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Fuzzy Control of DTC for Three Level Neutral Point Clamped Inverter Fed Induction Motor

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Abstract

Direct torque control (DTC) of induction motors fed by a two level inverter has drawbacks like more torque, flux and current ripples in steady state. This results in incorrect speed estimations. All these drawbacks can be overcome by DTC of induction motor fed by a three level inverter. Speed performance of the drive will be poor because of the uncertainties caused by load disturbances. In this paper a fuzzy controller is proposed to improve the speed performance of the drive. To validate the proposed method, simulation results are presented.

Keywords: Direct torque control, fuzzy control, Neutral point clamped inverter, space vector.

Introduction

One of the prominent members of the AC motors, Induction motors are called as the work horses of the industry. For low performance applications, open loop voltage/frequency control strategies are employed. For high-performance applications, vector control (VC), and Direct Torque Control (DTC) are used. Vector controlled drives were introduced in Germany by Blaschke and Hussey. Later Direct torque controlled drives were introduced in Japan by Takahashi. The mentioned control techniques have undergone research over the last decade. Vector control is very dependent on knowledge of the rotor time constant when using an induction machine. DTC, in its traditional form, results in a non-constant inverter switching frequency, which may result in high inverter/motor losses. DTC of induction motor is preferred because, this technique is based on the space vector approach, where the torque and flux of an induction motor can be directly and independently controlled without any coordinate transformation [1]. The merits of DTC can be summarized as fast torque response, simple structure (no need of complicated coordinate transformation, current regulation or modulation block), and robustness against motor parameter variation [2]–[5]. Multi-level inverters were extensively used especially in high power application areas [6]–[9]. The three-level neutral-point-clamped (NPC) inverter is one of the most commonly used multilevel inverter topologies. Three-level inverter offers superiority in terms of lower voltage distortion, lower stress across the semiconductors, less harmonic content and lower switching frequency when compared with the conventional two level inverters[10]. Variable speed drives for Induction Motor requires wide operating range of speed and fast torque response, regardless of load variations. Hence there is a need to go for more advanced control methods to meet the real demand. Conventional control methods have the difficulties like dependency on the accuracy of mathematical model of the system, shows good performance at only one speed, model of the control system should be known etc. Fuzzy logic is a technique which incorporates human-like thinking into a control system that is, the process how people use to infer conclusions from what they know.

The aim of this paper is to achieve high performance DTC for a three-level inverter-fed induction motor drive, as well as considering the neutral point potential balance and smooth vector switching. To enhance the low speed performance, a fuzzy logic controller (FLC) is incorporated in the system. Simulation is carried out to validate the effectiveness of the schemes proposed.

Mathematical Modeling of Induction Motor

The induction motor has been modeled by using the following equations.

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} \tag{1}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} \tag{2}$$

$$R_r i_{qr} + \frac{d}{dt}\psi_{qr} - \omega_r \Psi_{dr} = 0 \tag{3}$$

$$R_r i_{dr} + \frac{d}{dt}\psi_{dr} + \omega_r \Psi_{qr} = 0 \tag{4}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \tag{5}$$

Neutral Point Clamped Inverter

The three level neutral point clamped inverter has many advantages over the conventional two level inverter, such as smoother waveform, less distortion, less switching frequency and low cost [11]. The topology of a three level NPC inverter is shown in figure 1.

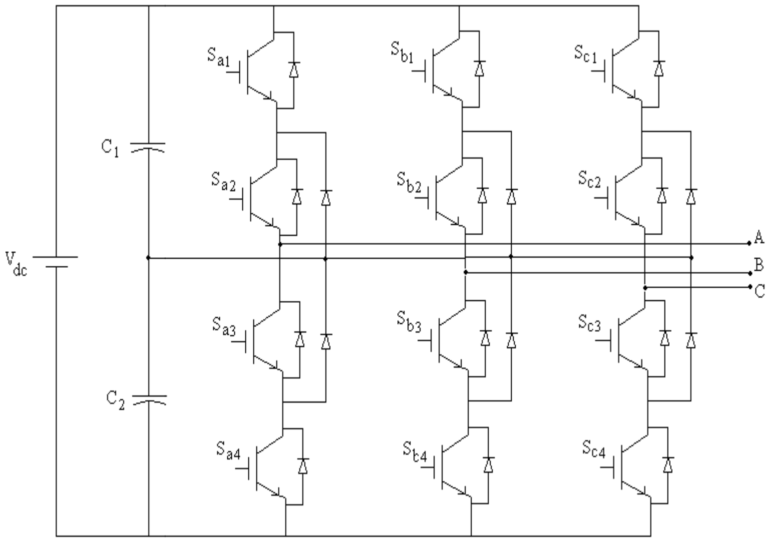

Figure 1: Schematic diagram of NPC three level Inverter

The three level inverter has a total of 27 switching states (3^3). When the upper switches S_{a1}, S_{a2} are in the on state, that corresponds to the state ‘1’. When the lower switches S_{a3}, S_{a4} are on, that corresponds to state ‘-1’. When the auxiliary switches S_{a2}, S_{a3} are on, that results in state ‘0’. The space vector diagram of all the switching states is represented in figure 2.

