Journal of Information Systems Engineering and Management
2024, 9(4s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Fuzzy based Direct Torque Control of Induction Motor for Electric Vehicles

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ARTICLE INFO	ABSTRACT

Received: 10 Oct 2024
Revised: 28 Nov 2024
Accepted: 12 Dec 2024

Introduction: The growing emphasis on sustainable transportation, driven by climate change awareness, is accelerating the adoption of electric vehicles (EVs). A critical challenge is the precise control of induction motors (IMs) used in EVs. Traditional control methods like Field Oriented Control (FOC) and Direct Torque Control (DTC) suffer from parameter sensitivity and high torque ripple, reducing efficiency. This research proposes a Fuzzy DTC scheme to address these limitations.

Objectives: The primary objectives of this research are to develop and implement a Fuzzy-based Direct Torque Control (DTC) scheme for Induction Motor (IM) drives in Electric Vehicles (EVs), specifically designed to overcome the limitations of conventional DTC methods. This entails achieving a significant reduction in torque ripple, a common issue in traditional DTC, which directly impacts the smoothness and efficiency of the EV's operation. Furthermore, the research aims to enhance the dynamic response of the IM drive system, enabling faster and more precise control of the motor's torque and speed, crucial for the dynamic driving conditions experienced by EVs. Ultimately, the successful implementation of the Fuzzy DTC scheme should lead to an overall improvement in the efficiency and robustness of the IM speed control within the EV system, ensuring reliable and high-performance operation across all driving scenarios, including acceleration, deceleration, and constant speed maintenance.

Methods: The methodology employed in this research centers around the development and implementation of a Fuzzy-based Direct Torque Control (DTC) scheme for Induction Motor (IM) drives. Departing from traditional DTC, which relies on hysteresis bands and a switching table, this approach integrates a Fuzzy Logic Switching Controller (FLSC) to optimize inverter switching decisions. The FLSC takes as inputs the torque error, stator flux error, stator flux angle, and the count of switching updates, providing a more refined control mechanism. A Mamdani fuzzy inference system (FIS) is utilized, employing triangular and trapezoidal membership functions to fuzzify these input variables. The output of the fuzzy controller dictates the switching state, selected from seven possible states represented by crisp triangular membership functions. This fuzzy logic-based approach allows for a more nuanced and adaptive control strategy, enabling the system to respond effectively to the nonlinearities and uncertainties inherent in IM drives. The fuzzy rules, developed based on engineering expertise and practical experience, guide the selection of the optimal switching state. The research leverages simulations using MATLAB/Simulink to model the IM drive system and evaluate the performance of both conventional and Fuzzy DTC schemes under various operating conditions. This allows for a comparative analysis of torque ripple, dynamic response, and overall efficiency, validating the effectiveness of the proposed fuzzy-based control strategy.

Results: The simulation results presented in this paper demonstrate the superior performance of the proposed Fuzzy-based Direct Torque Control (DTC) scheme compared to conventional DTC methods for Induction Motor (IM) drives in Electric Vehicles (EVs). Across various operating conditions, including different load and speed combinations, the Fuzzy DTC consistently exhibited a significant reduction in torque ripple. This reduction translates to a smoother and more efficient motor operation, crucial for enhancing the driving experience and overall performance of EVs. Furthermore, the Fuzzy DTC showed improved dynamic response, characterized by lower overshoot and faster settling times. These findings indicate that the fuzzy

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logic-based control strategy enables more precise and rapid control of the IM's torque and speed, effectively addressing the limitations of traditional DTC. Specifically, the data presented in Table 3 and Figures 18, 19, and 20 highlight the quantifiable improvements in parameters such as torque ripple percentage, slew rate, and overshoot. The comparative analysis consistently favored the Fuzzy DTC scheme, validating its effectiveness in achieving robust and efficient IM speed control under the dynamic operating conditions typical of electric vehicles.

Conclusions: This paper has investigated the application of fuzzy based DTC to induction motor (IM) drives in electric vehicles (EVs). The proposed Fuzzy DTC approach addresses the limitations of conventional technique of DTC, including high ripple of torque by integrating fuzzy logic into the control scheme. Simulation results show the proposed Fuzzy DTC effectively achieves precise and robust speed control under various EV operating conditions. The approach optimizes switching decisions based on fuzzy rules, resulting in improved performance compared to traditional DTC methods. The proposed Fuzzy DTC scheme offers reduced torque ripple, improved efficiency, enhanced dynamic performance, and a smoother driving experience.
Keywords: : Induction Motor (IM), Electric Vehicles (EVs), Direct Torque Control (DTC), Fuzzy Logic

1. INTRODUCTION

However, with the increasing global awareness of climate change and the rise in fossil fuel usage and an unavoidable preference for sustainable transportation, the practicality of successfully running electric vehicles (EVs), regardless of gasoline-powered internal combustion vehicles, becomes more viable with efficiencies and cleaner modes of operation. [1] However, the problem is to control the electric motor needed for proper real-time functionality of the EV at a consistently high output. Then, traditional control techniques are not without mistakes; for example, Field Oriented Control (FOC) and Direct Torque Control (DTC) are vulnerable to parameter fluctuations, and torque ripple is excessively high.[2] These mistakes decrease efficiency and quality of operation, which increases operating costs for maintenance purposes. Thus, to alleviate such mistakes, many powerful control techniques have been studied and proposed as solutions for implementation. [3] These include neural network-based speed control, fuzzy rules-based speed control and model predictive speed control. This research proposes a Fuzzy DTC scheme for IM drives of an electric vehicle. The contribution is that using fuzzy logic on the DTC scheme for better switch control and reduced torque ripple allows the scheme to possess better speed control precision, increased efficiency, and reduced torque ripple. Multiple control strategies are required to maintain optimal operation of EVs and ensure adequate power flow regulation between the battery, motor, and other vehicle components. Induction motors have been widely used as the motor in an EV setting because they are trustworthy and low-cost.[4] Yet, the challenge with controlling speed in an EV that uses an induction motor is that this type of system is not easily controllable because of uncertainties and nonlinearities. Thus, this project will investigate the concept and realization of a Fuzzy DTC scheme for automotive IM drives. The superiority of the new approach over conventional control methods will be validated via simulation and experimental results.[5][6][7]

