FLC-Based DTC of Induction Motor Sensorless Drive to Improve the Dynamic Performance

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Abstract- This paper focuses on the direct torque control (DTC) of induction motor sensorless drive using multiple Fuzzy Logic Controller (FLC). Compared to conventional DTC scheme FLDTC can achieve a reduction in torque and flux ripples and, hence to improve the motor dynamic response. Also in traditional DTC PI controller is used in the speed controller. PI controller is more suitable in steady state condition and for linear system. But since DTC along with IM is mostly nonlinear, fuzzy controller will be more suitable.

This control technique is verified through simulation. Finally the simulation results of traditional DTC drive and FLDTC drive are compared.

Index Terms— Direct torque control (DTC); PI controller; fuzzy logic controller (FLC); induction motor (IM); fuzzy logic direct torque control (FLDTC).

I. INTRODUCTION

The inverter-fed IM control techniques are basically parted into scalar and vector control methods. The scalar based controllers offer adept steady state but poor dynamic response. From the traces of the dynamic responses, the deviation of air gap flux linkage from their fixed value is the reason of such poor dynamic response. The invention of Vector controllers solved the foregoing problems. One of the vector control method is the Field Oriented Control (FOC) [1]. In this scheme, fast torque response and speed control can be obtained. Vector control made the AC drives equivalent to DC drives in the independent control of torque and flux and superior to them in their dynamic response. One of the vector control method is the Field Oriented Control (FOC) [1]. In this scheme, torque and flux of an induction motor are controlled independently by decoupling the stator current into its rectangular components. The FOC technique has attained a fast torque response. But in FOC, precise recognition of parameters is necessary.

In the mid- 1980s, an advanced scalar control technique, [1] known as direct torque and flux control (DTFC or DTC) or direct self-control, was introduced for voltage fed PWM [2] inverter drives. In this scheme as the name indicates, is the direct control of the torque and stator flux of a drive by inverter voltage space vector selection through a lookup table. Presence of ripples in the motor - developed torque and stator flux are the major drawback in a DTC based motor drive. Generally torque ripples are reduced by using two important techniques. Use of multilevel inverter [4] is the first method, since it provides more accurate control of flux and torque. But, the complexity and cost of the controller is very high as number of levels increases. The second method is the space vector modulation [5]. Continuous variation of switching frequency is its major drawback.

Intelligent controllers such as fuzzy logic, neural network, neuro - fuzzy, etc., don't depend upon accurate mathematical modeling of the system and they can handle nonlinearity of arbitrary complexity [5]-[7]. Compared to different intelligent algorithms, fuzzy logic control (FLC) is the best, because intense numerical analysis is not required in FLC.

Hence, in this paper, a mere practically feasible FLC is configured that picks out the suited bandwidth for the torque hysteresis controller to optimize the ripple level in the developed torque and, hence, to improve the motor speed response. Using MATLAB/Simulink a complete simulation model for the proposed drive is developed. The effectiveness of the proposed drive is corroborated at distinct dynamic operating conditions by simulation results.

II. DIRECT TORQUE AND FLUX CONTROL PRINCIPLE

The block diagram for the conventional DTC scheme of an IM drive is depicted in Fig. 1, and the Fig. 2 explains the control strategy. In 1986 Takahashi and Noguchi suggested the basic concept of the Direct Torque and flux Control. This technique is more exploited in controlling the induction motor because it is reckoned a simple and robust method. The significant key in this technique is the power inverter operational control and modern power electronics has attained this cost effective also. The aim of this method is to control two quantities which are the stator flux vector and the electromagnetic torque. Those measures are directly controlled by choosing the appropriate inverter state through a lookup table.

Output digit of torque hysteresis controller, output digit of flux linkage hysteresis controller, and sector number where stator flux-linkage space vector is placed are the three inputs of direct torque control scheme. Based on the three inputs the DTC switching table develops the logic signals S_a , S_b and S_c. The switches of the three-phase voltage source inverter (VSI) are actuated using the logic signals S_a, S_b, S_c. The electromagnetic developed torque expression as a function of the stator and rotor fluxes is given by [8]

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r L_s^{'}}\left|\psi_r\right|\left|\psi_s\right|\sin\gamma\Big| \qquad (1)$$

Where γ is the angle between the fluxes, P is the number of pole pairs and $L_s^{'} = L_s L_r - L_m^2$. In the steady state condition the electromagnetic torque depends on the torque angle and also the magnitude of the stator and rotor fluxes are almost constant.