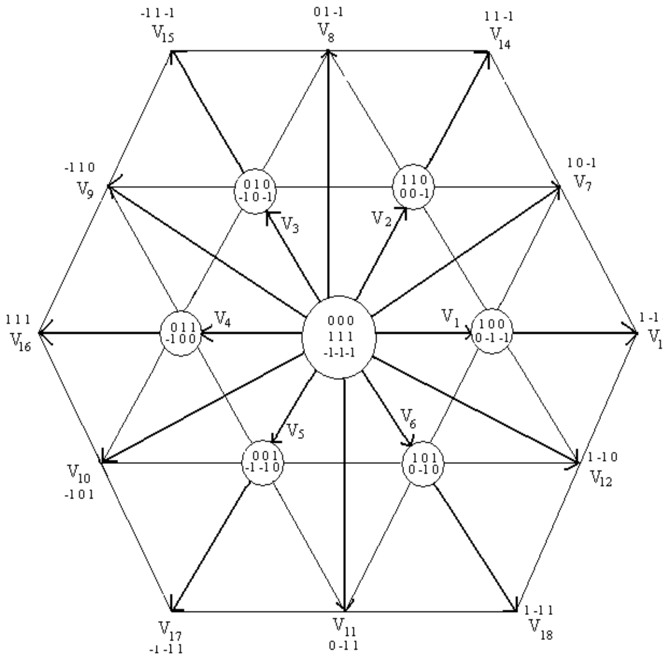

Figure 2: Space vector diagram

The space vector diagram consists of two hexagons, the inner hexagon and the outer hexagon. A three level inverter has basically 27 switching states out of which three are zero states and the remaining twenty four states are the active states. The zero states produce a zero vector where as the twenty four active states produce eighteen different voltage vectors. These eighteen active vectors are classified as small, medium and large voltage vectors based on their magnitude. This classification is shown in Table 1.

Table I: Classification of Voltage Vectors.

Type	Vector numbers	Magnitude
Small	V_1, V_2, V_3, V_4, V_5, V_6	0.5 V_d
Medium	V_7, V_8, V_9, V_{10}, V_{11}, V_{12}	0.866 V_d
Large	V_{13}, V_{14}, V_{15}, V_{16}, V_{17}, V_{18}	V_d

Direct Torque Control of Induction Motor

Principle of DTC

The electromagnetic torque of 3-phase induction motor is given by,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\psi_r||\psi_s|\sin\eta \tag{6}$$

Where ψ_r and ψ_s are the rotor and stator flux linkages and η is the angle between the fluxes and σ is the leakage coefficient. The direct torque control of induction motor fed by a three level NPC inverter is as shown in figure 3.

According to this block diagram, the scheme includes two hysteresis controllers. They are the torque hysteresis and the flux hysteresis controllers. The flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory. The torque controller determines the time duration of the zero vector, which keeps the developed electromagnetic torque within the defined hysteresis band.

The adaptive motor controller block provides the information related to the actual torque, speed, flux and the angle to the hysteresis torque and flux controllers and the sector estimator blocks. The stator flux, torque and the stator flux linkages phase angle can be estimated by using the equations (7) - (9).

$$\Psi_S = \int (V_S - R_S i_S)dt \tag{7}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(i_{qs}\Psi_{ds} - i_{ds}\Psi_{qs}\right) \tag{8}$$

$$\theta = \tan^{-1}\left(\frac{\Psi_{qs}}{\Psi_{ds}}\right) \tag{9}$$

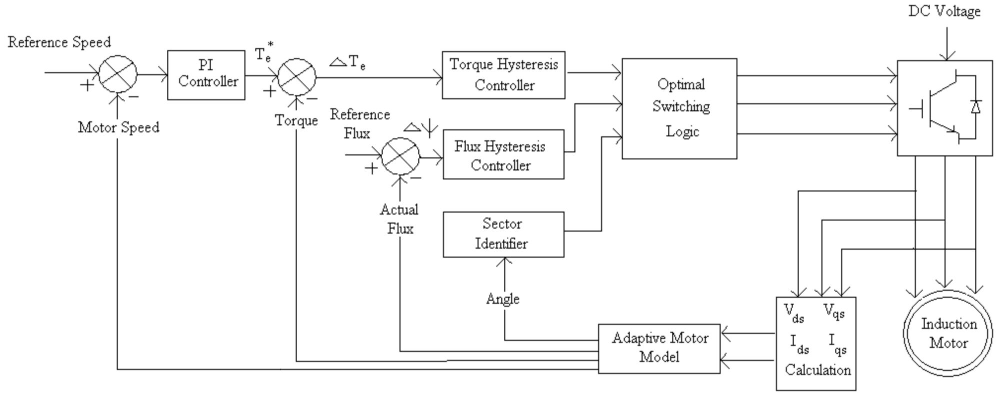

Figure 3: DTC of Induction Motor fed by a three level Inverter

The PI controller employed in the system results in the torque command signal. This PI controller should be tuned properly so as to observe the dynamic behavior of the system. The optimal switching logic block generates the control signals S_a, S_b, S_c to the three level inverter.