2. METHODOLOGY

2.1 Direct Torque Control (DTC)

DTC is a common approach to control of IM Drive.In this scheme,the stator flux and torque are controlled directly. While other control methods manage current, DTC functions in the torque-flux plane to achieve faster transient response and improved dynamics. Direct torque control operates by sensing voltage and current fed to the motor and determining what the motor torque and flux of stator should be.[8] Once the actual motor torque comparison and flux of stator torque, derived from estimations, versus the expected reference values is established, appropriate inverter switching actions are selected based upon the error values generated to maintain torque and flux at desired levels. This is essentially a controllable closed-loop system that facilitates rapid, decoupled control of torque and speed.[9]

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Block Diagram of Conventional method of DTC

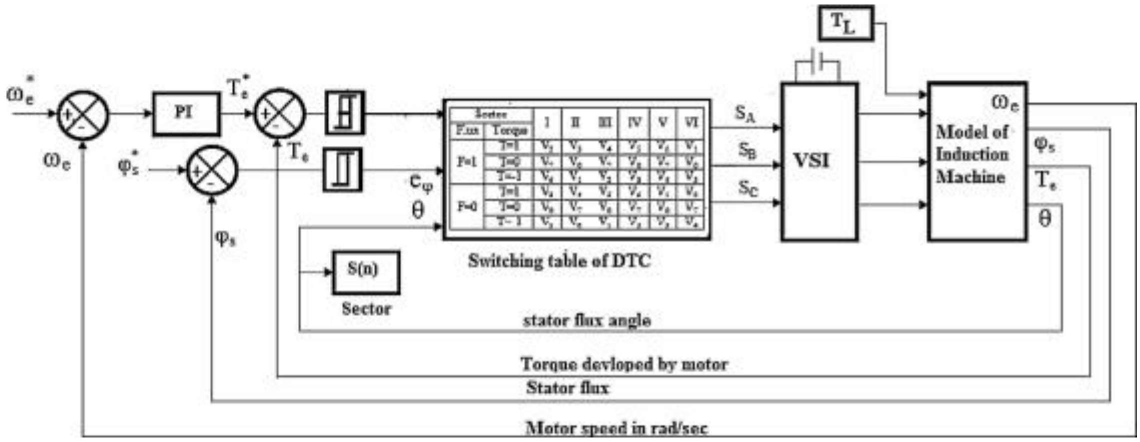

Fig. 1. Block Diagram of Conventional method of DTC

Effective DTC Estimation The proposed Direct Control of Torque scheme will be applied based on effective electromagnetic flux and torque estimation of the induction motor, which occurs through a Simulink dynamic simulation model of the induction motor. Induction motor dynamics are state-space defined by the coupled differential equations of its operation. In other words, the characteristics of the motor are transferable from a 3-phase stationary reference frame to a 2-phase— with the two-phase α, β stationary reference frame being more optimal.[10]

$$\begin{pmatrix} \dot{i}_s^{\alpha} \\ i_s^{\beta} \\ \Psi_s^{\alpha} \\ \Psi_s^{\beta} \end{pmatrix} = \begin{pmatrix} \frac{-R_a}{L_{ss}} & -\omega & \frac{R_r}{L_{ss}L_r} & \frac{-\omega}{L_{ss}} \\ \omega & \frac{-R_a}{L_{ss}} & \frac{-\omega}{L_{ss}} & \frac{R_r}{L_{ss}L_r} \\ -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \end{pmatrix} \begin{pmatrix} i_s^{\alpha} \\ i_s^{\beta} \\ \Psi_s^{\alpha} \\ \Psi_s^{\beta} \end{pmatrix} + \begin{pmatrix} \frac{1}{L_{ss}} & 0 \\ 0 & \frac{1}{L_{ss}} \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v_s^{\alpha} \\ v_s^{\beta} \end{pmatrix} \quad (1)$$

$$s = 1 - \frac{L_m^2}{L_s L_r}, \quad L_{ss} = s * L_s \quad T_r = \frac{L_r}{R_r} \qquad R_a = R_s + R_s \frac{L_m^2}{L_r^2} \quad (2)$$

Speed Error and Reference Torque Generation As per Figure 1, this is the block diagram of the Closed-Loop conventional DTC of an IM. The flux and torque are controlled directly via selection of voltage vector, where the stator flux rotates through the proper angle to create the appropriate (post speed error created) torque that needs to be generated, thus creating the torque reference. The actual induction motor speed is determined relative to rated speed, meaning a speed offset is created which is given to a PI type of controller. The controller's output is the reference torque (Te*) given to the motor to achieve the attempted operating speed. Stator Flux Reference Generation The reference frame of stator flux is generated to guarantee that the motor runs with the expected value of reference torque.[10][11][12] This is accomplished through Equation (3).

$$|\psi_s^*| = \sqrt{\frac{4 L_{ss}^2 L_r}{3 p L_m^2}} \quad (3)$$

$$\psi_{s(\alpha,\beta)} = \int_0^t v_{s(\alpha,\beta)} - R_s i_{s(\alpha,\beta)} \quad (4)$$

$$|\psi_s| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \quad (5)$$

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$$\theta_s = \tan^{-1}\frac{\psi_{s\beta}}{\psi_{s\alpha}} \tag{6}$$

$$T_e = \frac{3}{2}p\left(\psi_{s\alpha}\ i_{s\beta} - \psi_{s\beta}\, i_{s\alpha}\right) \tag{7}$$

CDTC Control Principle

The vector of voltage is created from error of flux, the error of torque, and calculated flux angle so that the stator flux is rotated to produce the generated electromagnetic torque (Te), where |ψs| is the calculated flux of stator amplitude and θs is flux angle of the stator. Hysteresis Band Control. A double-level hysteresis band is implemented in order to having the flux between certain limits. An error is created in a binary fashion relative to the expected upper and lower limits. The stator flux space is sectioned off into 60° increments, creating a total of six to create the required voltage vector.