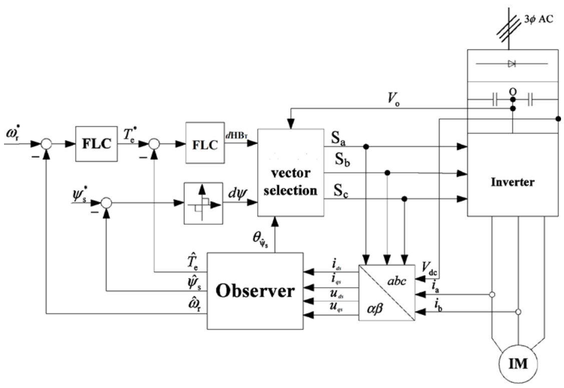


Fig. 1 Direct torque and flux control block diagram for sensorless IM drive.

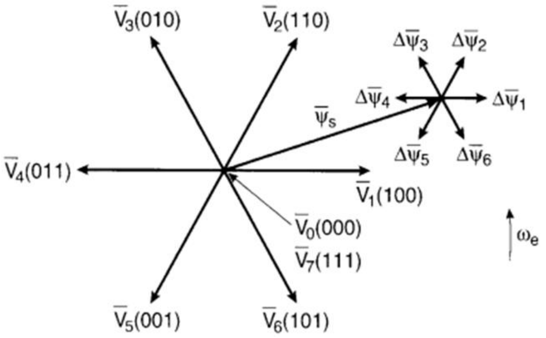


Fig. 2 Inverter voltage vectors and corresponding stator flux variations

A. Hysteresis Controllers

For the DTC schema, the torque and stator flux linkage expression is given as,

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{ds} i_{ds} - \psi_{qs} i_{qs}\right) \qquad (2)$$

$$\psi_s = \sqrt{\psi_{ds}^2 + \psi_{qs}^2}\angle\theta_e \qquad (3)$$

Where ψ_{ds} and ψ_{qs} are the direct and quadrature components of stator current, respectively. As evinced in Fig.1, these estimated values of torque and flux are compared with the command values of torque and flux, and the error signals are fed to the torque and flux hysteresis controllers respectively. Each hysteresis controller creates a digit, on the basis of the magnitude of the error signals and permissible bandwidth. Then, the stator flux-linkage space vector position can be evaluated as

$$\theta_e = \tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \qquad (4)$$

Using the flux sector algorithm, the flux sector number (1 to 6) is determined. The VSI switch decides the suitable voltage vectors which are activated using two digits produced by hysteresis controllers and one by flux position [10]. Fig. 2 depicts the feasible voltage vectors which are applied in the DTC scheme. The appropriate voltage vector in each sampling period is chosen in such a way that the torque and flux persist within their respective band limits.

B. Torque Ripple Analysis

The motor torque keeps on increasing or decreasing between the boundary delineated by torque hysteresis bands, since none of the inverter switching vectors is capable to give the accurate stator voltage required to produce the desired alterations in torque and flux. The torque ripple is solely affected by the width of the torque hysteresis band and is almost independent of the flux hysteresis band width [11].

According to the principle of functioning of DTC, the torque pulsation is directly related to the amplitude of its hysteresis band. The torque pulsation produces vibration and acoustic noise so, it must be as small as possible. Even so, there could be still torque ripples even with the zero bandwidth of the hysteresis controller due to the discrete nature of the control system. A small flux hysteresis bands should be preferred when high switching speed semi-conductor devices are employed since their switching losses are generally negligible with respect on state losses. In this way the output current harmonic can be strongly cut down. The hysteresis band has to be set large enough to bind the inverter switching frequency beneath a certain level that is generally fixed by thermal restriction of power devices. Therefore, the bandwidth of the torque hysteresis controller must be optimized in such as a way that the torque ripple level and switching frequency of the inverter are within boundaries. A too small band may result in the choice of reverse voltage vector besides zero vectors to repress the torque.

