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Neuro-Speed Controller of Five Phase Induction Motor Driven Using Direct Torque Control Strategy

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Abstract: In this paper, performances of five-phase induction motor controlled with direct torque control strategy are studied. In order to perform the control system, a speed controller based on artificial neural network is designed. Power required motor is ensured via two levels voltage source inverter. Five-phase induction machine modeling and their control are defined and described. The proposed scheme control is simulated using Matlab/Simulink software in four quadrant operation. Simulation results have been illustrated and he improves significantly behavior and dynamic response, mainly, of the speed response, quick electromagnetic torque and the rate of stator flux due to the proposed neuro-speed controller design.

Keywords: Neuro-speed controller, five-phase induction motor, direct torque control, control performance.

Introduction

Currently many industrial applications require multi-phase voltage source inverters (VSI) feeding multi-phase machines. The various aspects covered have included advantages of multi-phase machines over their three-phase counterparts, modelling and control of multi-phase machines, three-phase motor drives [1,2]. However, the multiphase induction motors are earning interest as viable alternative solutions to a three phase induction motors drives because he possesses many advantages such as less torque ripple, increasing the frequency of the torque pulsation, reducing the rotor harmonic currents, reducing the current per phase, etc [3-7]. Also, by increasing the number of phases, it is possible to reduce the torque per ampere for the same amount machine. Although the literature review was focuses, generally, on five-phase and six-phase designer [1, 8].

The configuration comprising two VSI feeding five-phase induction motor (FPIM) using a direct torque control (DTC) and a speed controller based on artificial neural network is feature investigated in this particular work. For this reason, modelling of FPIM and VSI are developed. Direct torque control strategy is based on instantaneous space vector theory [9]. It is possible to control directly the stator flux and torque by selecting an appropriate switching inverter states and consequently, the voltage vectors according to the errors of stator flux and torque. The switching table DTC based on the estimated stator flux position, hysteresis controllers for torque and flux generate the available inverter switching states. DTC is one of the powerful control for high performance control of electrical motor drives. Three-phase voltage source inverter has only eight (8) voltage space vectors that can be applied to a load, while in five-phase inverter it has Thirty-two (32) possible voltage space vectors. There is therefore a greater flexibility in controlling a five-phase motor. This control type provides high performance of smaller current with little flux and torque ripples due to the application of large number of space vectors. In the electrical drives the intelligent controllers has been progressively utilized to solve any complex control problems.

In this paper, a speed controller based on artificial neural network has been insured in order to perform the control performance. Numerous simulation studies are achieved for drives using direct torque control principles and proposed intelligent speed control.

The organization of this paper is as follows. Section 2 is devised into two parts. The first deals with the presentation of a five-phase induction motor model and a voltage source inverter. In the second part, principal of DTC strategy is described in detail. Section 3 examined the designing of the proposed neuro-speed controller. Simulation study performed at condition of four quadrant of speed mode operation is presented in section 4. Finally, a conclusion is avowed.

Five phase induction motor model

The FPIM has five phase windings. The windings axes of five stator winding are displaced by 72 degrees as shown in Fig.1.

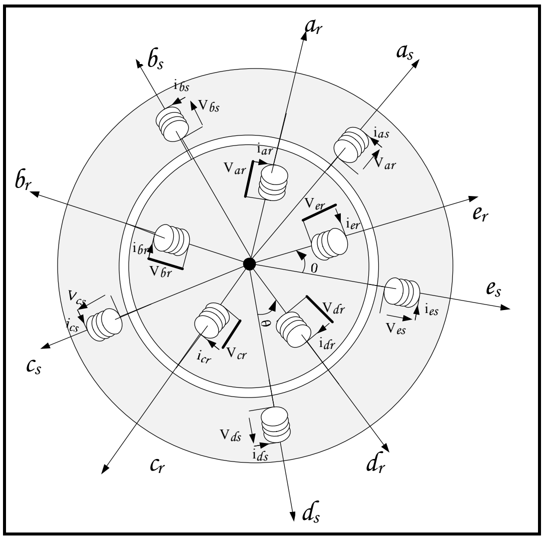

Figure 1. Space representation of phases

The voltage equations of the stator and rotor motor are given by (1) and (2), respectively:

$$[V_s]=[R_s].[I_s]+\frac{d[\psi_s]}{dt} \tag{1}$$

$$[V_r]=[R_r].[I_r]+\frac{d[\psi_r]}{dt} \tag{2}$$

Where,

$[V_s]=[v_{as} \quad v_{bs} \quad v_{cs} \quad v_{ds} \quad v_{es}]^T$ and $[V_r]=[v_{ar} \quad v_{br} \quad v_{cr} \quad v_{dr} \quad v_{er}]^T$

The electromagnetic torque (Γ_e) is given by:

$$\Gamma_e=\frac{p}{2}\left([I_s]^T.\frac{d[L_{s,r}]}{dt}.[I_r]\right) \tag{3}$$

The use of the transformation Park given by (4) , allows to transform a five phases system (a, b, c, d and e) , presented by the equations (1) et (2) in a two phases equivalent (d, q) rotating frame to obtain a simple mathematical model [10, 11].