Switching Table-Based Control

The utilization of the active or zero voltage source inverter (VSI) vector switching happens based upon the response of the flux band hysteresis and torque band hysteresis as well as the identified flux sector. A switching table is presented in Table 1 to determine the necessary switching vector needed. The VSI has six active and two zero switching states, providing flexibility for motor operation.. Relative to the CDTC Method of the Active Switching Vector Application Relative to the active switching vector application in the CDTC method, once the active switching vector is used, it does not change for the rest of the sampling time. Hence, this method successfully regulates flux and torque.[13]

Table 1:Switching Logic of Conventional DTC

Sector		I	II	III	IV	V	VI
Flux	Torque						
F = 1	T = 1	V_2	V_3	V_4	V_5	V_6	V_1
	T = 0	V_7	V_0	V_7	V_0	V_7	V_0
	T = −1	V_6	V_1	V_2	V_3	V_4	V_5
F = 0	T = 1	V_3	V_4	V_5	V_6	V_1	V_2
	T = 0	V_0	V_7	V_0	V_7	V_0	V_7
	T = −1	V_5	V_6	V_1	V_2	V_3	V_4

2.2 Fuzzy Logic-Based Direct Torque Control (FLDTC) of Induction Motor

Conventional DTC methods suffer from high ripple of flux , high ripple of torque and low-speed transient response deficiencies. Therefore, a DTC method that incorporates fuzzy logic would solve these issues. FDTC Method The fuzzy direct torque control (FDTC) method uses a fuzzy logic switching controller (FLSC) to determine switching instead of hysteresis bands and alogic table of switching. The FLSC inputs are error of torque, error of flux, flux angle of stator and the count of switching updates to determine the optimal switching state. The fuzzy logic controller is based on a Mamdani fuzzy inference system (FIS). The input variable joins the fuzzy variables through triangular and trapezoidal membership functions. Unlike other methods, the fuzzy controller output uses seven switching states with crisp triangular membership functions. Figures 3(a), 3(b), and 3(c) show the membership function distributions for error of torque, error of stator flux and the error of stator flux angle, respectively. Such membership functions enable a softer and softer control output. The fuzzy controller selects one of seven switching states (represented by a crisp triangular membership function shown in Fig. 3) as its output.[14]

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θ		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ10	θ11	θ12
e_T	e_ϕ												
PL	P	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
	Z	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1
	N	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
PS	P	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
	Z	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
	N	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2
ZE	P	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	Z	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	N	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
NS	P	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
	Z	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0	V_0
	N	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4
NL	P	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
	Z	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5
	N	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4

Table 2 :Fuzzy switching logic rule base.

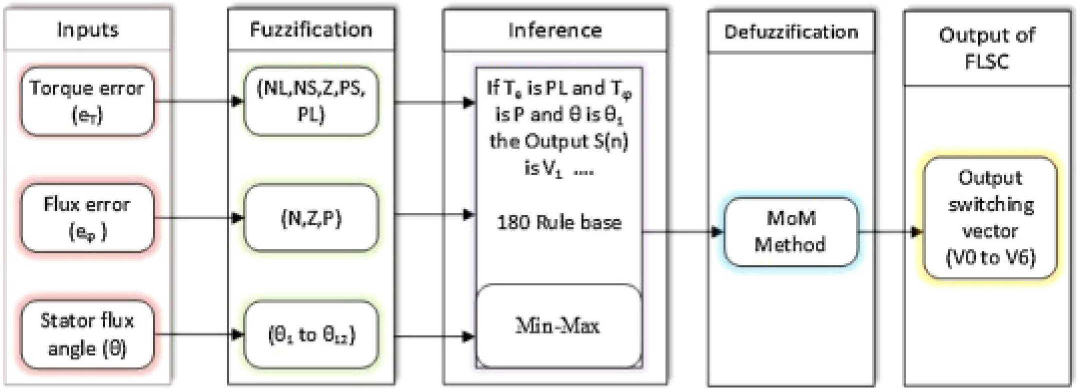

Fig 2 :Flow chart of FLC.

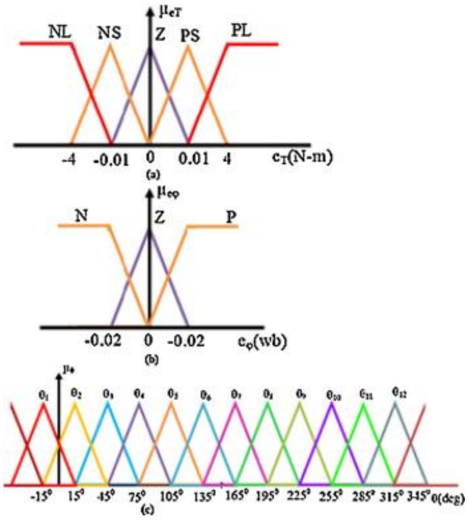

Fig. 3. (a), (b) & (c). Membership functions of inputs flux error, torque error and sector.

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The optimal switching state is selected using fuzzy rules after fuzzification. Fuzzy rules are developed based on engineering expertise and experience with the process to meet controller objectives. For example, obtain the sector of the stator flux from the stator flux angle, and subsequently, obtain the switching state according to the obtained sector to boost flux and motor torque to obtain their reference values. With three inputs (3 × 5 × 12) fuzzified, 180 fuzzy AND rules are generated, selecting the minimum membership degree of e_T, e_φ, and θ.

4.Simulations,Results and Discussion

Power: 102 kW (137 hp)Voltage(RMS):312 V,Frequency:50 Hz,Ploe:4,
Stator Resistance:0.435 Ω, Rotor Resistance:0.216 Ω,Rated Speed:1440 RPM
Torque base:671.5 Nm
Base Torque at 50 % Load=335.75 Nm,Base Torque at 120% Load=805.8 Nm
Torque Reference signal is given at 0.5 s
Speed reference signal is given at 0.1s