Table. I Rules For Speed Control

Change in speed	Speed							
	PH	PM	PS	ZE	NS	NM	NH	PH
PH	ZE	NS	NM	NH	NH	NH	NH	ZE
PM	PS	ZE	NS	NM	NH	NH	NH	PS
PS	PM	PS	ZE	NS	NM	NH	NH	PM
ZE	PH	PM	PS	ZE	NS	NM	NH	PH
NS	PH	PH	PM	PS	ZE	NS	NM	PH
NM	PH	PH	PH	PM	PS	ZE	NS	PH

The choice of reverse voltage vector may then cause torque undershoots. Hence, the torque ripple will become higher than those defined by the hysteresis controller band limits.

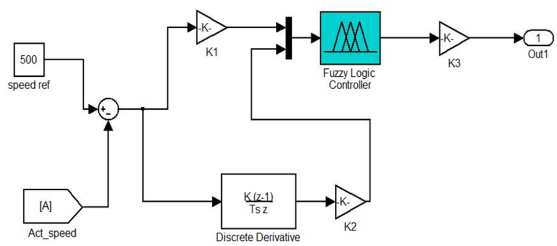


Fig. 3 FLC for speed control

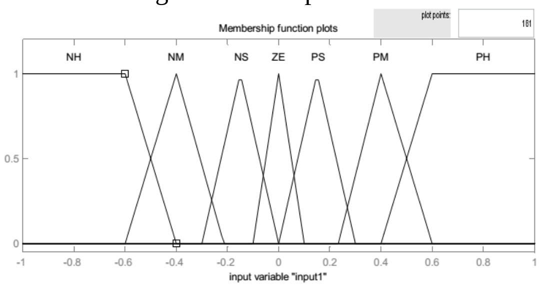


Fig. 4 Representation of speed error

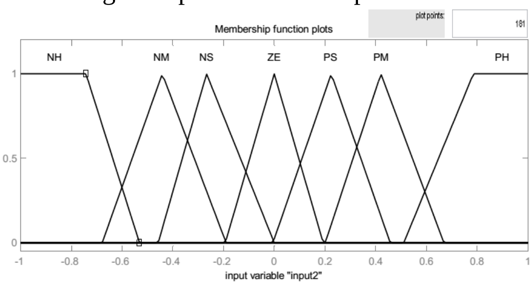


Fig. 5 Representation of change in speed error

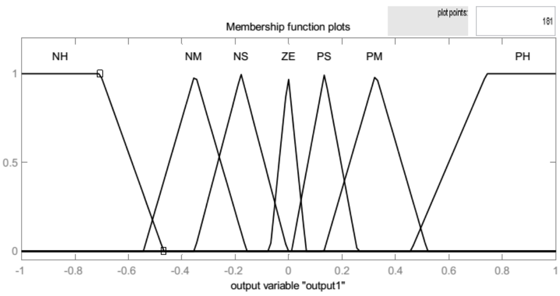


Fig. 6 Representation of output

III. PERFORMANCE ENHANCEMENT OF DTC

FLC is employed in both outer speed loop and torque hysteresis controller to enhance the steady-state accuracy and dynamic performance, also to limit external disruption and motor parameters fluctuations. FLC can handle perplexed nonlinear systems, which have a degree of uncertainty. It does not compel accurate system modeling and parameters; this makes FLDTC very suited for motor drive control [8], [10].

A. Fuzzy Logic Speed Control

The direct torque control technique could be employed even for controlling the motor torque or for speed control of 3-phase induction motors by adding up an outer speed control loop to the principal core of the direct torque controller as shown in Fig.1. In the conventional speed controllers, the actual speed is compared with the reference one. And so the resulting speed error is controlled by a PI controller in order to acquire fast speed response and to abbreviate the steady state error to zero. The output signal from the PI controller is employed as a torque reference for the hysteresis torque comparator. PI controller is more suited in steady state condition and for linear system. Just as DTC along with IM is generally nonlinear, fuzzy controller will be more suited. Here the fuzzy logic controller is applied to control the speed of DTC-based adaptable speed induction motor instead of the traditional PI controllers to get over its drawbacks.

Table. II Fuzzy Rules for Torque Ripple Minimization

Torque variation	Stator current variation		
	P	ZE	N
PH	NH	NL	NL
PL	ZE	NH	NS
ZE	NL	NL	ZE
NL	PH	PL	PL
NH	ZE	ZE	PH

A Plot for the FLC employed for speed control is exemplified in Fig. 3. The inputs are the error between commanding value and actual value (E), and its derivative (ΔE). The output is the control increment, whose integral is the actual output. The input and output variables are scaled to the range of (-1, 1). These arrangements called PD-type fuzzy logic control, the speed error is the proportional part and the change of speed error is the derivative part. The derivative part is employed to prefigure the speed error and to improve the closed loop stability. The two input signals are multiplied by two scaling factors (K1 , K2) to make the input signals matched with E and ΔE range.