Modulation Strategy of three level DTC

The space vector diagram of the three level inverter is partitioned into twelve sectors by using a diagonal between the adjacent short vector and the medium vector [12]-[14]. This partitioned space vector diagram is as shown in figure 4.

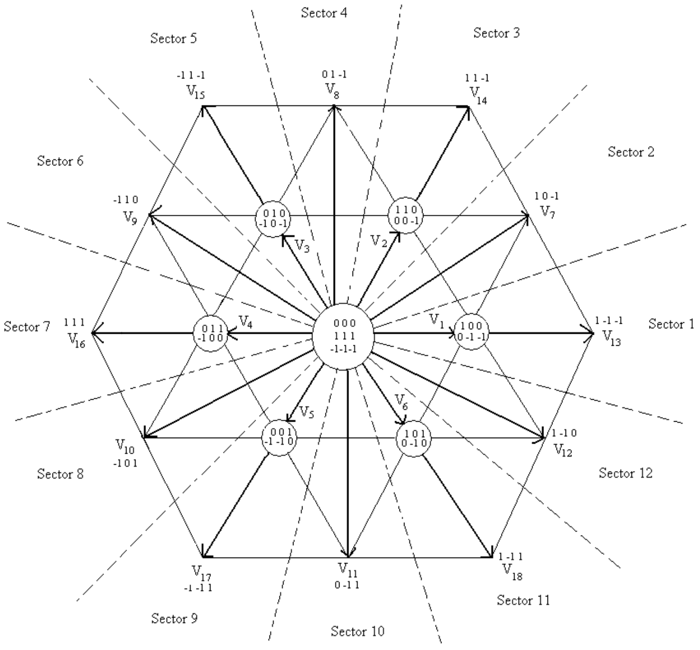

Figure 4: Space vector diagram for three level DTC

The adaptive motor model shown in figure 3 generates the angle as one of the output signals. Based on this angle, the sector number will be selected. For example, if the angle is in the range of 23π/12 to π/12, that corresponds to sector 1. According to the DTC control principle, the voltage vectors should be selected based on the increase or decrease of the torque and flux [15]-[17]. In order to select the voltage vectors, the sector selection should be done primarily. This sector selection is done based on the Table 2.

Table 2: Selection of the Sectors.

Flux	Torque	Selected Sector Number
Increase	Increase	$S_m = S_{n+1}, S_{n+2}$
Increase	Decrease	$S_m = S_{n-1}, S_{n-2}$
Decrease	Increase	$S_m = S_{n+4}, S_{n+5}$
Decrease	Decrease	$S_m = S_{n-4}, S_{n-5}$
No Change		Zero Vector

In the table, S_m represents the selected vector and S_n represents the sector where the current flux linkage is located. Variable n is selected between 1 and 12. If the value of m is over 12, m is forced to be m-12. If m is less than 1, then m is forced to be m+12.

Fuzzy Speed Control for DTC of Induction Motor

Fuzzy control is an adaptive and nonlinear control which gives robust performance for any system with parameter variation. These controllers can handle complicated non linear systems which have a degree of uncertainty. It does not require exact system modeling and parameters which makes the controller suitable for the motor control [18]-[20]. The fuzzy logic controller has two inputs (1) speed error 'E'(2) derivative of the speed error 'CE'. The block diagram of a fuzzy PI controller is shown in figure 5 [21].

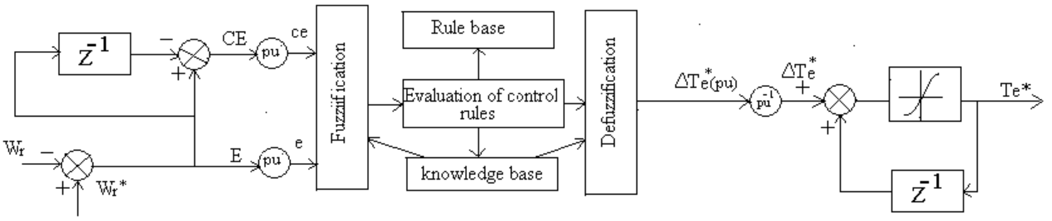

Figure 5: Block diagram of fuzzy PI controller

Inputs E and CE are expressed in per unit values. Expressing fuzzy control in terms of PU variables ensures that the algorithm can be applied to all the plants of the same family. The output of the controller is dT_e^* which is the change in the torque command. This is a PU value. The actual value of the torque command is obtained as shown in the figure 5. The membership functions of the input and output variables are shown in figures 6 – 7 [21].

