NEURO-FUZZY SPEED CONTROLLER FOR DUAL STAR INDUCTION MACHINE

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Abstract— This paper presents the modeling, design, and simulation of an adaptive neuro fuzzy inference strategy (ANFIS) for controlling the speed of the Double Star induction Machine, the machine is fed by a five-level inverter. Analytical solutions of Pulse Width Modulation (PWM) strategies for multilevel Neutral Point Clamped (NPC) are presented. Double star Induction motor is characterized by highly non-linear, complex and time-varying dynamics and inaccessibility of some of the states and outputs for measurements. Hence it can be considered as a challenging engineering problem in the industrial sector. Various advanced control techniques has been devised by various researchers across the world. Some of them are based on the neuro-fuzzy techniques (ANFIS). The main advantage of designing the ANFIS coordination scheme is to control the speed of the DSIM to increase the dynamic performance, to provide good stabilization. To show the effectiveness of our scheme, the proposed method was simulated on an electrical system composed of a 4.5 kW six-phase induction machine and its power inverter. Digital simulation results demonstrate that the deigned ANFIS speed controller realize a good dynamic of the DSIM, a perfect speed tracking with no overshoot, give better performance and high robustness

Index Terms— Dual star; Field Oriented Control; Neural Network; Fuzzy Logic; Multilevel Inverter

1. Introduction

The induction motor takes a large place in industry and we can find it in electrical ships. However, when high reliability is required, the control using the field-oriented method is often necessary and on-line diagnosis or off-line diagnoses have to be considered. The use of a double star induction motor or six-phase induction motor is slowly increasing and we find it in the high power process. Its main advantage lies in most reliability in case of a normal operating system [1]. Double star machine supplied with non sinusoidal waveforms causes perturbations in the torque (harmonics in torque). Recently for high performance power application multi level converters are widely used such as static var compensators, drives and active power filters. The advantage of multilevel inverter is good power quality, low switching losses and high voltage capability. Increasing the number of voltage levels in the inverter without requiring high ratings on individual devices can increases the power rating, and can gives sinusoidal waveforms, add at this multilevel structures which reduce harmonics in output voltages [3][4].

The DSIM it is desirable to control the flux and torque separately in order to have the same performances as those of DC motors. One way of doing this is by using the field oriented control. This method assures the decoupling of flux and torque [2]. The vector-controlled DSIM with a conventional PI speed controller is used extensively in industry, because has easily implemented. Alongside this success, the problem of tuning PI-controllers has remained an active research area. Furthermore, with changes in system dynamics and variations in operating points PI-Controllers should be returned on a regular basis. Today there are many methods for designing intelligent controllers, such as predictive controller, fuzzy control, neural networks and expert systems. Various combinations of these controllers give a number of design possibilities. Artificial Neural Networks (ANNs) and Fuzzy Logic (FL) have been increasingly in use in many engineering fields since their introduction as mathematical aids [7][8]. A combination of neural networks and fuzzy logic offers the possibility of solving tuning problems and design difficulties of fuzzy logic [9]. The resulting network will be more transparent and can be easily recognized in the form of fuzzy logic control rules or semantics [10]. This new approach combines the well established advantages of both the methods and avoids the drawbacks of both.

2. Double star induction modiling

The machine stydied is represented with two stators windings: sa_1, sb_1, sc_1 and sa_2, sb_2, sc_2 which are displaced by $\alpha = 30^0$ and the rotorical phases: ra, rb, rc, this is a most rugged and maintenance free machine