$$[V_{idq}]=P(\theta).[V_{sk}] \tag{4}$$

Where: i = s or r, respectively index for stator and rotor; k = a,b,c,d and e; index for phases and ,

$$P(\theta)=\sqrt{\frac{2}{5}}.\begin{bmatrix}\cos(\theta) & \cos(\theta-2.\pi/5) & \cos(\theta-4.\pi/5) & \cos(\theta-6.\pi/5) & \cos(\theta-8.\pi/5)\\ \sin(\theta) & \sin(\theta-2.\pi/5) & \sin(\theta-4.\pi/5) & \sin(\theta-6.\pi/5) & \sin(\theta-8.\pi/5)\end{bmatrix}$$

For this, we obtain the following system:

$$\begin{cases} V_{sd}=R_s.I_{sd}+\dfrac{d\psi_{sd}}{dt}-\omega_s.\psi_{sq}\\ V_{sq}=R_s.I_{sq}+\dfrac{d\psi_{sq}}{dt}-\omega_s.\psi_{sd}\\ V_{rd}=0=R_r.I_{rd}+\dfrac{d\psi_{rd}}{dt}-\left(\omega_s-\omega_r\right).\psi_{rq}\\ V_{rq}=0=R_r.I_{rq}+\dfrac{d\psi_{rq}}{dt}-\left(\omega_s-\omega_r\right).\psi_{rd}\end{cases} \tag{5}$$

Where:

$$\psi_{sd}=L_sI_{sd}+L_mI_{rd}$$
$$\psi_{sq}=L_sI_{sq}+L_mI_{rq}$$
$$\psi_{rd}=L_rI_{rd}+L_mI_{sd}$$
$$\psi_{rq}=L_rI_{rq}+L_mI_{sq}$$

where R_s , R_r , L_s , L_r ,L_m are respectively stator resistance , rotor resistance , stator inductance, rotor inductance and mutual inductance.

The representation of the phase in the coordinate's d-q is show by the figure. 2.

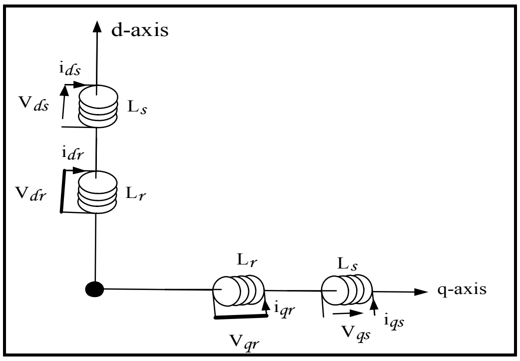

Figure 2. Phases in coordinate's d-q

So, the mechanical equation can be written as follows:

$$\frac{J}{p}\frac{d\omega_r}{dt}=\Gamma_e-\Gamma_l-\frac{k_f}{p}\omega_r \tag{6}$$

With,

$$\Gamma_e=\frac{p.L_m}{L_r}(\psi_{rd}.I_{sq}-\psi_{rq}.I_{sd}) \tag{7}$$

Where *J* is total inertia; *p* is the number of pole pairs; Γ_l is the load torque and k_f is the friction coefficient.

Modeling of five-phase voltage source inverter

The five-phase voltage source inverter (VSI) is comprised of five (5) legs every one contains two power switches (S_k and S_k', where k=a, b, c, d,e) as show in figure 3. Both power switches Sa and Sa' eg work in complementarily ie if the top one (Sa) is open (Sa=1) then the low switch (Sa') is closed (Sa'=0) and vice versa. So, the output phase voltage can be computed using the switching function associated to one inverter leg [8, 12]. Therefore, it considered the same operation with the other leg it result 32 possible states: 30 non-zero active voltage switching space vectors together with 2 zero space vectors.

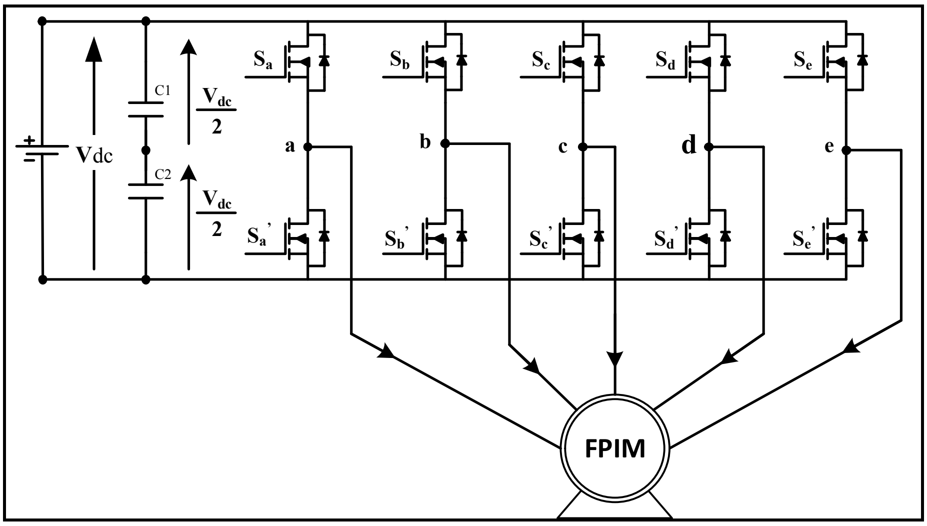

Figure 3. Structure of five phase voltage source inverter

The voltage equations of five-phases VSI.