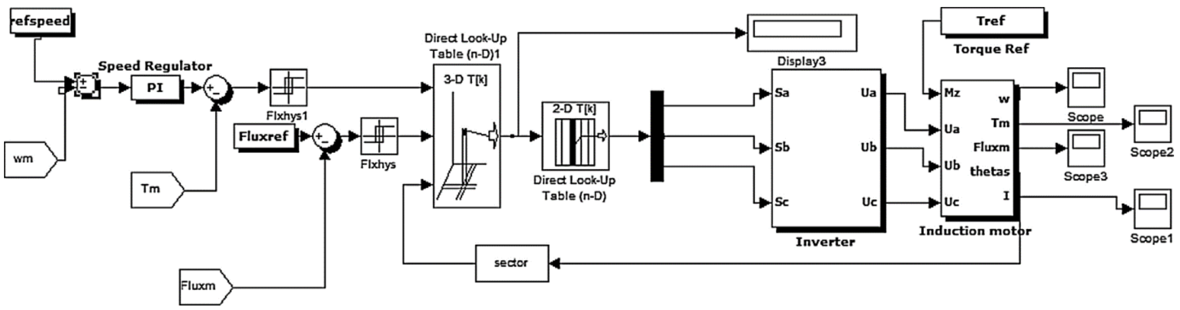

Fig:4: Simulink model of DTC

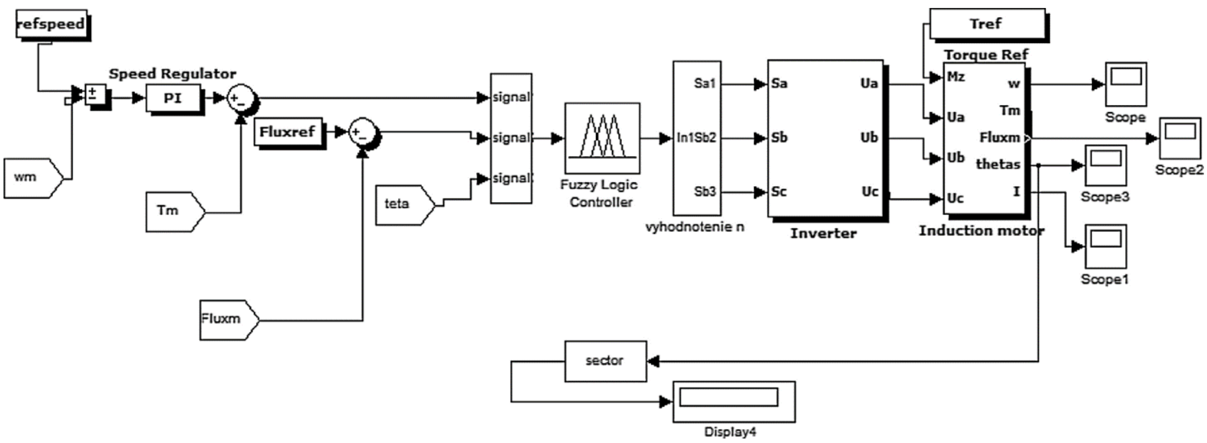

Fig:5: Simulink model of Fuzzy-DTC

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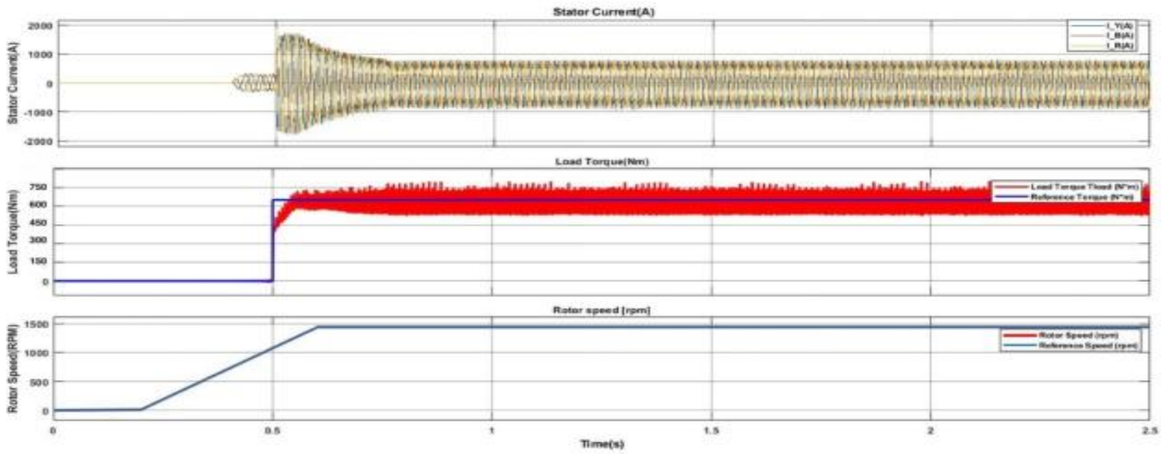

Fig:6: Stator Current, Torque Speed in DTC Control Scheme at 100% load and 100% Speed

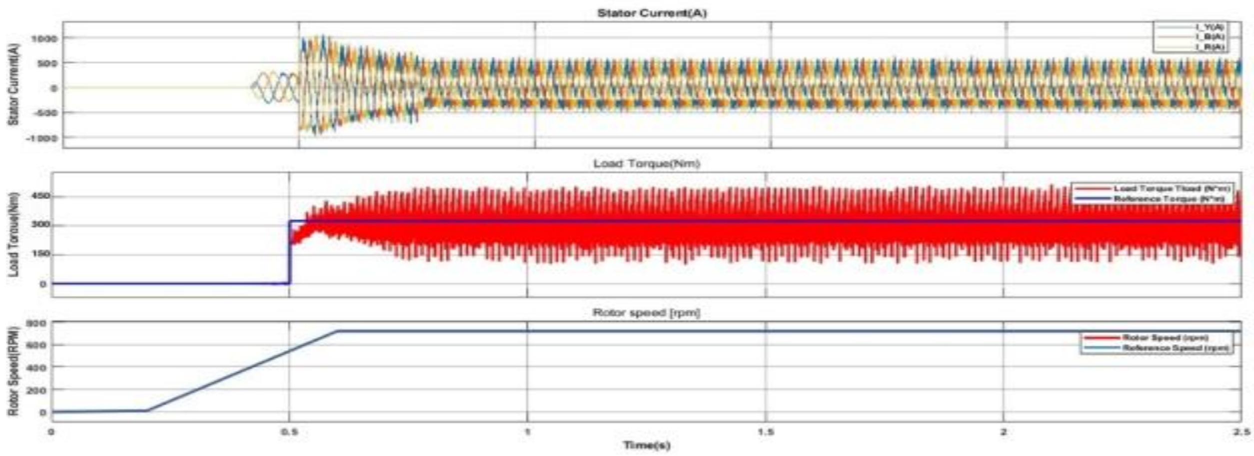

Fig:7: Stator Current, Torque Speed in DTC Control Scheme at 50% load and 50% Speed