Figs. 4, 5 and 6 depict the membership functions of the inputs and the output, respectively. The asymmetric triangle is taken as the membership function, to get a quick response for dynamic performance, and high accuracy for steady state, which is dissimilar from the conventional design. Table I indicates the linguistic rule applied in this paper, which is the central part of the FLC. By careful design of the linguistic rule, excellent performance can be attained.

B. Fuzzy Logic Torque Ripple Minimization

Fuzzy logic control (FLC) is an algorithmic rule based on a linguistic control scheme which tries to account the

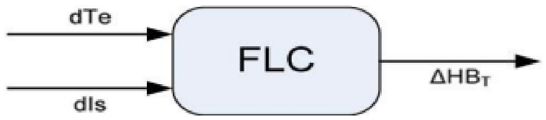


Fig. 7 FLC for torque ripple reduction

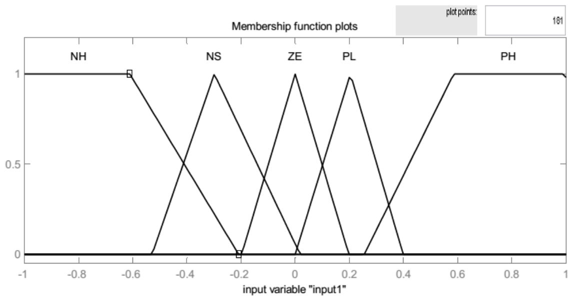


Fig. 8 Representation of torque variation

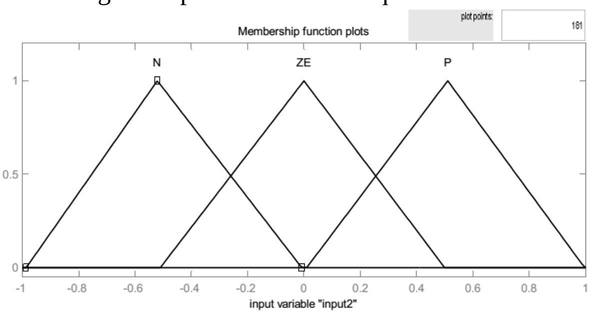


Fig. 9 Representation of stator current variation

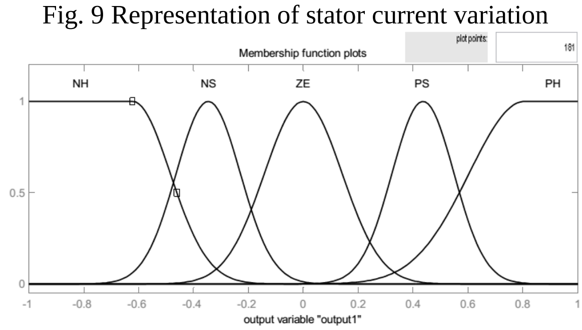


Fig. 10 Representation of output variable

Human's knowledge about how to control a system without demanding a mathematical model. Here, a Mamdani-type FLC is formulated to adjust the torque hysteresis band in order to repress the ripples in the motor-developed torque [8]-[10]. In traditional DTC scheme, the of the torque hysteresis band amplitude is fixed. Even so, in this proposed scheme, the FLC controls the upper and lower boundaries of the torque hysteresis band on the ground of its feedback input signal. The FLC is employed as a nonlinear function approximations [11] making a desirable alteration in the bandwidth of the torque hysteresis controller in order to hold the torque ripples minimal. Inputs for Fuzzy Logic controller are the motor-estimated torque (2) fluctuation ΔT_e and stator current fluctuation ΔIs, over a sampling period are opted as inputs to the FLC which can be characterized by the following equations:

$$\Delta T_e = T_e[k] - T_e[k-1] \qquad (5)$$

$$\Delta I_s = I_s[k] - I_s[k-1] \qquad (6)$$

Where $T_e[k]$ and $T_e[k-1]$ present the existing and past samples of motor-estimated torque, respectively.

