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Advanced Direct Torque Control: Employing Fuzzy Logic for Dynamic and Adaptive Regulation

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***Abstract:* -** this article presents a novel approach to Direct Torque Control (DTC) for doubly fed induction machines using fuzzy logic. Traditional DTC suffers from limitations due to its inflexible switching strategy, treating large and small torque and flux errors identically. This can lead to suboptimal performance, particularly during start up or when reference values fluctuate. Our proposed solution leverages a streamlined fuzzy logic controller with a minimized rule set to enhance the switching strategy. This approach replaces the conventional hysteresis-based regulators and switching table, resulting in reduced computational burden and a faster sampling period. This improved sampling rate translates to significantly smoother torque and flux control with reduced ripple. Furthermore, we've integrated fuzzy logic as a supervisory element to dynamically adjust the PI controller gains for speed regulation, effectively creating a nonlinear PI controller with adaptive parameters. Simulations conducted in MATLAB/SIMULINK showcase the effectiveness and superior performance of this advanced DTC strategy.

Keywords: doubly fed induction motor, direct torque control conventional (DTC-C), direct torque fuzzy control (DTC-F), Fuzzy-PI.

I. INTRODUCTION

Today, a significant proportion of the total electrical energy is converted into mechanical energy through electric motors [1]. Depending on the application, these motors come in various types, and their performance requirements vary widely. As a result, these motors must effectively respond to changes in set points such as speed, position, and torque. The doubly fed Induction machine is indeed a popular choice for variable speed applications, and its use as a wind generator or motor in the electromechanical conversion chain has grown significantly in recent years, as indicated in references [2–5].

Notably, the energy converter used to rectify and convert the rotor's alternating currents has a fractional nominal power compared to that of the generator, which reduces costs compared to competing topologies. This work introduces numerical tools to derive control laws that enable the DFIM to operate at its operating points while optimizing performance.

Torque control systems can be divided into two categories: scalar control and vector control. Scalar control relies on steady-state relationships to control only the magnitude and frequency (angular speed) of voltage, current, and flux linkage space vectors. Therefore, scalar control does not affect the position of space vectors during transients [6-8]. In contrast, vector control uses relationships that are valid for dynamic states to control not only the magnitude and frequency (angular speed) but also the instantaneous positions of voltage, current, and flux space vectors. This ensures the correct orientation of space vectors both in steady-state and during transients [8-10].

Direct torque control was proposed in the mid-1980s as an alternative to vector control for AC machine control. This strategy is based on the direct determination of inverter switching states and offers a simpler scheme with less sensitivity to machine parameters. However, the variable switching frequency in DTC leads to high flux and torque ripples, resulting in acoustic noise and degraded control technique performance [11–14]. Classical direct torque control (DTC-C) has been the focus of numerous studies over the past four decades due to its excellent control features compared to field-oriented control (FOC). The use of hysteresis controllers to regulate stator

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magnetic flux and torque naturally leads to high torque ripples and variable switching frequency, which varies with speed, load torque, selected hysteresis bands, and poses difficulties in controlling torque and flux at very low speeds [15].In recent years, there have been several improvements to optimise the management of direct torque control. Researchers have investigated intelligent control approaches, such as fuzzy logic, for their potential to integrate human intuition into the design process [16-18]. Fuzzy logic has gained attention in various fields of electromechanical device control because it can operate without relying on mathematical models of systems. It has attracted significant attention due to this capability, unlike traditional controllers. Fuzzy logic is a soft computing technique that can regulate complex systems based on human expertise. Many fuzzy logic algorithms have been developed for autonomous systems in engineering. The main advantages of using fuzzy logic are its ease of implementation, efficient computation, and improved performance [19-21].According to the researchers [4, 18], in this article, we have employed a fuzzy controller structure with reduced fuzzy rules. Reducing the number of rules helps to decrease computation time and eliminate any redundancy that exists in the fuzzy rules. Consequently, it improves the sampling period and enhances the responses of torque and flux in terms of ripple reduction. Increasing the number of rules, on the other hand, poses difficulties in real-time implementation due to the small sampling period required by DTC. In the same approach, we have utilized a hybrid PI-fuzzy controller. This approach combines a PI controller and a supervisor composed of fuzzy rules. This adaptive control strategy allows us to leverage the advantages offered by both PI controllers and fuzzy logic. By using this hybrid controller, we can benefit from the strengths of PI controllers and fuzzy logic simultaneously.