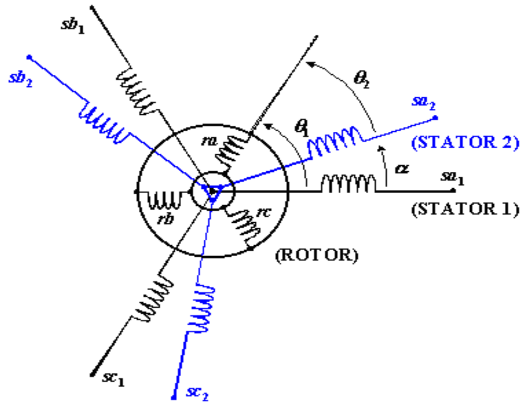

Fig. 1. Double stator winding representation

The following assumptions have been made in deriving the machine model

- ✓ Machine windings are sinusoidally distributed
- ✓ Machine magnetic saturation and the mutual leakage inductances are neglected
- ✓ The two stars have same parameters

The mathematical model of the machine is written as a set of state equations, both for the electrical and mechanical parts, the voltage equation is[2][3]:

$$\begin{aligned}
[V_{dqs1}] &= R_{s1}.[I_{dqs1}] + \frac{d}{dt}[\Phi_{dq1}] - \omega_s.[\Phi_{qds1}] \\
[V_{dqs2}] &= R_{s2}.[I_{dqs2}] + \frac{d}{dt}[\Phi_{dq2}] - \omega_s.[\Phi_{qds2}] \\
[V_{dqr}] &= R_r.[I_{dqr}] + \frac{d}{dt}[\Phi_{dqr}] - (\omega_s - \omega_r).[\Phi_{qdr}]
\end{aligned} \tag{1}$$

with:

$$\begin{aligned}
[\Phi_{dqs12}] &= L_{s12}[I_{dqs12}] + L_m\left(I_{dqs1} + I_{dqs2} + I_{dqr}\right) \\
[\Phi_{dqr}] &= L_{s12}[I_{dqr}] + L_m\left(I_{dqs1} + I_{dqs2} + I_{dqr}\right)
\end{aligned} \tag{2}$$

the electrical state variables in the “dq”system are the flux represented by vector [Φ], while the input variable in the “dq”system are expressed by vector [V].

$$\frac{d}{dt}[\Phi] = [A][\Phi] + [B][V] \tag{3}$$

with:

$$[\Phi] = \begin{bmatrix}\Phi_{dqs1} & \Phi_{dqs2} & \Phi_{dqr}\end{bmatrix}^T, [V] = \begin{bmatrix}V_{dqs1} & V_{dqs2} & V_{dqr}\end{bmatrix}^T$$

the equation of the electromagnetic torque is:

$$C_{em} = p\frac{L_m}{L_m + L_r}\left[(I_{qs1} + I_{qs2}).\Phi_{dr} + (I_{ds1} + I_{ds2}).\Phi_{qr}\right] \tag{4}$$

the equation of flux is:

$$[\Phi_{dqm}] = L_m (I_{dqs1} + I_{dqs2} + I_{dqr}) \quad (5)$$

or:

$$[\Phi_{dqm}] = L_a \cdot \left(\frac{\Phi_{dqs1}}{L_{s1}} + \frac{\Phi_{dqs2}}{L_{s2}} + \frac{\Phi_{dqr}}{L_r} \right) \quad (6)$$

where

$$L_a = \frac{1}{\frac{1}{L_m} + \frac{1}{L_{s1}} + \frac{1}{L_{s2}} + \frac{1}{L_r}} \quad (7)$$

the state matrix A and vector B in the d-q axis are:

$$[A] = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & a_{15} & 0 \\ a_{21} & a_{22} & 0 & a_{24} & a_{25} & 0 \\ a_{31} & 0 & a_{33} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & a_{46} \\ a_{51} & a_{52} & 0 & 0 & a_{55} & a_{56} \\ 0 & 0 & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \quad (8)$$

$$[B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (9)$$

where:

$$a_{11} = a_{33} = \frac{L_a}{T_{s1} L_{s1}} - \frac{1}{T_{s1}}$$

$$a_{12} = a_{24} = -a_{31} = -a_{42} = \omega_s, a_{15} = a_{35} = \frac{L_a}{T_{s1} L_r}$$