There are five membership functions for one input signal (dT_e) and three membership functions for another input signal (dI_s). Automatically, there will be fifteen rules. For the inputs, in order to bring down the computational burden we use triangular/trapezoidal membership functions. In order to obtain a smooth variation of torque hysteresis bandwidth, Gaussian membership functions are selected for the output. The nonlinear mapping from the input signal to the output signal of FLC is done by trial and error. The motor mechanical equation, omitting the friction coefficient, can be indicated as [9]

$$T_e - T_l = J\frac{d\omega_r}{dt} \qquad (7)$$

Combine (5), (6), and (7) directs to the decision that repressing the motor torque ripples straightaway reduces the motor speed ripples also. The output signal of the FLC is the change in torque hysteresis bandwidth "ΔHBT". The updated upper and lower bandwidths of the torque hysteresis controller are found as

$$HB_{TU}^{n} = HB_{TU} - K_U^{*}\Delta HB_T \qquad (8)$$

$$HB_{TL}^{n} = HB_{TL} + K_L^{*}\Delta HB_T \qquad (9)$$

Where HB_{TU} and HB_{TL} are the torque hysteresis comparator base fixed upper and lower bandwidths. K_U and K_L are the grading factors. The linguistic rule applied are depicted in table II

IV. SIMULATION RESULTS

The functioning of the FLC-based DTC strategy for IM drive has been inquired extensively at dissimilar operating conditions. Sample simulations results are showed below. The nominal IM parameters, employed for simulation are given in the Appendix.

Figs. 11, 12 depict the various IM drive responses for step alteration in motor load and speed. The shift in load is applied at a time of 0.4 s. Fig. 11 indicates the simulated speed response using the conventional and the FLDTC schemes. The speed response distinctly shows that both the speed overshoot and speed ripples have been decreased substantially by the usage of the proposed scheme. The average speed ripples with the conventional DTC scheme are close to 0.23 and 0.05 rpm, respectively. The usage of the FLDTC scheme has contracted these values to 0.1 and 0.09 rpm, respectively.

Fig. 12 shows the proportionate torque responses for the conventional and the proposed DTC schemes for a step change in load at 0.4 s. The torque ripple has significantly been decreased in the proposed scheme both in the transient and steady states.

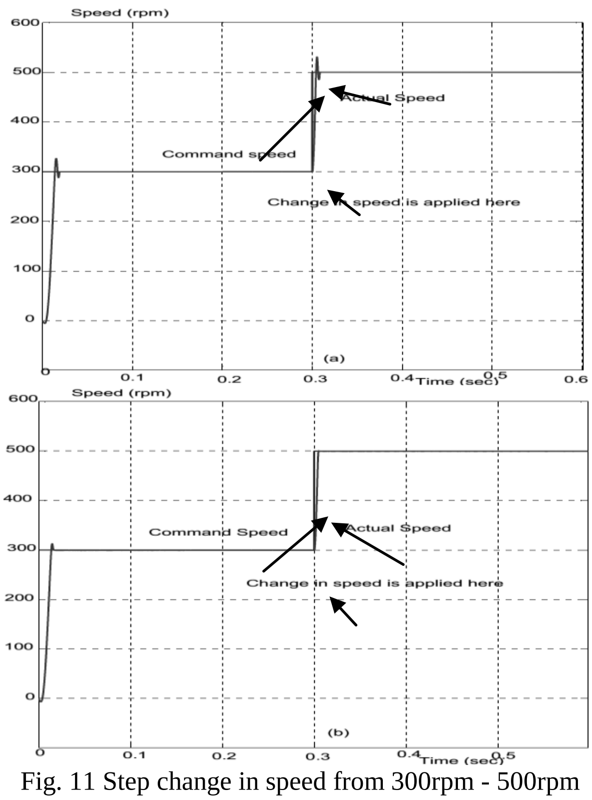
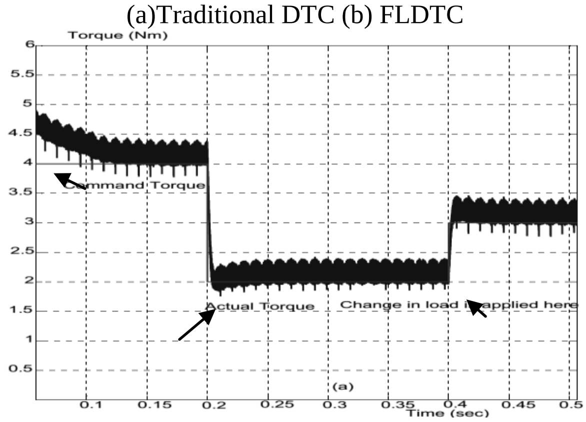