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ v_{ds} \\ v_{es} \end{bmatrix} = \begin{bmatrix} \frac{4}{5} & \frac{-1}{5} & \frac{-1}{5} & \frac{-1}{5} & \frac{-1}{5} \\ \frac{-1}{5} & \frac{4}{5} & \frac{-1}{5} & \frac{-1}{5} & \frac{-1}{5} \\ \frac{-1}{5} & \frac{-1}{5} & \frac{4}{5} & \frac{-1}{5} & \frac{-1}{5} \\ \frac{-1}{5} & \frac{-1}{5} & \frac{-1}{5} & \frac{4}{5} & \frac{-1}{5} \\ \frac{-1}{5} & \frac{-1}{5} & \frac{-1}{5} & \frac{-1}{5} & \frac{4}{5} \end{bmatrix} . \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \\ v_{dn} \\ v_{en} \end{bmatrix} \qquad (8)$$

In general terms of switching states, the phase voltage space vectors of the 5-phase is given as follow relation and the possible states vectors are presented in Table 1.

$$vk = \frac{2.Vdc}{5}(S_a + a.S_b + a^2.S_c + a^{-2}.S_d + a^{-1}S_e$$
$$Where, \quad a = e^{j2\pi/5} \quad and \quad k = 0,1,2,3,4.......,30,31. \qquad (9)$$

DTC method for five-phase induction machine

The aim of the DTC method is to compensate the error between reference and actual quantities of torque and flux by selecting appropriate voltage vector from the inverter. Hysteresis controllers for torque and flux are used to generate the inverter switching states. Since the five phase voltage source inverter has five (5) legs and each switch takes 2 states ("1" and "0") , the five phase voltage source inverter has thirty-two (32) switching combinations [13, 14]. Consequently, all possibilities of selecting combinations are given by Table 1 and the voltage space vectors, as showing by figure 4.

Table 1:

v_0	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
v_1	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
v_1	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
v_1	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**	**v_1**
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0

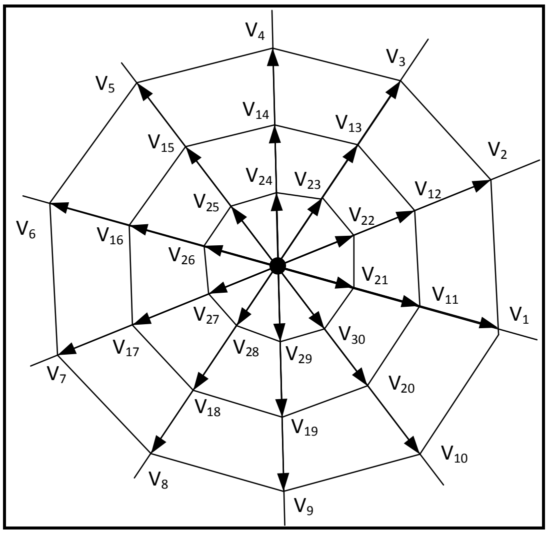

Figure 4. Space voltage vectors available

DTC is based on hysteresis comparators and switching tables provides a fast torque response. However, in steady state the torque has large ripples, due to the switching frequency of the inverter caused by the hysteresis bands. DTC requires accurate knowledge of the amplitude and angular position of the controlled flux with respect to the stationary stator axis in addition to the angular velocity for the torque control purpose [15]. The principle of DTC operation can also be explained by analyzing the stator voltage equation in the stator flux reference frame [16, 17].

$$\overrightarrow{u_s} = R_s \vec{i} + \frac{d\overrightarrow{\psi}}{dt} + j\omega_s \overrightarrow{\psi_s} \tag{10}$$

If this expression is separated into the direct (α) and the quadrature component (β) of the stator voltage, the following expression can be obtained:

$$u_{s\alpha} = R_s i_{s\alpha} + \frac{d\psi_{s\alpha}}{dt} \tag{11}$$

$$u_{s\beta} = R_s i_{s\beta} + \frac{d\psi_{s\beta}}{dt} \tag{12}$$

In the same reference frame fixed to the stator flux vector the electromagnetic torque can be expressed as:

$$\Gamma_e = \frac{3.p}{2}.\overrightarrow{\phi_{s\alpha}} \times \overrightarrow{i_{s\beta}}) \tag{13}$$

Combining the next expressions, we obtain the following torque expression form:

$$\Gamma_e = \frac{3.p.\psi_{s\alpha}}{2.R_s}(u_{s\beta} - \omega_s \psi_{s\alpha}) \qquad (14)$$

Electromagnetic torque can be controlled by means of the component of the stator voltage, under adequate decoupling of the stator flux. DTC requires the estimation of stator flux and torque, which can be performed by means of two different phase currents, the state of the VSI and the voltage level in the DC voltage bus. This work proposes a DTC schemes for an induction motor fed by two-level voltage source inverter (VSI). This estimation is based in the stator voltage equation.

$$\overrightarrow{\psi_s} = \int(\overrightarrow{u_s} - R_s\overrightarrow{i_s}).dt \qquad (15)$$

The following table gives the control vectors according to the outputs of the flux and torque regulators for the six (6) sectors for each inverter considered and dedicated to the control of FPIM.