The paper is structured as follows: Section 2 discusses the mathematical modeling of the DFIM. The conventional direct torque control method for controlling the DFIM is discussed in section 3. Section 4 proposes a DTC method for the DFIM that incorporates a fuzzy logic strategy. Section 5 presents the development of robust fuzzy gains for the PI controller, specifically for speed control of the DFIM. Section 6 presents the results and simulations obtained from the proposed methods. Finally, in section 7, a conclusion is presented with a summary of the work and the results obtained.

II. MODELLING OF DFIM

The model of the doubly fed induction motor is described using space vector notation and written in the (α, β) reference frame [22–24]. The following system represents the state model used for designing the drive, with the assumption that the stator current and flux are the state variables:

$$\dot{X} = AX + BU \tag{1}$$

$$X = [I_{s\alpha} \quad I_{s\beta} \quad \varphi_{s\alpha} \quad \varphi_{s\beta}] \quad U = [V_{s\alpha} \quad V_{s\beta} \quad V_{r\alpha} \quad V_{r\beta}]$$

$$A = \begin{bmatrix} -\frac{1}{\sigma}\left(\frac{1}{T_s}+\frac{1}{T_r}\right) & -\omega & \frac{1}{L_s.\sigma.T_r} & \frac{\omega}{L_s.\sigma} \\ \omega & -\frac{1}{\sigma}\left(\frac{1}{T_s}+\frac{1}{T_r}\right) & -\frac{\omega}{L_s.\sigma}\omega & \frac{1}{L_s.\sigma.T_r} \\ -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma.L_s} & 0 \\ 0 & \frac{1}{\sigma.L_s} \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

With $\sigma = 1 - \frac{M^2}{L_s.L_r}$, $T_s = \frac{L_s}{R_s}$ *and* $T_r = \frac{L_r}{R_r}$

The mechanical and the electromagnetic torque equations are given by:

$$J\, d\Omega/dt + f.\Omega = T_{em} - T_r \tag{2}$$

$$T_{em} = p(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}) \tag{3}$$

III. CONVENTIONAL DTC OF DFIM

DTC was introduced by I. Takahashi in 1985 as an extension of the flux-oriented control method and the principles of DC motors [25–26]. The approach suggested replacing the decoupling process in vector transformation with a nonlinear control technique, where the inverter's switching states are independently controlled to regulate the stator flux and electromagnetic torque of the motor. The basic structure of direct torque control is illustrated in Figure 1. DTC relies on selecting the optimal voltage vector to rotate the flux vector and generate the desired torque. During this rotation, hysteresis controllers are employed to ensure that the flux and torque errors remain within acceptable limits [27–29].

A. Estimation of Stator Flux and Electromagnetic Torque

The magnitude of the stator flux is estimated from its two-phase components $\varphi_{s\alpha}$and $\varphi_{s\beta}$:

$$\begin{cases}\varphi_\alpha = \int_0^t (V_{s\alpha} - R_{s.} I_{s\alpha})dt \\ \varphi_\beta = \int_0^t (V_{s\beta} - R_{s.} I_{s\beta})dt\end{cases} \tag{4}$$

The stator flux module is defined by:

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \tag{5}$$

Then, the position of the stator flux is evaluated as:

$$\theta_s = \text{atan}\left[\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}\right] \tag{6}$$