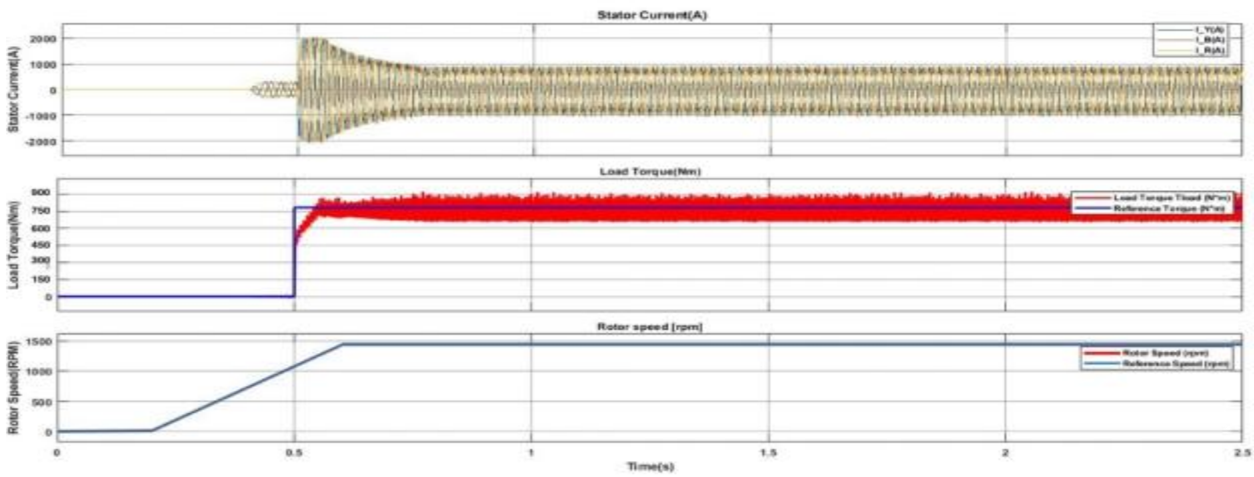

Fig:8: Stator Current, Torque Speed in DTC Control Scheme at 120% load and 100% Speed

Fig:6,Fig:7 and Fig:8 shows the Stator Current, Load Torque and Rotor Speed response of conventional DTC at different operating conditions.

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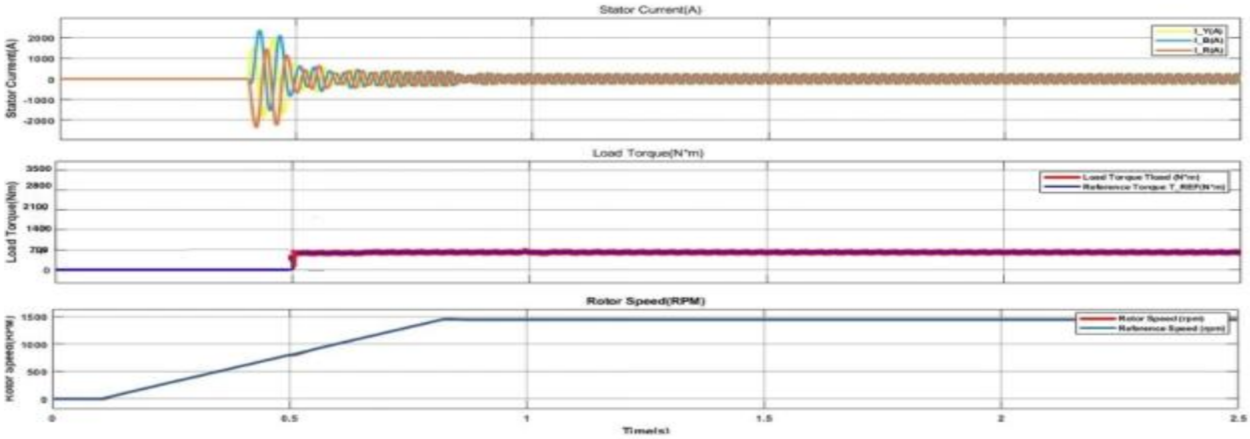

Fig:9: Stator Current, Torque Speed in FLC- DTC Control Scheme at 100% load and 100% Speed

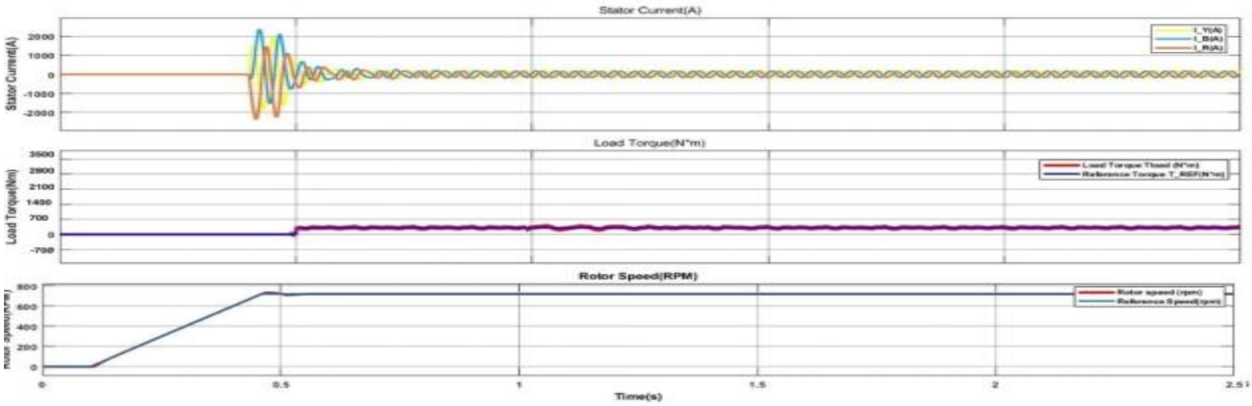

Fig:10: Stator Current, Torque Speed in FLC- DTC Control Scheme at 50% load and 50% Speed

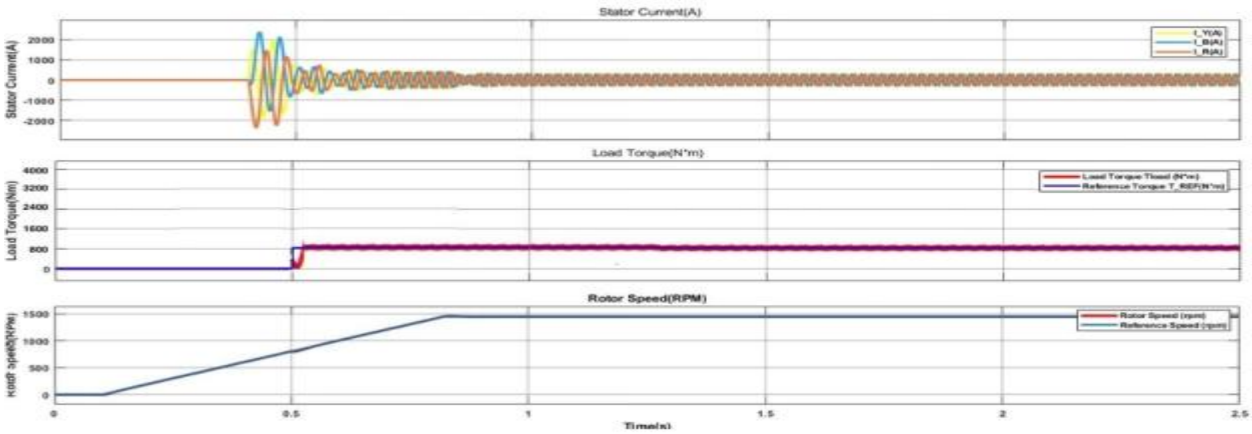

Fig:11: Stator Current, Torque Speed in FLC- DTC Control Scheme at 120% load and 100% Speed