The DTC strategy developed for the five phase induction motor requires the estimation of the stator flux and torque which are compared to their reference values and the resulting errors are fed to hysteresis controllers of stator flux and torque [18-22].The principle is to maintain the stator flux and torque within the limits of flux and torque hysteresis bands by proper selection of the stator space voltage vectors during each sampling period (See Figure 5) , meaning switching table 2.

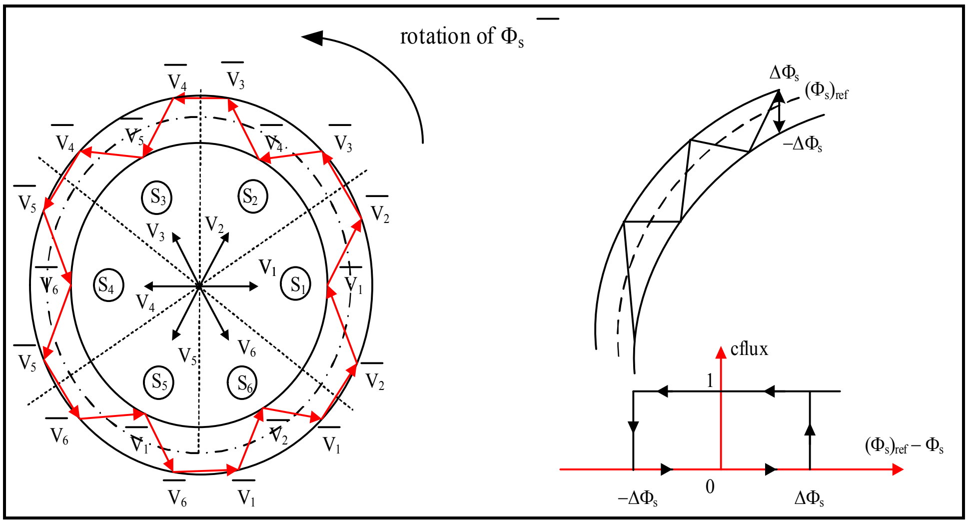

Figure 5. Space voltage vectors evolution

Table 2: Switching table

Flux	**1**			**0**		
Torque	**1**	**0**	**-1**	**1**	**0**	**-1**
***Sector* 1**	V_2	V_1	V_6	V_3	V_4	V_5
***Sector* 2**	V_3	V_2	V_1	V_4	V_5	V_6
***Sector* 3**	V_4	V_3	V_2	V_5	V_6	V_1
***Sector* 4**	V_5	V_4	V_3	V_6	V_1	V_2
***Sector* 5**	V_6	V_5	V_4	V_1	V_2	V_3
***Sector* 6**	V_1	V_6	V_5	V_2	V_3	V_4

Artificial Neural Network

Speed error is a result of a comparison of actual speed and the motor reference speed. Speed error and change in speed error are given as ANN controller inputs and the output is the electromagnetic torque (Γe*). The quadrature-axis stator current reference is calculated from electromagnetic torque equation.

The idea is to replace the PI speed regulator by a simple neuro-controller. For learning, we use the backpropagation algorithm Levenberg-Marquardt (LM) [16, 23, 24]. Each neural network fills a well defined function dependent the chosen architecture (number of hidden layers and the number of neurons in each hidden layer). The problem is to find a structure that gives better results. For this, we made several tests to determine the optimal architecture network. The most sensible choice was to take a neural network structure hidden layer containing three to 20 neurons using the activation function sigmoid, show Fig.6.