The rule base of a fuzzy system is IF – THEN statement. The execution of the rules goes like this: IF there exists a case, THEN a particular condition has to be executed.

For example, IF e(PU) = PS AND ce(PU) = NM, THEN $dT_e^*(PU)$ = NVS.

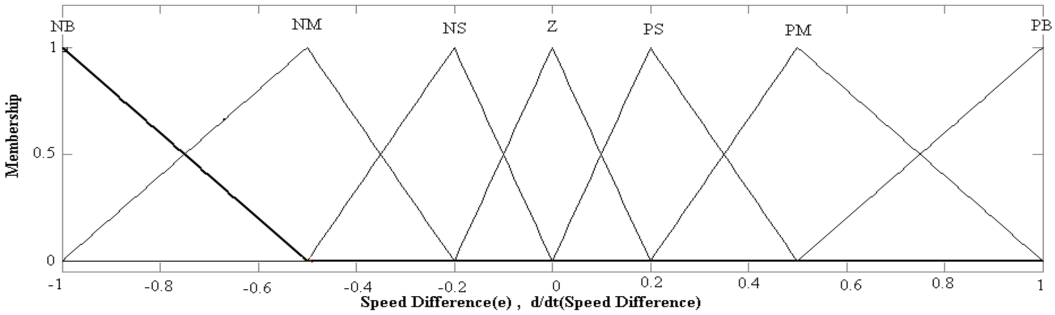

Figure 6: Membership functions of the input variables (a) speed error (e) (b) change in speed error (de)

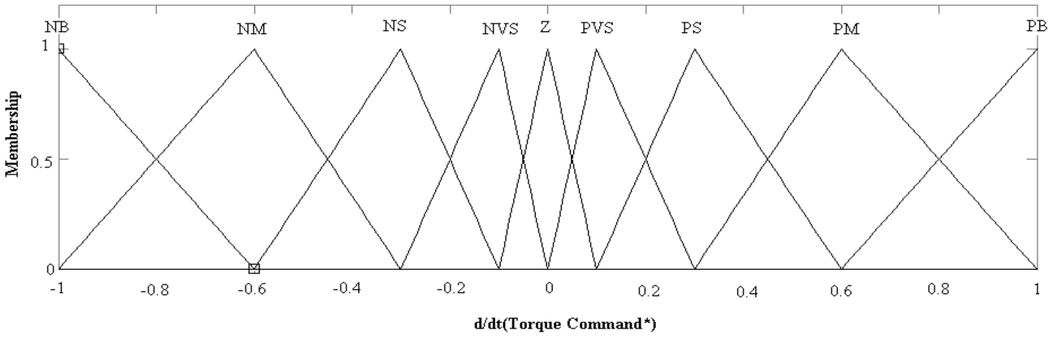

Figure 7: Membership functions of the output variable change in torque command(dT_e^*)

The number of input variables chosen is 7 and hence the possible number of fuzzy rules is 7X7 = 49. All these rules are shown in table 3. The membership functions and the rules are purely based on the knowledge of the system.

Table 3: Fuzzy Rules

e(pu) ce(pu)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NVS	Z
NM	NB	NB	NM	NS	NVS	Z	PVS
NS	NB	NM	NS	NVS	Z	PVS	PS
Z	NM	NS	NVS	Z	PVS	PS	PM
PS	NS	NVS	Z	PVS	PS	PM	PB
PM	NVS	Z	PVS	PS	PM	PB	PB
PB	Z	PVS	PS	PM	PB	PB	PB

Where NB=Negative Big, NM=Negative Medium, NS=Negative Small, Z=Zero, PS=Positive Small, PM=Positive Medium, PB=Positive Big, NVS=Negative Very Small, PVS=Positive Very Small.

The mapping relationship between the input variables and output variables is shown in figure 8.