Fig:9,Fig:10 and Fig:11 shows the Stator Current, Load Torque and Rotor Speed response of Fuzzy DTC at different operating conditions.

The MATLAB simulation is carried out for induction motor having ratings listed below:

Power:2.2 kW(3 HP),Voltage(RMS):220 V,Frequency:50 Hz,Ploe:4,

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Stator Resistance:0.435 Ω, Rotor Resistance:0.216 ΩRated Speed:1440 RPM
Torque base:14.5 Nm
Torque Reference signal is given at 0.5 s
Speed reference signal is given at 0.1s

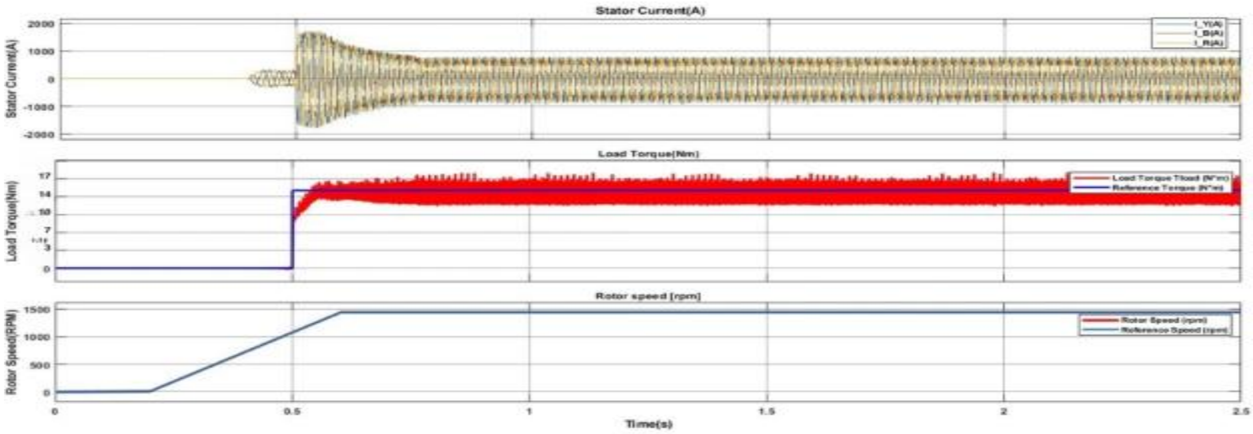

Fig:12: Stator Current, Torque Speed in DTC Control Scheme at 100% load and 100% Speed

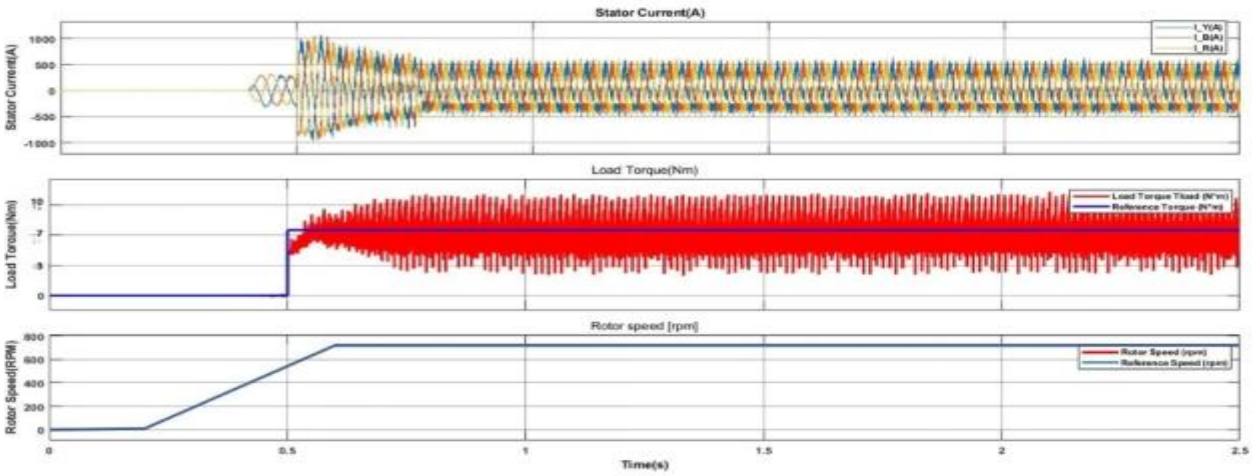

Fig:13: Stator Current, Torque Speed in DTC Control Scheme at 50% load and 50% Speed

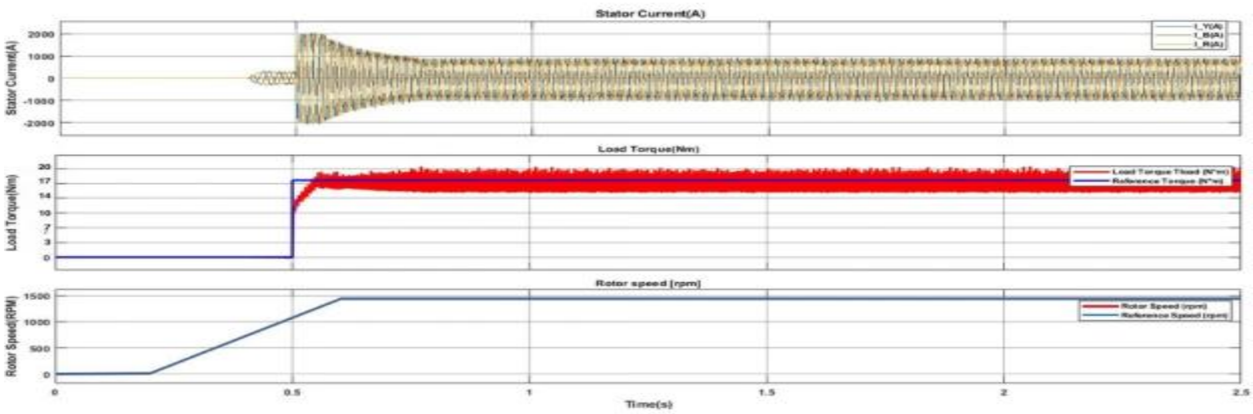

Fig:14: Stator Current, Torque Speed in DTC Control Scheme at 120% load and 100% Speed

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Fig:12,Fig:13 and Fig:14 shows the Stator Current, Load Torque and Rotor Speed response of conventional DTC at different operating conditions.