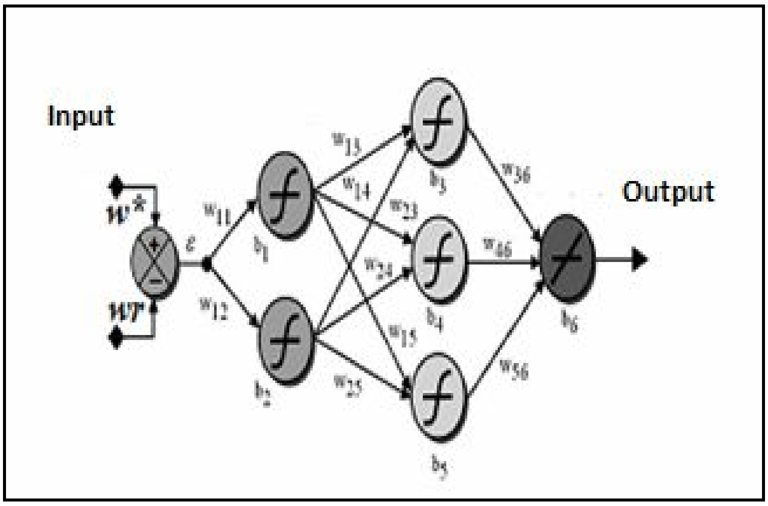

Figure 6. Structure of multilayer perception

Speed control is based on controller of ANN (20 multi-phase). The multi layer preceptor, the number of hidden layers and hidden neurons is not known a priori. Furthermore, there is no general rule for predicting the number of hidden Fig. 6 Scheme of neural speed control neurons necessary to achieve a specified performance of the model. The proposed application, an ANN with a single layer with activation function tansig type is used. In this step, the authors execute several tests and analyzing the performance of the system [25]. The neural network controller considered is shown in Fig. 7 have two neurons in input layer, 30 neurons in hidden layer and one neuron in output layer.

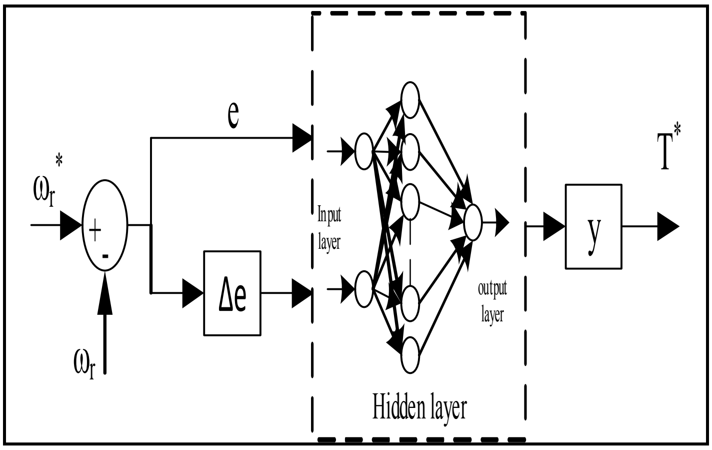

Figure 7. Scheme of speed control using ANN

Simulation and results

In this section, the simulation results of torque, flux, and speed motor under several conditions are represented and discussed for to investigate the performance of the system studied. The block diagram in Fig 8 shows the schematic drawing of five-phase motor driven using DTC with an ANN speed controller.

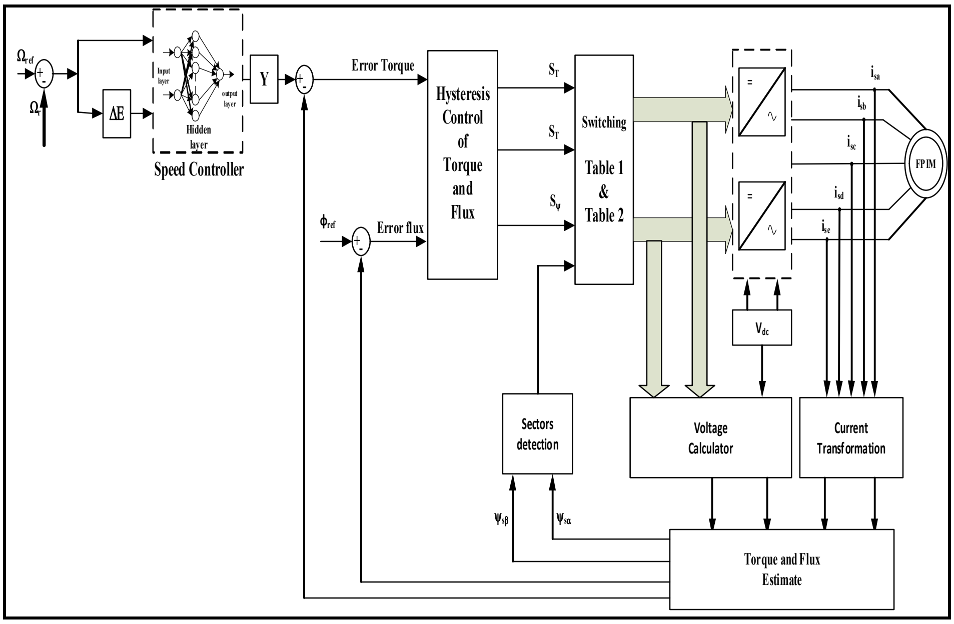

Figure 8. ANN speed control of DTC for FPIM

The simulations are considered to verify the performance of the DTC in controlling the speed of the machine. The dynamic behavior of the system has been tested under different speed and torque references illustrate by figure 9.

