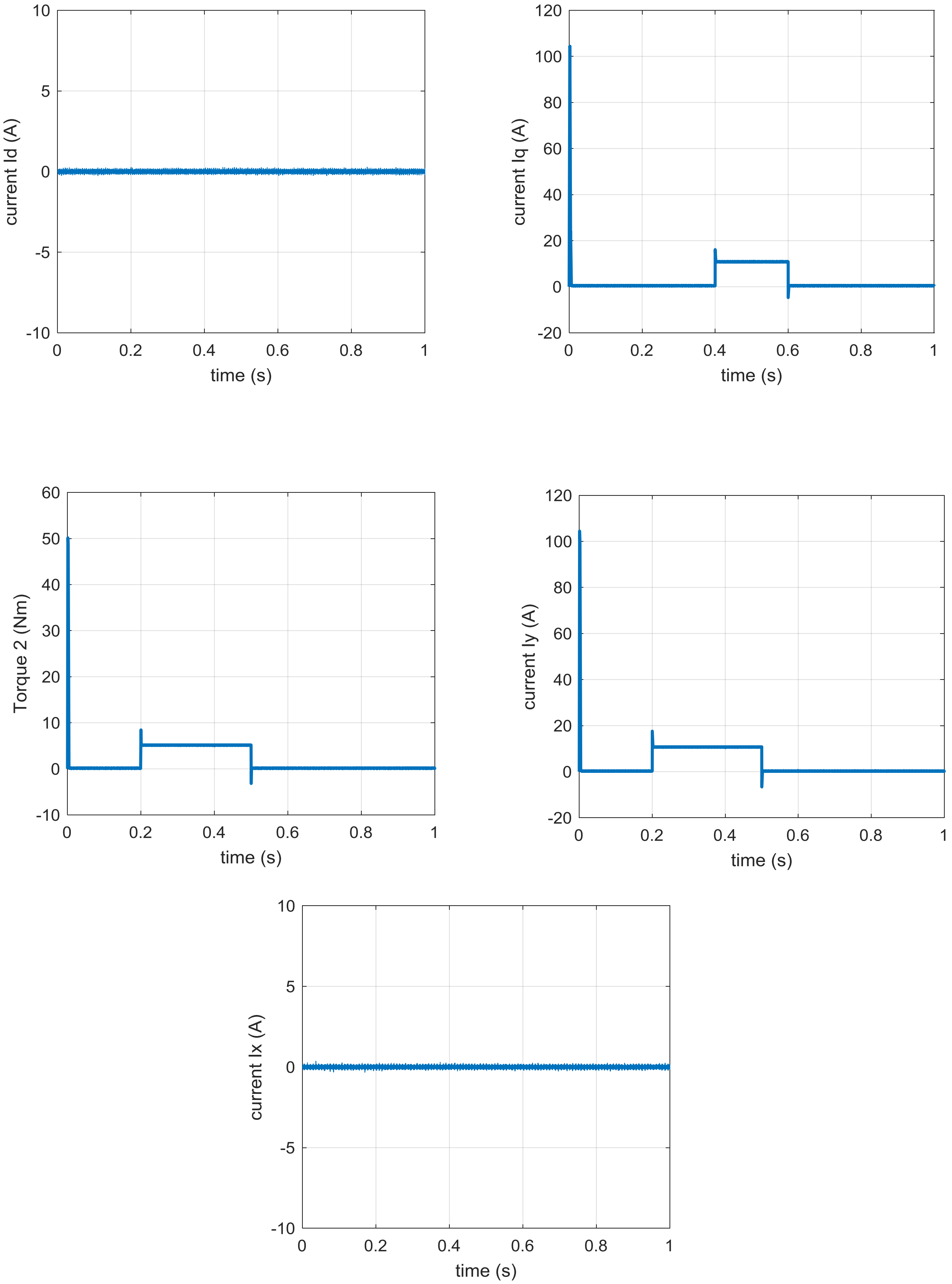


Figure 5. *Simulation results of the Fuzzy Logic Control of a Series-Connected Two Five-Phase Synchronous Magnet Permanent Machines (PMSM).*

6. Conclusions

In this paper, model of the two PMSM five-phase connected in series is developed which is supplied by single inverter five phase. An FLC controller is employed, which can control the torque and current of each motor independently, the simulation results show that the suggested controller in this study is capable of tracking the speed and current references, as well as being robust against rapid changes in load.

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