$$a_{21} = a_{43} = \frac{L_a}{T_{s2} L_{s1}}, a_{22} = a_{44} = \frac{L_a}{T_{s2} L_{s2}} - \frac{1}{T_{s2}}$$

$$a_{25} = a_{46} = \frac{L_a}{T_{s2} L_r}, a_{51} = a_{63} = \frac{L_a}{T_{s1} L_r}$$

$$a_{52} = a_{64} = \frac{L_a}{T_{s2} L_r}, a_{55} = a_{66} = \frac{L_a}{T_r L_r} - \frac{1}{T_r}$$

$$a_{56} = -a_{65} = \omega_r, T_s = \frac{L_s}{R_s}, T_r = \frac{L_r}{R_r}$$

and $\omega_r = \omega_s - \omega_m$

3. Five level inverter with NPC structure

The NPC inverter uses a series string of capacitors to subdivide a single high voltage DC bus into the required number of voltage levels, and each phase leg output can be switched to any one of these levels. [4] [5].

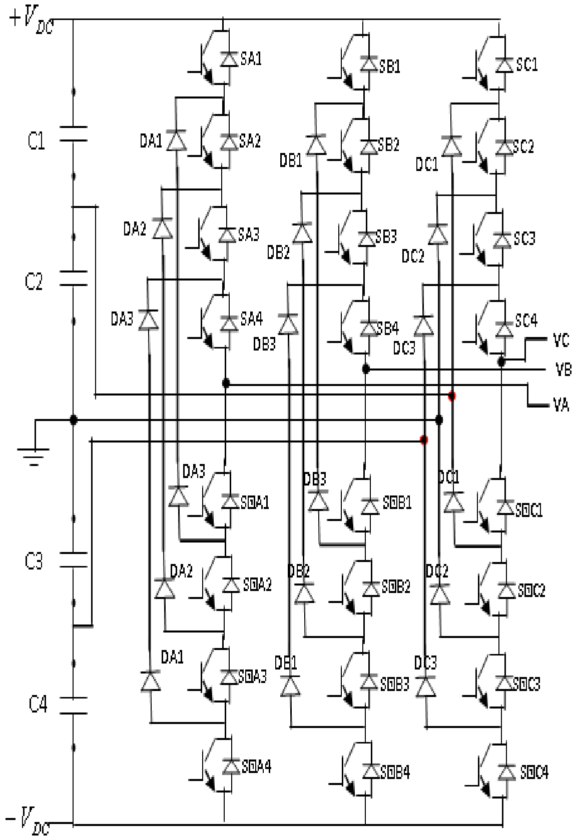

Fig.2. Five-level tension inverter with NPC structure

For the NPC inverter, most carrier based PWM schemes that have been investigated derive from the carrier disposition strategies originally proposed by Carrara et al [6]. for an NPC inverter with five levels, four triangular carriers with the same frequency and amplitude are arranged so that they fully occupy contiguous bands in the range of +VDC and -VDC. A sinusoidal reference centered in the middle of the carrier set is then compared with each carrier to determine the voltage level that the converter should switch to. The inverter produces output voltage in five levels: 0, +1/2Vdc, Vdc, −1/2Vdc, and −Vdc assuming that Vdc is the supply voltageThe carrying equations are given as follows:

$$U_{p1}(t) = \left\{ U_{pm}\left(\frac{2t}{T_p} - 1\right), 0 \le t \le T_p \right. \qquad U_{p2}(t) = \begin{cases} U_{pm}\left(\frac{2t}{T_p} - \frac{1}{2}\right), 0 \le t \le \frac{T_p}{4} \\ U_{pm}\left(\frac{2t}{T_p} - \frac{3}{2}\right), \frac{T_p}{4} \le t \le T_p \end{cases} \quad (10$$

$$U_{p3}(t) = \begin{cases} U_{pm}\left(\frac{2t}{T_p}\right), 0 \le t \le \frac{T_p}{2} \\ U_{pm}\left(\frac{2t}{T_p} - 2\right), \frac{T_p}{2} \le t \le T_p \end{cases} \qquad U_{p4}(t) = \begin{cases} U_{pm}\left(\frac{2t}{T_p} - \frac{1}{2}\right), 0 \le t \le \frac{T_p}{4} \\ U_{pm}\left(\frac{2t}{T_p} - \frac{5}{2}\right), \frac{3T_p}{4} \le t \le T_p \end{cases}$$