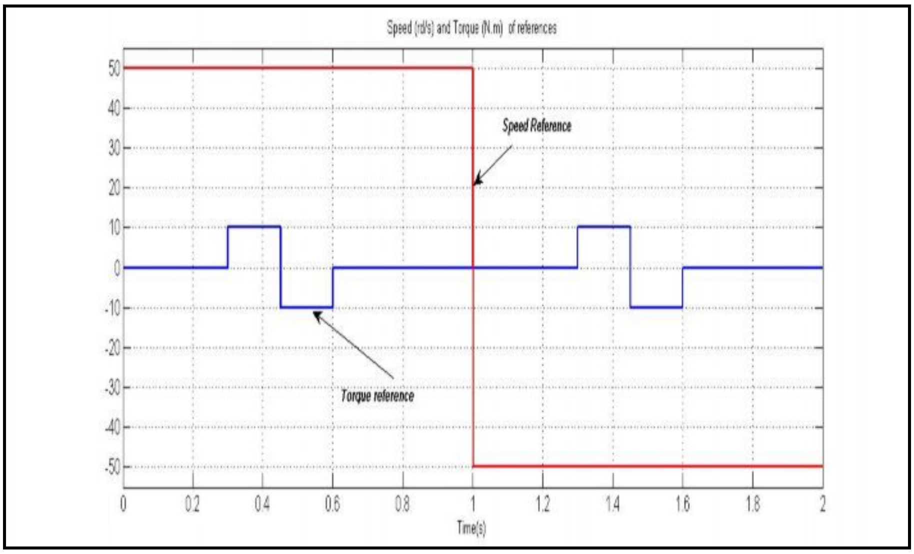

Figure 9. Speed and Torque load references

The choice of these references is fixed as to ensure a good comprehension of the component of the control motor in four quadrant operations. Thus, the speed reference is changed from 50 to -50 rd/s at t=1 second and the torque is changed de 10Nm at -10Nm for case of positive speed and in the case of negative.

The simulation model parameters of the five phase induction motor are done in Table 4. The dynamic responses of the speed, electromagnetic torque, phase currents and stator flux are represented in figures 10, 11, 12 and 13, respectively. In figure 10, the speed follows the speed reference very well. Figure 11 illustrates the torque in the conditions of speed and load variations. Figure 12 shows the evolution of the flux where it is important to note, that the flux and torque can be controlled independently. In fact, after the fast flux response, it retains its value despite the variation of the torque. It is notice a good dynamic response of the five-phase currents induction motor is shows in figure 13 with the zoom.

Table.3 - Simulation FPIM parameters			
Five Phases Induction Motor (FPIM):			
Parameter	**Symbol**	**Value**	**Unit**
Nominal power	P_n	4.50	Kw
Stator resistance	R_s	3.72	Ω
Rotor resistance	R_r	2.12	Ω
Stator inductance	L_s	0.022	H
Rotor inductance	L_r	0.006	H
Mutual inductance	L_m	0.3672	H
Moment of inertia	J	0.0625	Kg.m^2
Friction coefficient	B	0.001	N.m.s/rad
Pole number	P	2	---