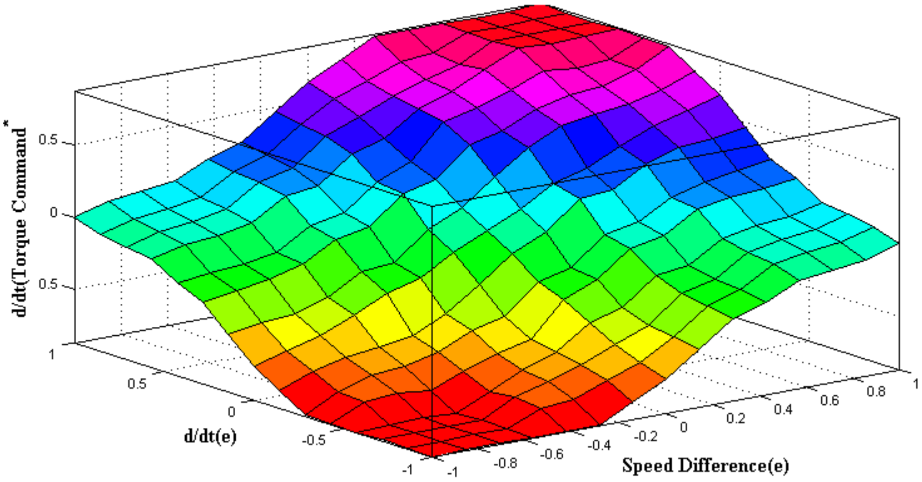

Figure 8: Control surface of the fuzzy logic controller

Results and Discussion

To validate the effectiveness of the fuzzy logic controller, simulation of the three level DTC of induction motor with PI and fuzzy logic controllers is done. The block diagram of the system employing the fuzzy logic controller is shown in figure 9.

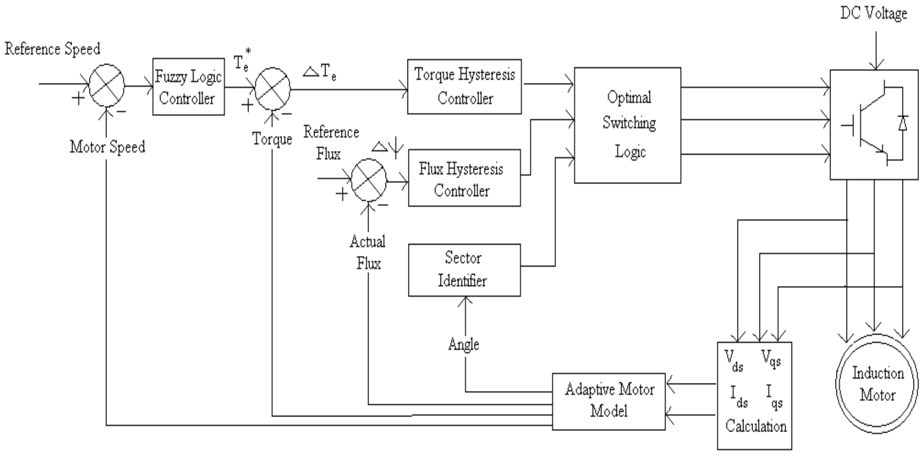

Figure 9: Three level DTC drive with fuzzy logic controller

Fuzzy logic controller is employed in the outer loop to control the speed of the motor. Parameters of the induction motor used in this paper are as shown below [22].

Stator resistance = 1.57 Ohms
Rotor resistance = 1.21 Ohms
Magnetizing inductance = 0.165H
Stator leakage inductance = 0.17H
Rotor leakage inductance = 0.17H
Number of pole pairs = 4
J = 0.089 Kg-m^2.

For the simulation, the reference flux is taken as 1wb. The reference speed is chosen as 600 rpm. At 0.5 seconds, the reference speed is changed to 1200 rpm. The speed response of the motor employing the fuzzy logic controller is as shown in figure 10.

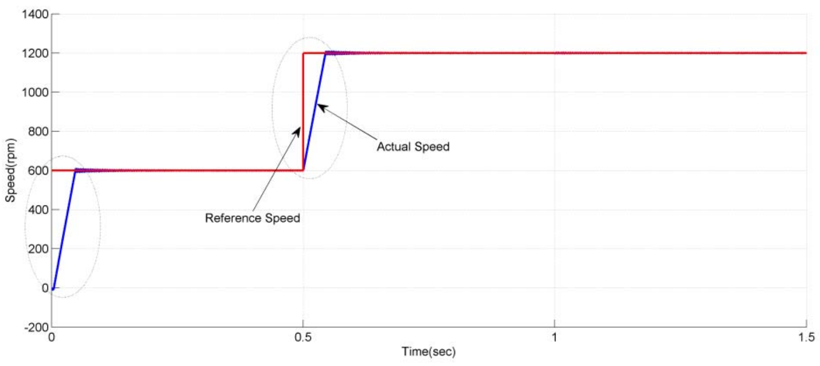

Figure 10: Speed response of the motor during speed change

The dotted circles shows the time taken by the motor to reach the steady state speed. The stator currents, torque and the speed of the motor during the transient period when the reference speed is set as 600 rpm is as shown in figure 11. The transient behavior of the system when the speed is changed from 600 rpm to 1200 rpm is as shown in figure 12.