Figure.3. shows the reference and carrier waveform arrangements necessary to achieve PWM for a five level converter

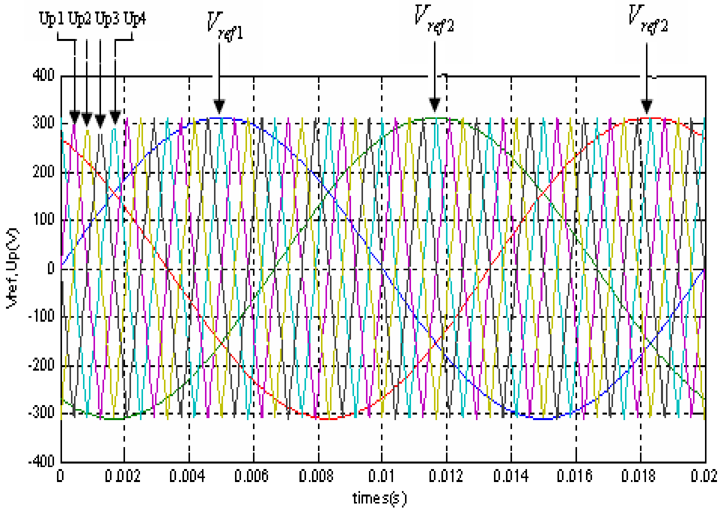

Fig.3. Reference and Carrier Waveform arrangement for PWM

5. Design of ANFIS Controller

The acronym ANFIS derives its name from adaptive neuro-fuzzy inference system. Using a given input/output data set, the toolbox function anfis constructs a fuzzy inference system (FIS) whose membership function parameters are tuned (adjusted) using either a backpropagation algorithm alone, or in combination with a least squares type of method. This allows your fuzzy systems to learn from the data they are modeling.

ANFIS's network organizes two parts like fuzzy systems. The first part is the antecedent part and the second part is the conclusion part, which are connected to each other by rules in network form. If ANFIS in network structure is shown, that is demonstrated in five layers. It can be described as a multi-layered neural network as shown in Fig.4. Where, the first layer executes a fuzzification process, the second layer executes the fuzzy AND of the antecedent part of the fuzzy rules, the third layer normalizes the membership functions (MFs), the fourth layer executes the consequent part of the fuzzy rules, and finally the last layer computes the output of fuzzy system by summing up the outputs of layer fourth. Here for ANFIS structure (fig.4.) two inputs and two labels for each input are considered. The feed forward equations of ANFIS are as follow[8]

In order to model complex nonlinear systems, the ANFIS model carries out input space partitioning that splits the input space into many local regions from which simple local models (linear functions or even adjustable coefficients) are employed. The ANFIS uses fuzzy MFs for splitting each input dimension; the input space is covered by MFs with overlapping that means several local regions can be activated simultaneously by a single input. As simple local models are adopted in ANFIS model, the ANFIS approximation ability will depend on the resolution of the input space partitioning, which is determined by the number of MFs in ANFIS and the number of layers. Usually MFs are used as bell-shaped with maximum equal to 1 and minimum equal to 0 such as[9][10]:

$$\mu_{Ai}(x) = \frac{1}{1+[(\frac{x-c_i}{a_i})^2]^{bi}} \tag{11}$$

$$\mu_{Ai}(x) = \exp\left\{-[(\frac{x-c_i}{a_i})^2]^{bi}\right\} \tag{12}$$

Where $\{a_i\ b_{i,}\ c_i\}$ are the parameters of MFs which are affected in shape of MFs