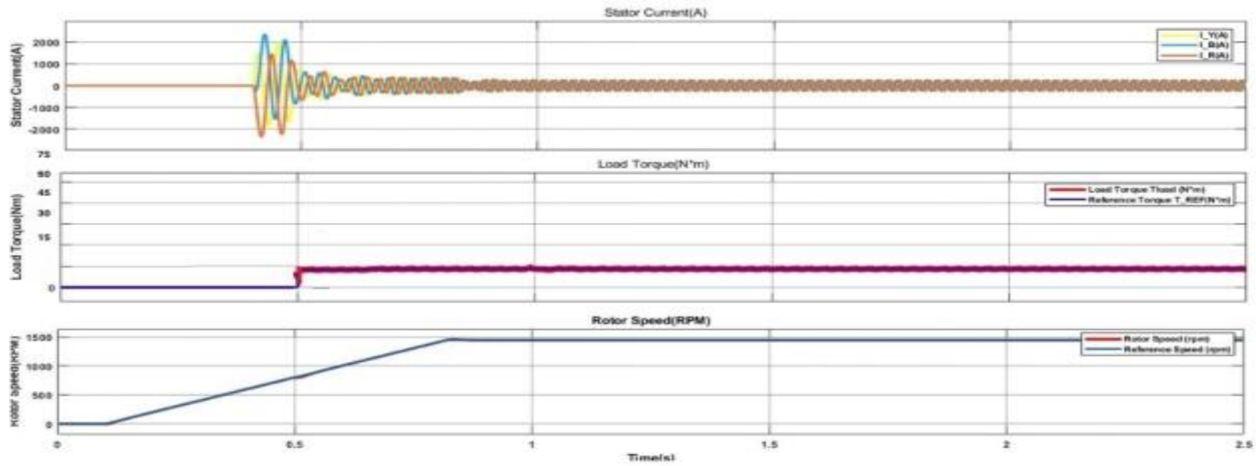

Fig:15: Stator Current, Torque Speed in FLC- DTC Control Scheme at 100% load and 100% Speed

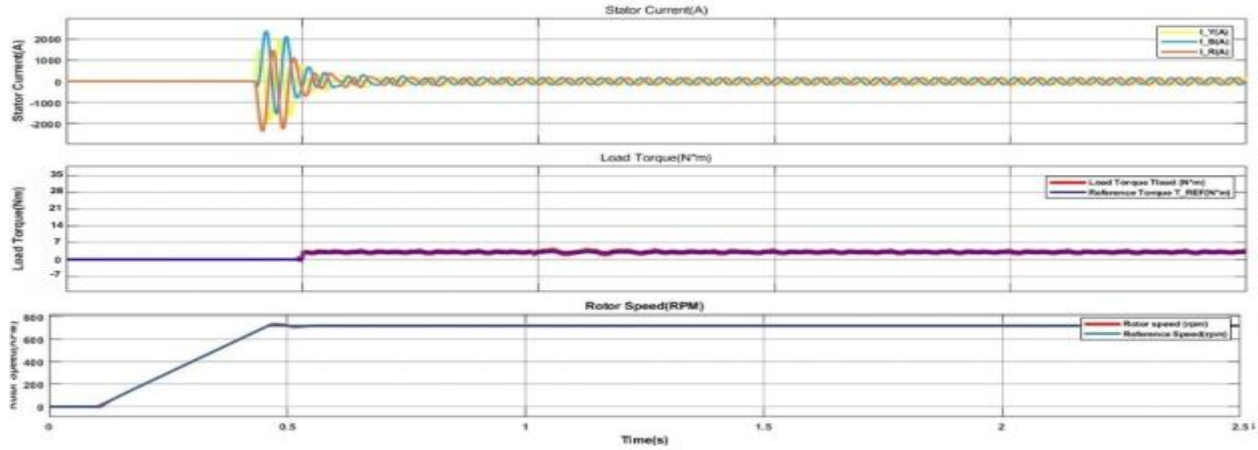

Fig:16: Stator Current, Torque Speed in FLC- DTC Control Scheme at 50% load and 50% Speed

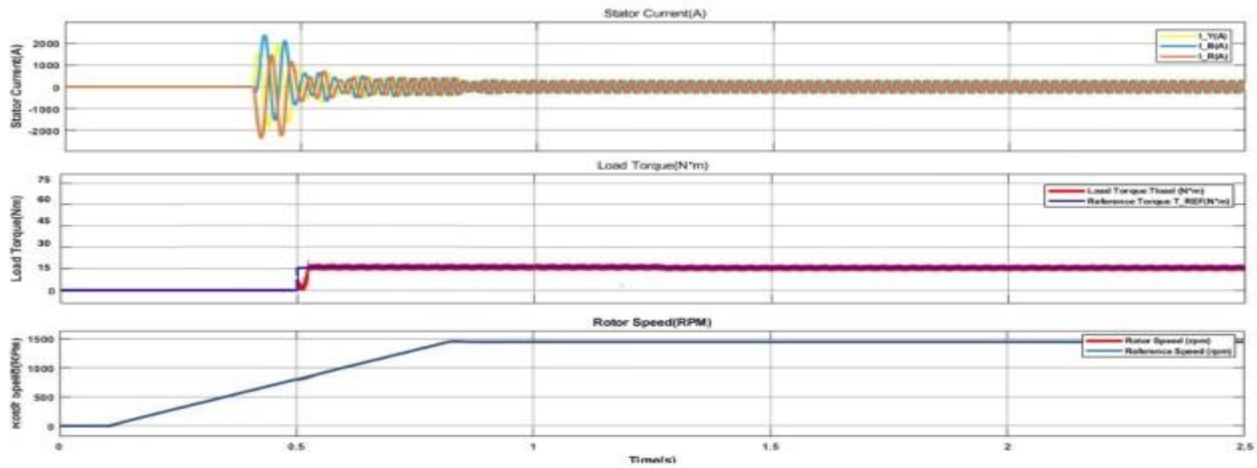

Fig:17: Stator Current, Torque Speed in FLC- DTC Control Scheme at 120% load and 100% Speed

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Fig:15,Fig:16 and Fig:17 shows the Stator Current, Load Torque and Rotor Speed response of Fuzzy DTC at different operating conditions.