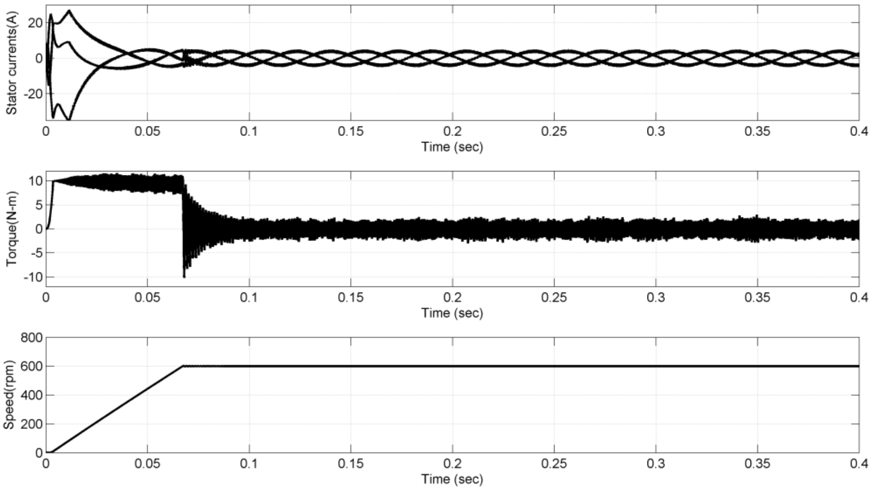

Figure 11: Starting transients with the reference speed as 600 rpm

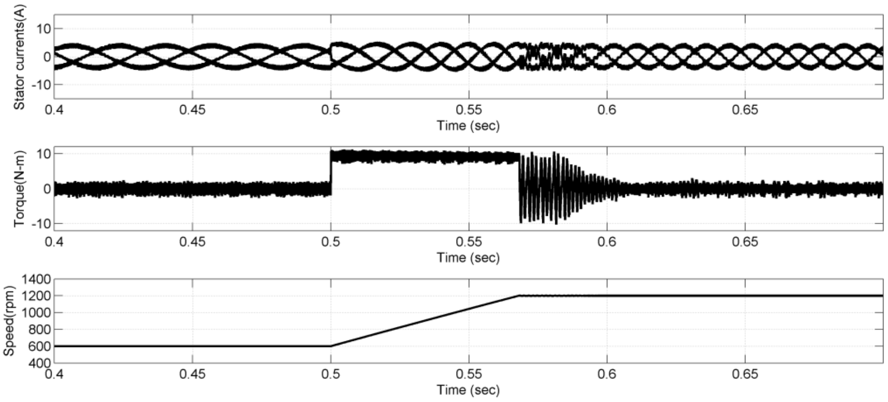

Figure 12: Transients during the speed change from 600 rpm to 1200 rpm at 0.5 seconds

Steady state plots of the stator currents, torque and speed at 1200 rpm is as shown in figure 13.

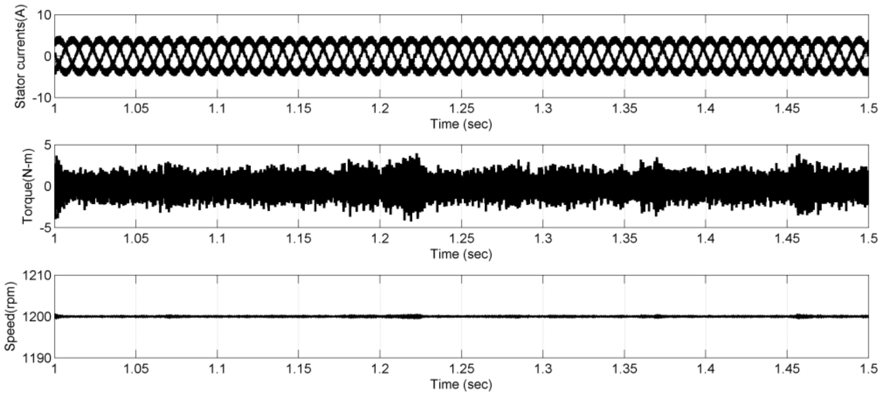

Figure 13: Steady state waveforms at 1200 rpm

Waveforms of the stator currents, torque and the speed when a load torque of 5 Nm is applied at 0.5 sec is as shown in figure 14. The locus of the stator flux is shown in figure 15.