The electromagnetic torque is estimated, only from the fluxes and stator currents in the frame (∝, β) which can be put in the following form:

$$\{T_{em} = p.\left(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}\right) \tag{7}$$

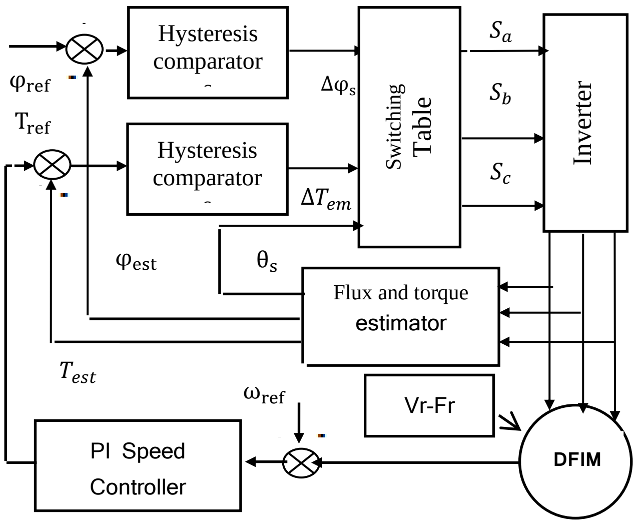

Figure. 1. Structure of conventional DTC of DFIM

B. Control of stator flux and electromagnetic torque

The magnitudes of the stator flux $\varphi_s$and torque T_{em}commands are juxtaposed with their corresponding estimated values. Subsequently, the disparities are subjected to processing through two hysteresis comparators one dedicated to flux and another to torque which operate autonomously. Both the flux and torque controllers function as two-level comparators. The digital outputs of the flux controller adhere to the following logic:

$$\begin{cases}\Delta\varphi_s = 1 \ \text{ for } |\varphi_s| \le |\varphi_{s-ref}| - |\Delta\varphi_s| \\ \Delta\varphi_s = 0 \ \text{ for } |\varphi_s| \ge |\varphi_{s-ref}| + |\Delta\varphi_s|\end{cases} \tag{8}$$

Where: $\Delta\varphi_s = |\varphi_{s-ref}| - |\varphi_s|$

$$\begin{aligned} &\Delta T_{em} = 1 \ \text{ for } |T_{em}| \leq |T_{em.ref}| - |\Delta T_{em}| \\ &\Delta T_{em} = -1 \ \text{ for } |T_{em}| \geq |T_{em.ref}| + |\Delta T_{em}| \\ &\Delta T_{em} = 0 \\ &\text{for} \\ &|T_{em.ref}| - |\Delta T_{em}| \leq |T_{em}| \leq |T_{em.ref}| + |\Delta T_{em}| \end{aligned} \tag{9}$$

Where: $\Delta T_{em} = T_{em.ref} - T_{em}$

The rotor reference speed is compared with the feedback speed and by suitable PI controller. This error is converted into reference torque. The digital outputs of the torque controller have following logic.

C. Switching Table

The voltage vector selection depends on the errors in flux and torque, as presented in Table 1

Table 1. Generalized switching table.

Flux	Torque	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
$\Delta\varphi_s$=0	ΔT_{em}=1	V_3	V_4	V_5	V_6	V_1	V_2
	ΔT_{em}=0	V_0	V_7	V_0	V_7	V_0	V_7
	ΔT_{em}=-1	V_5	V_6	V_1	V_2	V_3	V_4
$\Delta\varphi_s$=1	ΔT_{em}=1	V_2	V_3	V_4	V_5	V_6	V_1
	ΔT_{em}=0	V_7	V_0	V_7	V_0	V_7	V_0
	ΔT_{em}=-1	V_6	V_1	V_2	V_3	V_4	V_5

Where:

V1= (1 0 0), V2= (1 1 0), V3= (0 1 0), V4= (0 1 1), V5= (0 0 1), V6= (1 0 1), V0= (0 0 0),V7= (1 1 1).