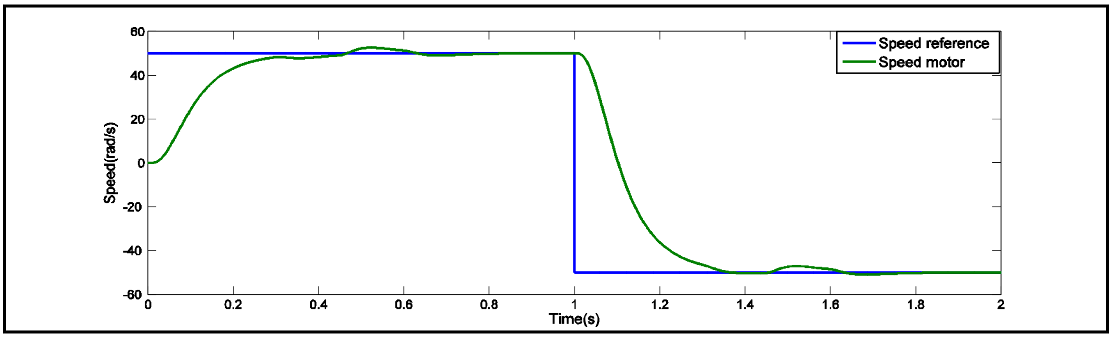

Figure 10. Real and reference speed

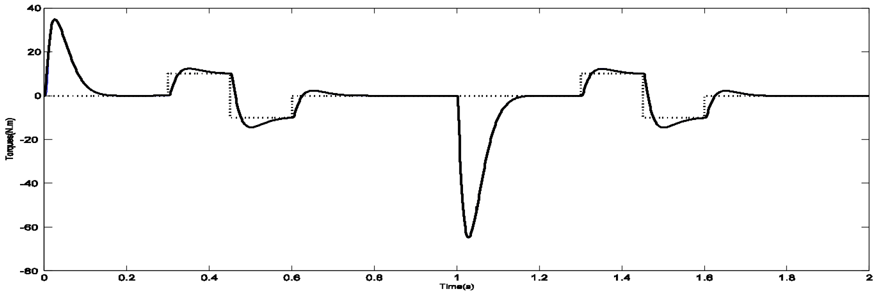

Figure 11. Electromagnetic, estimated torque and load torque

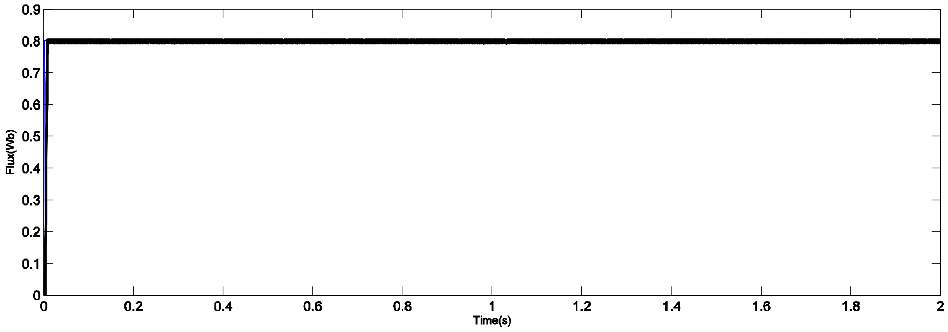

Figure 12. Flux motor

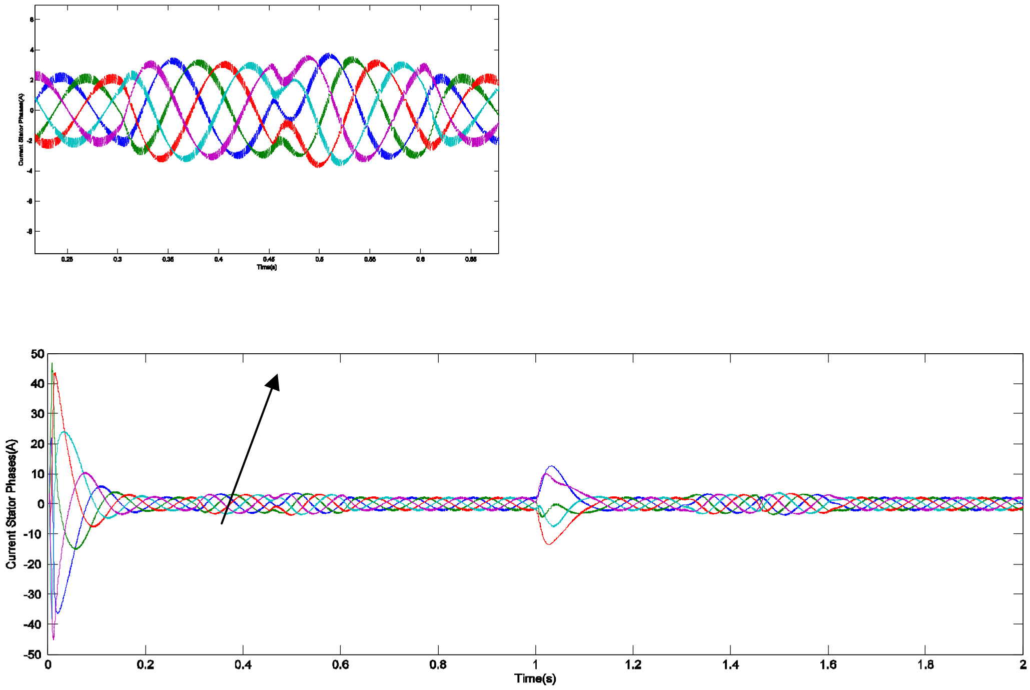

Figure 13. Current phases of FPIM

Conclusion

Neuro-speed controller was performing five-phase induction machine driven using direct torque control switching strategy. Obtain results verify the purpose. A five leg voltage inverter was emotionally involved five-phase machine controlled with DTC method so as to introduce towards provide a fast dynamic torque and flux. The proposed intelligent speed controlled often a high dynamic in speed response. The proposed scheme can be applied also to high power multiphase drive control systems.

References

1. Jones, M., A Novel Concept of a Multi-phase, Multi-motor Vector Controlled Drive System, PhD Thesis, Liverpool John Moores University, Liverpool, UK, 2005.
2. Sul, K., Analysis and Prediction of Inverter Switching Frequency in Direct Torque Control of Induction Machine Based on Hysteresis Bands and Machine Parameters, IEEE Trans. Ind. Electron., Vol. 48, N^o. 3, p. 545–553, 2001.
3. Toliyat, H. A., Analysis and Simulation of Five-phase Variable Speed Induction Motor Drives Under Asymmetrical Connections, IEEE Trans. Power Electronics, Vol. 13, N^o. 4, p. 748-756, 1998.
4. Pavithran, K.N, Parimelalagan, R., and Krishnamurthy, M., Studies on Inverter-fed five-phase Induction Motor Drive, IEEE Trans. Power Electron., Vol. 3, N^o. 3, p. 224-235, 1988.
5. Levi, E., Jones, M., Vukosavic, S. N. and Toliyat, H. A., Steady- state modeling of series-connected five-phase and six-phase two-motor drives, IEEE Trans. on Ind. Appl., Vol. 44, N^o. 5, 2008.
6. Levi, E., Bojoi, R., Profumo, F., Toliyat, H. A., and Williamson, S.,Multiphase induction motor drives - a technology status review, Electric Power Applications, IET, Vol. 1, p. 489-516, 2007.
7. Ghanbari, D., Abjadi, N.R., Ghanbari, A., Direct Torque and Flux Control of Five-Phase Induction Motor Using Fuzzy Logic, International Journal Of Innovative Research In Electrical, Electronics, Instrumentation And Control Engineering, Vol. 2, N°12, p. 2196-2202, 2014.
8. Iqbal, A., Modelling and control of series-connected five-phase and six-phase two-motor drives, PhD Thesis, Liverpool John Moores University, Liverpool, UK , August 2005.