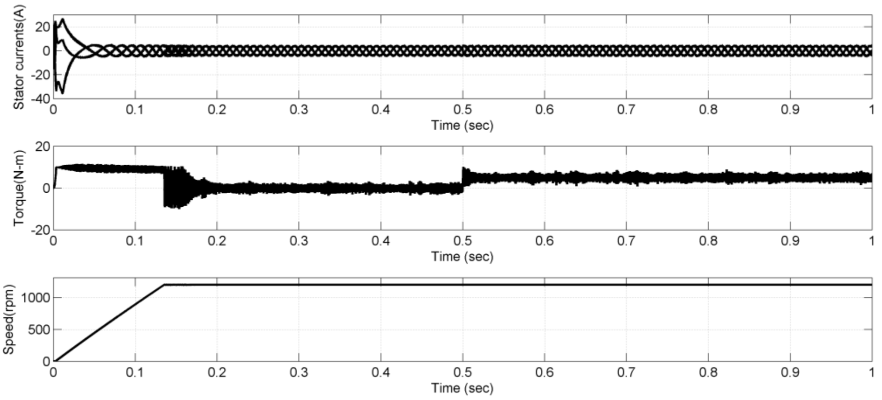

Figure 14: Waveforms when load torque of 5Nm is applied at 0.5 seconds

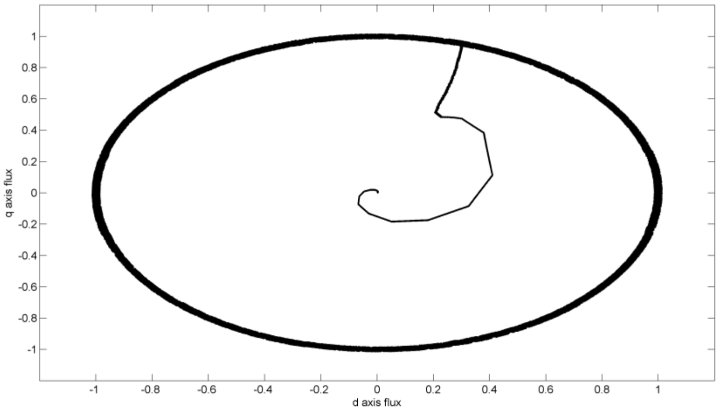

Figure 15: locus of the stator flux

The proposed fuzzy logic controller is tested by considering different load torque disturbances. Figure 16 shows the external load torque disturbance. The speed response of the system with PI and fuzzy logic controller is as shown in figure 17.

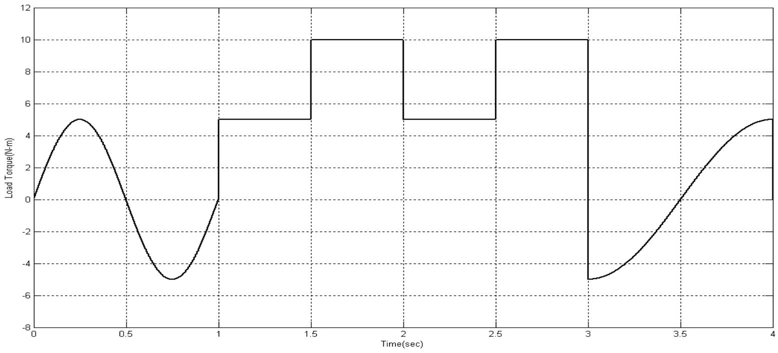

Figure 16: External load torque disturbance

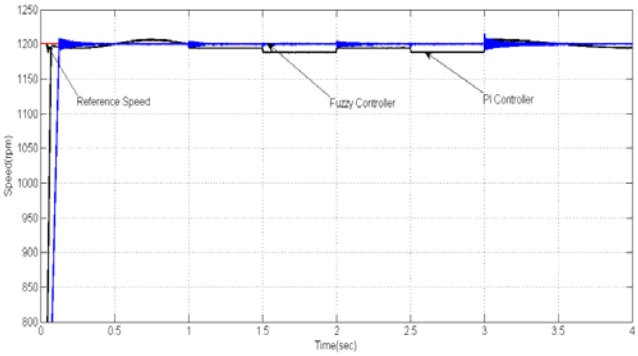

Figure 17: Speed comparison of the motor with PI, Fuzzy logic controller

Conclusions

Fuzzy logic controller which has been proposed in this paper has achieved high performance speed control of the DTC of three level inverter fed induction motor. Also the problems of neutral point clamped inverter such as neutral point balance, torque ripple has been minimized by choosing appropriate intermediate vectors and by using a new vector synthesis sequence. A fuzzy logic controller is incorporated into the system to control the speed of the system. The comparison of speed responses with PI controller and with fuzzy logic controller is validated by considering external load disturbance that consists of step changes in load torque. It can be observed that, when the load disturbance is added or removed the speed response is almost same as that of the reference speed in case of the proposed controller. Thus, the speed tracking is not affected by the load torque. Finally it can be concluded that the fuzzy logic based DTC scheme gives a stable speed response even during the external load torque disturbance and hence provides the robustness for the system.

References

[1] Takahashi and T. Noguchi, "A new quick-response and high-efficiency control strategy of an induction motor," *IEEE Trans. Ind. Appl., vol. IA- 22, no. 5, pp. 820–827, Sept. 1986.*

[2] M. Depenbrock, "Direct self-control (dsc) of inverter-fed induction machine," *IEEE Trans. Power Electron.,vol. 3, no. 4, pp. 420–429, Oct. 1988.*

[3] G. Abad, M. A. Rodriguez, and J. Poza, "Two-level vsc based predictive direct torque control of the doubly fed induction machine with reduced torque and flux ripples at low constant switching frequency," *IEEE Trans.* Power Electron., vol. 23, no. 3, pp. 1050–1061, May 2008.