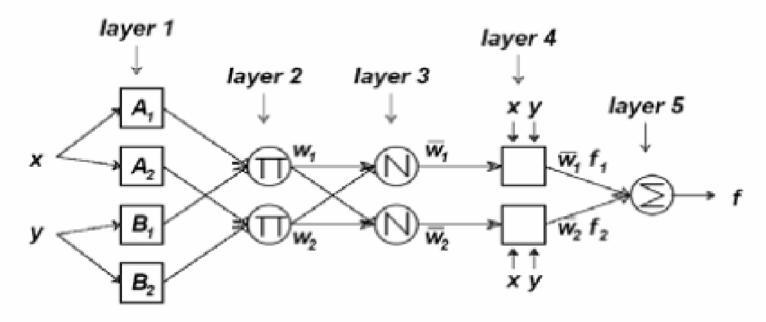

Fig.4.The equivalent ANFIS (type-3 ANFIS)

In this study the ANFIS controller generates change in the reference voltage V_{ref}, based on speed error *e* and derivate in the speed error *de* defined as:

$$e = \omega_{ref} - \omega \quad (13)$$
$$de = [d(\omega_{ref} - \omega)]/dt \quad (14)$$

where ω_{ref} and ω are the reference and the actual speeds, respectively.

Fig.5. shows The ANFIS model structure. Fig.6. shows Surface plot showing relationship between input and output parameters after trained.

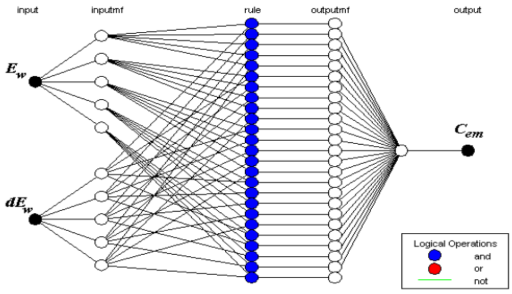

Fig.5.The ANFIS model structure

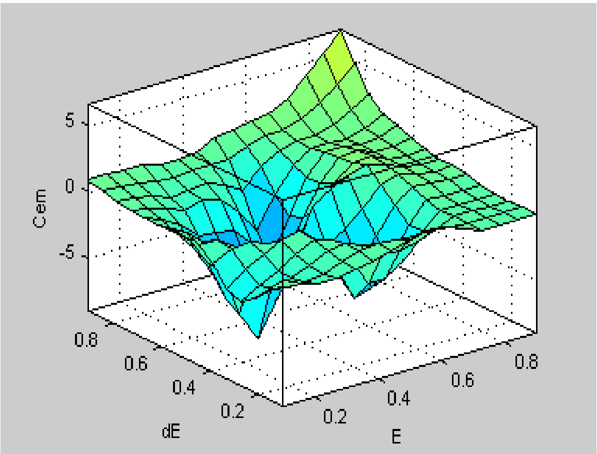

Fig.6.Surface plot showing relationship between input and output parameters

6. Simulation Results

The SIMULINK model for indirect FOC of the 4.5 Kw cage rotor DSIM associated with ANFIS controller is shown in Fig.7. The machine is fed by five-level tension inverter with NPC structure. The parameters of the induction motor are summarized in Appendix.

The first test concerns a no-load starting of the motor with a reference speed ω_{ref} = 288 rad/sec. and a nominal load disturbance torque (14N.m) is suddenly applied between 1sec and 2sec, followed by a consign inversion (-288rad/sec) at 2.5sec. At 4.5s, a -14Nm load disturbance is applied during a period of 2 s. this test has for object the study of controller behaviors in pursuit and in regulation.

The test results obtained are shown in Fig.8. The speed of the motor reaches ω_{ref} at 0.2 s with almost no overshoot. It then begins to oscillate inside a 0.4% error strip around ω_{ref} , The ANFIS controller rejects the load disturbance very quickly with no overshoot and with a negligible steady state error.