9. Takahashi, I. and Noguchi, T., Take a look back upon the past decade of direct torque control of induction motors, in Industrial Electronics, Control and Instrumentation, IECON 97. 23rd International Conference on, Vol.2, p. 546-551, 1997.
10. Mohamed, M. R., Nezli, L., Mahmoudi, M. O., High performances of five–phase induction machine feeding by a [3 × 5] matrix converter, journal of electrical engineering, Vol. 65, no. 2, 83–89, 2014.
11. Huang shen gxu., Toliyat, Ha., Petersen, L.J., Five-Phase Induction Motor Drives with DSP-Based Control System, IEEE Transactions on Power Electronics 17 N^o. 524–533, 2002.
12. Sharma, P. G., Rangari, S., Simulation of Inverter Fed Five Phase Induction Motor, International Journal of Science and Research (IJSR), India Online ISSN: (2319-7064), Vol, 2, N°2, 2013.
13. Parsa, L., and Toliyat, H. M., Five-phase permanent-magnet motor drives, IEEE Trans. Ind. Appl., Vol. 41, No. 1, p. 30–37, 2005.
14. Sharma, P. G., Rangari, S., Simulation of Inverter Fed Five Phase Induction Motor, International Journal of Science and Research (IJSR), India Online ISSN: (2319-7064), Vol 2 , N°2, 2013.
15. Teresa, O. K., Senior Member, IEEE, Mateusz Dybkowski, and Krzysztof Szabat, adaptive Sliding-Mode Neuro-Fuzzy Control of the Two-Mass Induction Motor Drive without Mechanical Sensors. IEEE transactions on industrial electronics.vol. 57, N^o. 2 , 2010.
16. Hassankhan, E. , and Davood ,A., DTCSVM Scheme for I M Fed with a Three-level Inverter, World Academy of Science, Engineering and Technology, Vol. 44, p: 168-172, 2008.
17. Hamidia, F. , Larabi , A., Boucherit, MS., Comparative Study of the DTC-IM Speed Controller Based on Artificial Intelligence, Computer Technology and Application p:347-3523 , 2012.
18. Toliyat, H. A., A Novel Direct Torque Control (DTC) Method for Five Phase Induction Machines, Applied Power Electronics Conference and Exposition, APEC 2000, Vol 1, p. 162-168, 2000.
19. Trounce, J.C. , Round, S.D., and Duke, R..M., Comparison by simulation of three-level induction motor torque control schemes for electrical vehicle applications, Proc. of international power engineering conference, Vol. 1, p. 294-299, 2001.
20. Zaimeddine, R., and Berkouk, E.M., A Novel DTC scheme for a three-level voltage source inverter with GTO thyristors, SPEEDAM 2004, Symposium on power electronics, electrical drives, automation & Motion, June, vol. 2, June, p. F1A-9-F1A, 2004
21. Trounce, J.C., Round, S.D. and Duke, R..M., Comparison by simulation of three-level induction motor torque control schemes for electrical vehicle applications,Proc. of international power engineering conference, Vol. 1, p. 294-299 , 2001.
22. Logan Raj Lourdes Victor Raj, Auzani Jidin, Kasrul Abdul Karim, Tole Sutikno, Sundram,R., Mohd Hatta Jopri., Improved Torque Control Performance of Direct Torque Control for 5-Phase Induction Machine, International Journal of Power Electronics and Drive System (IJPEDS) , Vol. 3, N^o. 4, p. 391~399, 2013.
23. Lekhchine, S., Bahi, T., Soufi, Y., Merabet, H., Neural Fuzzy Speed Control for Six Phase Induction Machines, Proceedings Engineering & Technology (PET), Vol.1, p. 12-26, 2013 .
24. Sesha Reddy, K., Srinivasa Rao,K., Rami Reddy, C., Khaleel, SI., Speed Control of Five-Phase Induction Machine using Direct Torque Control, International Journal of Advanced Research in Education & Technology (IJARET), Vol. 2, N° 4 , p.152-156, 2015.
25. Lekhchine, S., Bahi, T., Bouzeria, H., Variable Speed Control for Rotor Field Oriented Control of a Doubly Fed Induction Machines, International Conference on Control, Engineering & Information Technology (CEIT'14) , Proceedings - Copyright IPCO-2014, p:124-129, 2014.

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