[4] D. Casadei, G. Serra, and A. Tani, "Improvement of direct torque control performance by using a discrete svm technique," *in Proc. PESC 98 Record Power Electronics Specialists Conference 29th Annual IEEE, vol. 2, May 17–22, 1998, pp. 997–1003.*

[5] G. S. Buja and M. P. Kazmierkowski, "Direct torque control of pwm inverter-fed ac motors–a survey," *IEEE Trans. Ind. Electron., vol. 51, no. 4, pp. 744–757, Aug. 2004.*

[6] J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron., vol. 54, no. 6, pp. 2930–2945, Dec. 2007.*

[7] W. Yao, H. Hu, and Z. Lu, "Comparisons of space-vector modulation and carrier-based modulation of multilevel inverter," *IEEE Trans. Power Electron., vol. 23, no. 1, pp. 45–51, Jan. 2008.*

[8] S. Busquets-Monge, S. Alepuz, J. Bordonau, and J. Peracaula, "Voltage balancing control of diode-clamped multilevel converters with passive front-ends," *IEEE Trans. Power Electron., vol. 23, no. 4, pp. 1751–1758, Jul. 2008.*

[9] Y. Zhang and Z. Zhao, "Study on capacitor voltage balance for multilevel inverter based on a fast svm algorithm," *Proceeding of the CSEE (in Chinese), vol. 26, no. 18, pp. 71–76, 2006.*

[10] Amit kumar, ashwin.M , A space vector PWM scheme for multilevel inverters based on two level space vector PWM, *IEEE transactions on industrial electronics, vol. 53, (Issue 5) , October 2006.*

[11] K.-B. Lee, J.-H. Song, I. Choy, and J.-Y. Yoo, "Torque ripple reduction in dtc of induction motor driven by three-level inverter with low switching frequency," *IEEE Trans. Power Electron., vol. 17, no. 2, pp. 255–264, Mar. 2002.*

[12] A. Gharakhani and A. Radan, "Analytical study of affecting characteristic of voltage vectors of a three-level npc inverter on torque and flux of dtc controlled drives," *in Proc. IEEE International Electric Machines. Drives Conference IEMDC '07, vol. 1, May 3–5, 2007, pp. 754–759.*

[13] G. Brando and R. Rizzo, "An optimized algorithm for torque oscillation reduction in dtc-induction motor drives using 3-level npc inverter," *in Proc. IEEE International Symposium on Industrial Electronics, vol. 2, May 4–7, 2004, pp. 1215–1220.*

[14] X. del Toro Garcia, A. Arias, M. G. Jayne, and P. A. Witting, "Direct torque control of induction motors utilizing three-level voltage source inverters," *IEEE Trans. Ind. Electron., vol. 55, no. 2, pp. 956–958, Feb. 2008.*

[15] Y. Zhang, J. Zhu, Y. Guo, W. Xu, Y. Wang, and Z. Zhao, "A sensorless dtc strategy of induction motor fed by three-level inverter based on discrete space vector modulation," *in Proc. Australasian Universities Power Engineering Conference AUPEC 2009, Sep. 27–30, 2009, pp. 1–6.*

[16] Y. Zhang, Z. Zhao, J. Zhu, W. Xu, and D. G. Dorrell, "Speed sensorless direct torque control of 3-level inverter-fed induction motor drive based on optimized switching table," *in Industrial Electronics Society, 2009. IECON '09. The 35th Annual Conference of the IEEE, 2009, pp. 1318– 1323.*

[17] Y. Zhang, Z. Zhao, T. Lu, and L. Yuan, "Sensorless 3-level inverter-fed induction motor drive based on indirect torque control," *in Proc. IEEE 6th International Power Electronics and Motion Control Conference IPEMC '09, May 17–20, 2009, pp. 589–593.*

[18] Y. Zhang and Z. Zhao, "An improved direct torque control for three level inverter- fed induction motor sensorless drive," *IEEE Trans. Power Electron., vol. 21, no. 5, Nov. 2010.*

[19] M. N. Uddin, T. S. Radwan, and M. A. Rahman, "Performances of fuzzy logic based indirest vector control for induction motor drive", *IEEE Trans. Ind. Appl., vol. 38, no. 5, pp. 1219-1225, Sep. 2002.*

[20] Y. Zhang and Z. Zhao, " Comaparative study of PI, sliding mode and fuzzy logic controller for rotor field oriented controlled induction motor drives", *in proc. International Conference on Electrical machines and Systems ICEMS 2008, Oct. 17-20, 2008, PP. 1089-1094.*

[21] Adamidis Georgios, and Zisis Koutsogiannis " Direct torque control using space vector modulation and dynamic performance of the drive, via a Fuzzy

Logic controller for speed regulation", *Democritus University of Thrace, Greece.*

[22] T. Vamsee Kiran, J. Amarnath, " Speed performance of direct torque control for three level inverter fed induction motor : Sliding mode control approach", *ICGST-ACSE Journal, volume 1, issue 2, Nov 2011.*

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