Fig. 11 Step change in speed from 300rpm - 500rpm (a)Traditional DTC (b) FLDTC



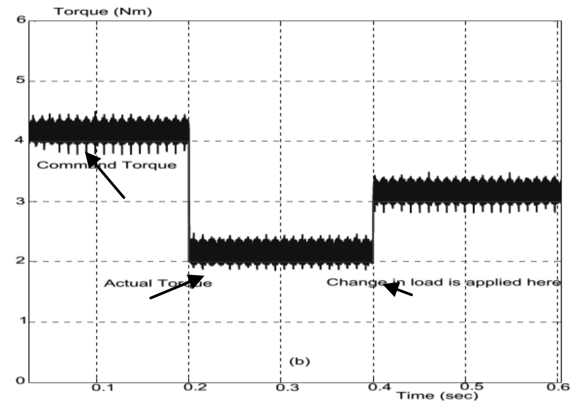


Fig. 12. Developed torque responses of the IM drive for a step change in load from 2 to 3 N-m at speed of 500 rpm. (a) Conventional DTC. (b) FLC-based DTC scheme.

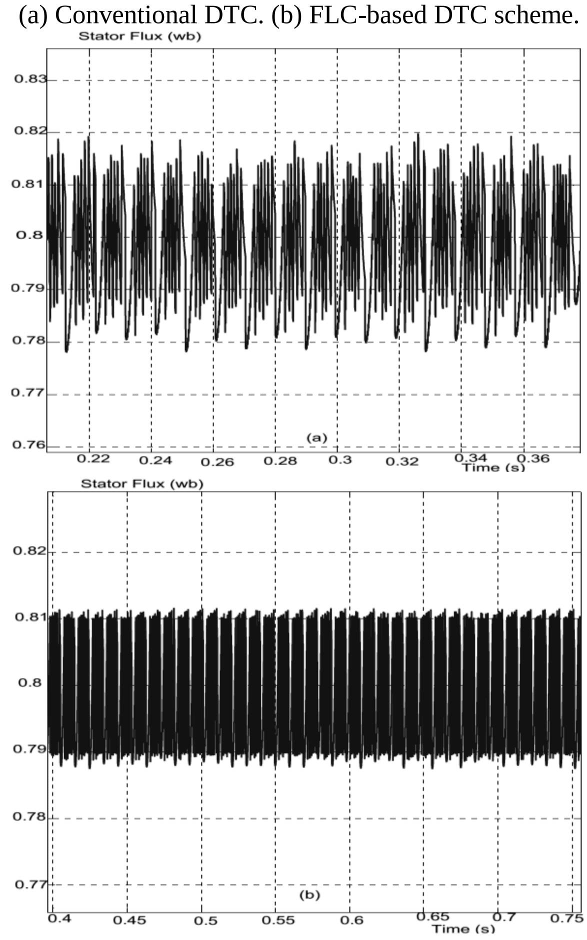


Fig. 13 Stator flux linkage response at 500rpm (a) Traditional DTC (b) FLDTC

Fig. 13 shows the flux responses of the drives while the motor is running at 500 rpm. It is found out that the proposed varying band torque hysteresis controller-based DTC scheme displays smooth response and small ripple in flux as compared to the traditional DTC scheme.

V. CONCLUSION

A new FLC-based DTC strategy for IM drive has been demonstrated in this paper. For improving the DTC performance Fuzzy logic controllers were designed. A fuzzy logic controller has been made for speed control although additional fuzzy controller is used to adjust the bandwidth of the torque hysteresis controller to reduce the torque ripple and to improve the dynamic performance. A performance comparison of the FLC-based DTC strategy with a traditional DTC scheme has also been provided using simulation. Relative results show that the torque ripple of the proposed drive has substantially decreased. The dynamic speed response of the proposed FLC-based DTC scheme has also been found better as compared to the traditional DTC scheme.

APPENDIX

PARAMETERS	VALUE
Stator and Rotor Inductance	0.07803H
Stator Resistance	1.405Ω
Mutual Inductance	0.1722H
Rotor Resistance	1.395Ω
Moment of Inertia	0.0131kg-m^2
Coefficient of Friction	0.002985Nm/rad/sec
Number of poles	4

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