In order to test the robustness of the used method we have studied the effect of the parameters uncertainties on the performances of the speed control. To show the effect of the parameters uncertainties, we have simulated the system with different values of the parameter considered and compared to nominal value (real value). The Fig.9. and Fig.10. show respectively the behavior of the DSIM when R*r* is 10% increased of its nominal value and J is increased 10% of its nominal value. An increase of the moment of inertia gives best performances, but it presents a slow dynamic response. The figures show that the proposed controller gave satisfactory performances thus judges that the controller is robust

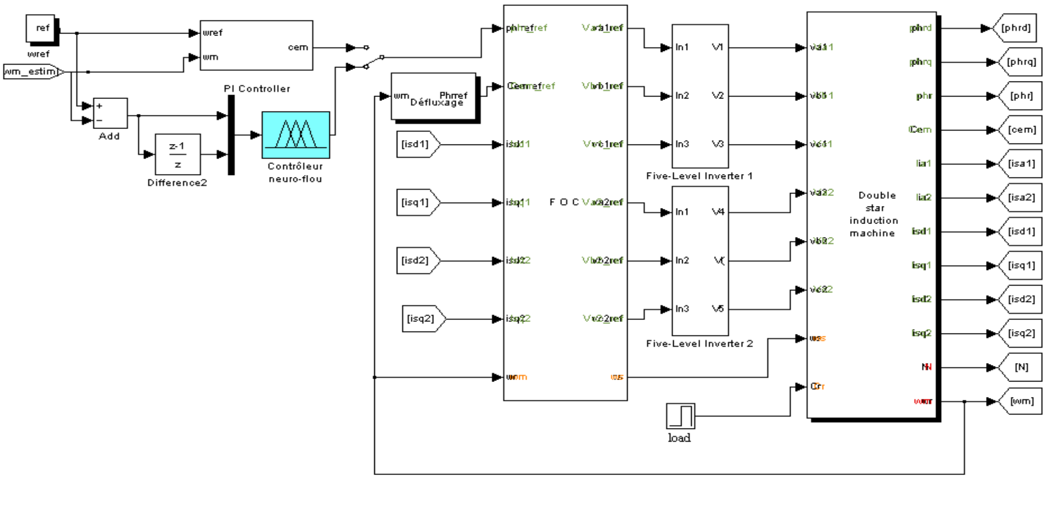

Fig.7. Simulink diagram for DSIM control systems

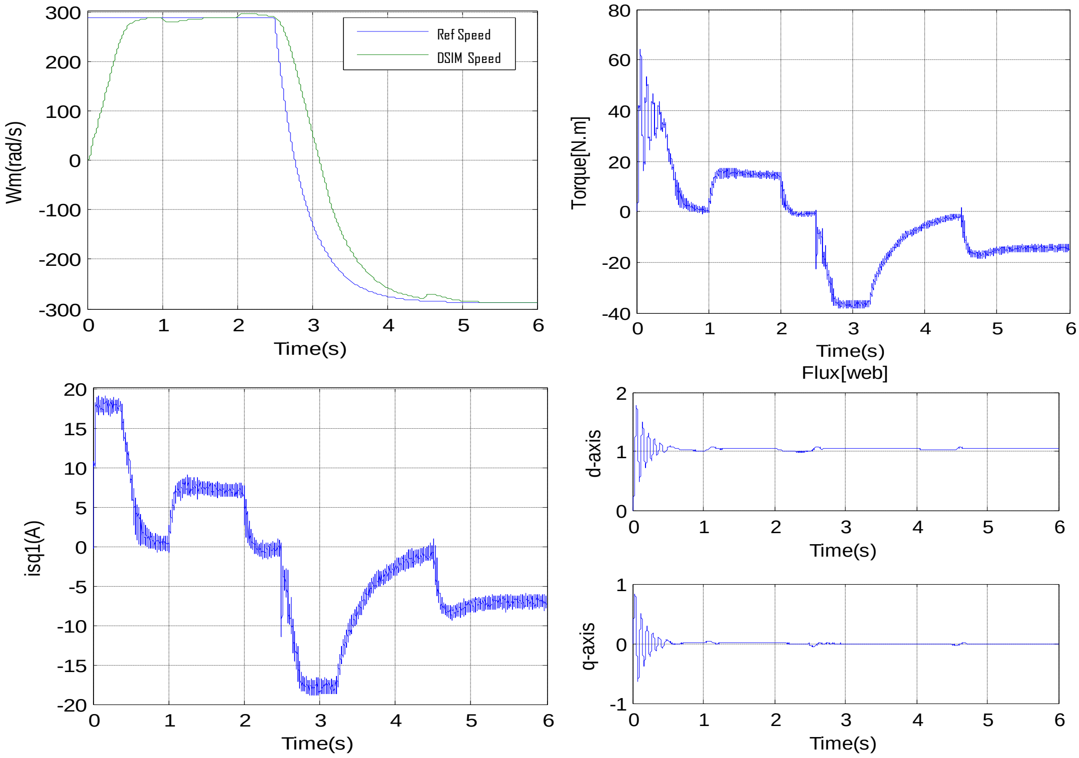

Fig.8. Simulated results of adaptive FLC-PI controller for DSIM

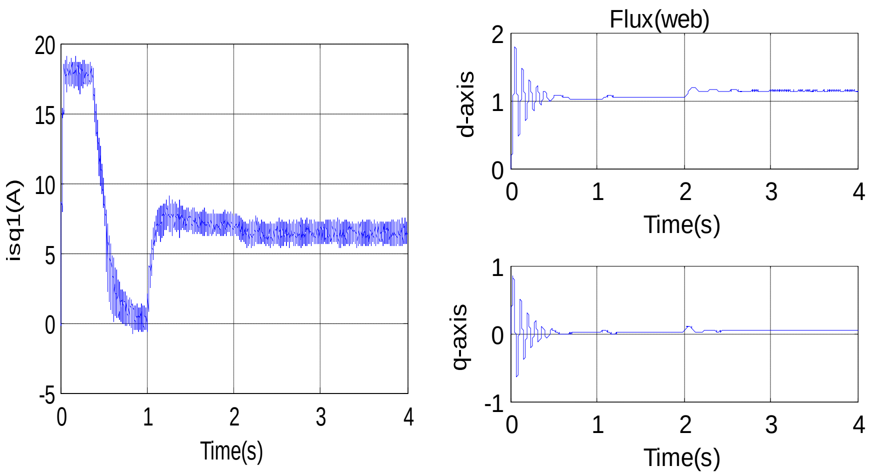

Fig. 9. Simulated results of adaptive FLC-PI controller for DSIM with variation of the rotor resistance at t=2s

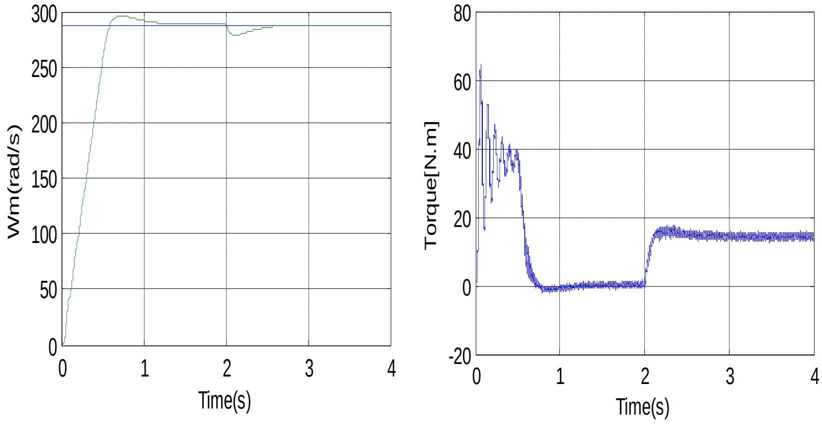

Fig .10. Simulated results of adaptive FLC-PI controller for DSIM with variation of the rotor inertia (+10%J)