Table 3 :Analysis of Results

Operating Condition:1:100% Load and 100 % Speed			
Sr Number	**Parameters**	**DTC**	**Fuzzy-DTC**
1	Overshoot (%)	18.9	16.02
2	Settling Time (s)	0.66	0.2
3	Rise Time (ms)	123.61	122.13
4	Slew Rate(Nm/ms)	272.86	5.7
5	Torque Ripple(%)	24.14	20.11
Operating Condition:2:50% Load and 50 % Speed			
Sr Number	**Parameters**	**DTC**	**Fuzzy-DTC**
1	Overshoot (%)	14.64	12.24
2	Settling Time (s)	0.172	0.25
3	Rise Time (ms)	115.52	123.14
4	Slew Rate(Nm/ms)	77.98	7.14
5	Torque Ripple(%)	31.72	15.33
Operating Condition:3:120% Load and 100 % Speed			
Sr Number	**Parameters**	**DTC**	**Fuzzy-DTC**
1	Overshoot (%)	80.9	19.17
2	Settling Time (s)	0.63	0.2
3	Rise Time (ms)	118.13	88.16
4	Slew Rate(Nm/ms)	8.77	3.89
5	Torque Ripple(%)	27.44	15.33

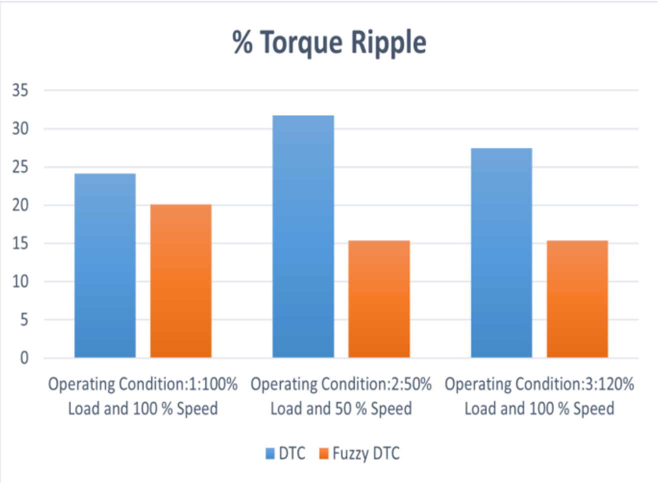

Fig:18:Torque Ripple(%) Comparison

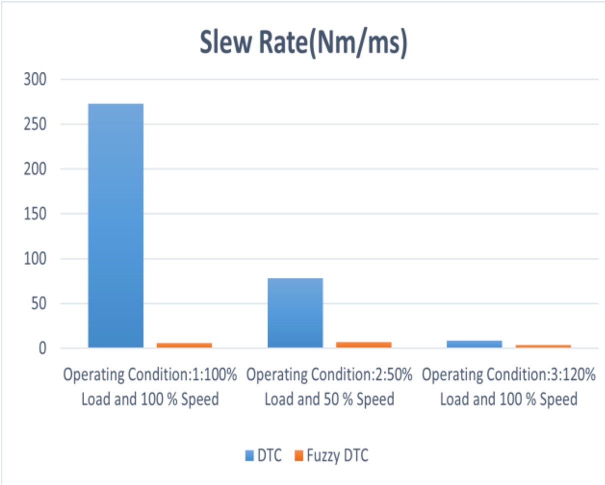

Fig:19:Slew Rates(Nm/ms) Comparison

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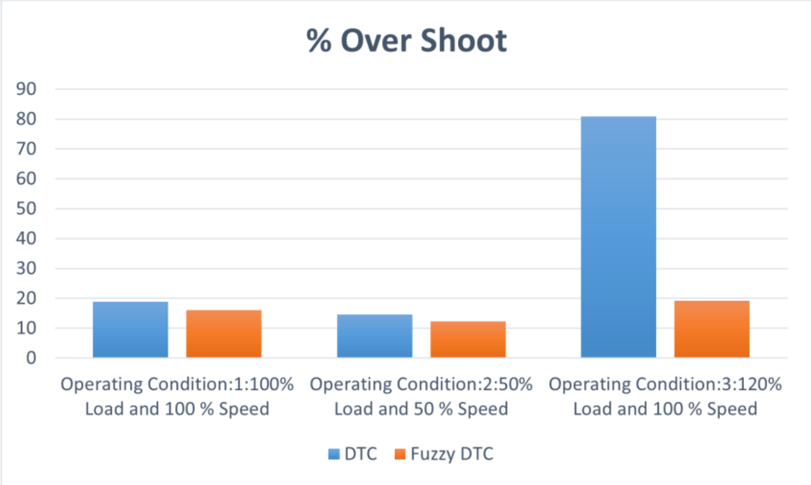

Fig:20:Over Shoot (%)Comparison

The comparison between Torque ripple(%),Over shoot(% and slew rate (Nm/ms) is illustrated in fig 18,fig 19 and fig 20.The comparison shows that the Fuzzy based DTC Control scheme is better in all operating conditions with respect to conventional DTC.

Conclusion

This paper has investigated the application of fuzzy based DTC to induction motor (IM) drives in electric vehicles (EVs). The proposed Fuzzy DTC approach addresses the limitations of conventional technique of DTC, including high ripple of torque by integrating fuzzy logic into the control scheme. Simulation results show the proposed Fuzzy DTC effectively achieves precise and robust speed control under various EV operating conditions. The approach optimizes switching decisions based on fuzzy rules, resulting in improved performance compared to traditional DTC methods. The proposed Fuzzy DTC scheme offers reduced torque ripple, improved efficiency, enhanced dynamic performance, and a smoother driving experience.

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Journal of Information Systems Engineering and Management
2024, 9(4s)
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https://www.jisem-journal.com/
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