7. Conclusion

This paper presents a study of an application of speed control with neuro fuzzy inference strategy (ANFIS) controller for a double stator induction machine based on the direct FOC, The machine is fed by a Five–Level Inverter, Simulation results on control robustness with speed variation parameters variation and the torque resistant are given. The results show that the controller could compensate for this kind of disturbances. The plant is also tested for the tracking property using different types of reference signals. Satisfactory performance was observed for most reference tracks and the results demonstrated the effectiveness of the proposed structure and the proposed control scheme it is believed will constitute a major step in the evolution of intelligent control.

Appendix

TABLE III
DSIM PARAMATERS

nominal values	Value	IS-Unit
Power	4.5	kW
Frequency	50	Hz
Voltage (Δ /Y)	220/380	V
Current (Δ /Y)	5.6	A
Speed	2751	rpm
Constant	Value	IS-Unit
Poles of pair	1	
$Rs_1 = Rs_2$	3.72	Ω
Rr	2.12	Ω
$Ls_1 = Ls_2$	0.022	H

Lr	0.006	H
L_m	0.3672	H
J	0.0625	Kgm^2
K_f	0.001	$Nm(rad/s)^{-1}$

References

[1] D. Hadiouche, "*Contribution to the study of dual stator induction machines: modelling, supplying and structure*", Ph. D. dissertation (in french), GREEN, Faculty of Sciences and Techniques, University Henri Poincaré-Nancy I, France, Dec. 2001.

[2] Bojoi R., Tenconi A., Griva G., Profumo F, "Vector Control of Dual-Three-Phase induction-Motor Drives Using Two Current Sensors ", *IEEE Trans. on Industry Applications*, vol. 42, no. 5, pp. 1284-1292, September/October 2006.

[3] Hechelef Mohammed, Abdelkader Meroufel, Omar .Ouledali, "Contribution to the Artificial Neural Network Direct Control of Torque Application Utilizing Double Stars Induction Motor", *Australian Journal of Basic and Applied Sciences*, 335-342**,** January,2014

[4] José Rodríguez, , Jih-Sheng Lai, and Fang Zheng Peng, , "Multilevel Inverters: A Survey of Topologies, Controls, and Applications", *IEEE Transactions On Industrial Electronics*, Vol. 49, No. 4, August 2002

[5] Dr.P. Usha Rani, "Modeling And Simulation Of Multilevel Inverter Based Dynamic Voltage Restorer For Voltage Sag Compensation", *Australian Journal of Basic and Applied Sciences*,162-167,FEBRUARY,2014

[6] G. Carrara, S. Gardella, M. Marchesoni, R. Salutari and G. Sciutto, "A New Multilevel PWM Method: A Theoretical Analysis", *IEEE Transactions on Power Electronics*, Vol. 7, NO. 3, July 1992, pp.497- 505.

[7] B. K. Bose, Neural Network , "Applications in Power Electronics and Motor Drives—An Introduction and Perspective*", IEEE Transactions on Industrial Electronics*, vol. 54, no. 1, pp. 14-33, February 2007.

[8] Jyh-Shing Roger Jang, " ANFIS : Adaptive-Network Based Fuzzy Inference System ", *IEEE Transactions on systems, Man, And Cybernetics*, Vol, 23, No,3, May/june 1993

[9] *V. Chitra, "ANFIS Based Field Oriented Control for Matrix Converter fed Induction Motor", IEEE international conference on power and energy (PECon2010),* Malaysia, 7478

[10] S.R. Khuntia, K.B. Mohanty, S. Panda and C. Ardil , "A Comparative Study of P-I, I-P, Fuzzy and Neuro-Fuzzy Controllers for Speed Control of DC Motor Drive" *International Journal of Electrical and Computer Engineering* 5:5 2010