IV. FUZZY DTC OF DFIM

In light of the provided information, the conventional DTC-C is afflicted by various shortcomings, encompassing fluctuating switching frequency and oscillations in electromagnetic torque, flux, and stator current, persisting in both transient and steady-state conditions.

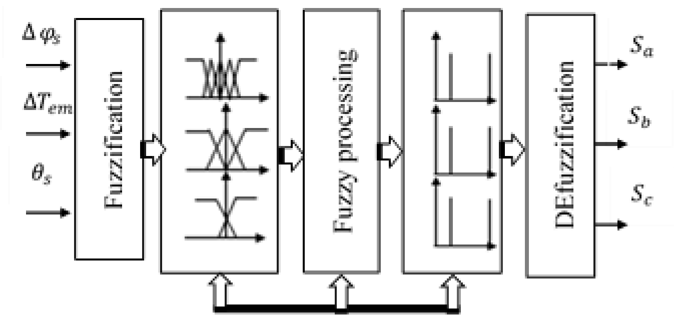

Figure. 2. Structure of the fuzzy DTC of DFIM

These issues arise due to the resistive term and the use of comparators with hysteresis, which result in a uniform control action across the entire range of error. To address these limitations, an improvement is proposed by incorporating a fuzzy logic switching controller (FLC) into the DTC-C system [4]. Figure 2 illustrates the configuration of the improved system.

The hysteresis bands and switching table are replaced by FLC. The selection of optimal switching state is a nonlinear function of flux error $(\varphi_{sref} - \varphi_s)$ torque error$(T_{e-ref} - T_e)$, stator flux angle (θ_s) and number of switching transitions is limited by hysteresis bands. Fuzzy logic represents a potent soft computing method that manages intricate systems by leveraging human expert insights. Numerous researchers have explored fuzzy logic algorithms for directing independent systems within the engineering domain. The fuzzy controller comprises four primary components, as elucidated in [30–32].

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A. Selection of Input/output Variables

In this work, the input variable is the torque error ΔT_{em} the stator flux error $\Delta\varphi_s$ and the stator flux angleθ_s. They are defined as after:

$$\begin{cases} \Delta T_{em} = T_{em.ref} - T_{em} \\ \Delta\varphi_s = \varphi_{s.ref} - \varphi_s \\ \theta_s = \mathrm{atan}\left[\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}\right] \end{cases} \tag{10}$$

B. Fuzzification

The fuzzification converts the three inputs into variables using membership functions (MFs):

➢ MFs of torque error ΔT_{em} are five linguistic variables: negative big noted (NB), positive big noted (PB), and negative Medium noted (MN),positive medium noted (MP), and zero noted (Z).As shown in Figure 3.

➢ MFs of flux error $\Delta\varphi_s$ are three linguistic variables: negative (N), positive (P), and zero (Z). As shown in Figure 4 .

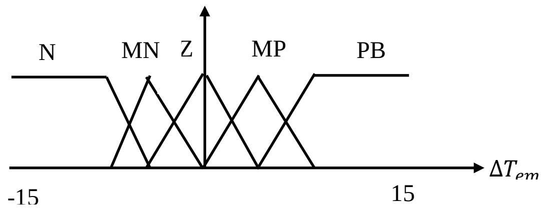


Figure 3. The membership function of torque error ΔT_{em}

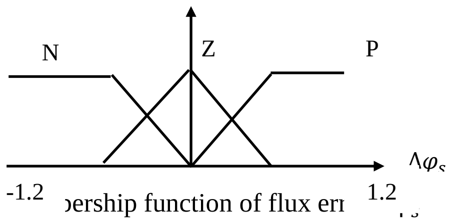


Figure 4. Th ership function of flux er

➢ The stator flux angle can be described by two linguistic variables (θ1→θ2) (-30° →30°) aims to reduce the size of fuzzy inference rules. The function membership is shown by Figure. 5.

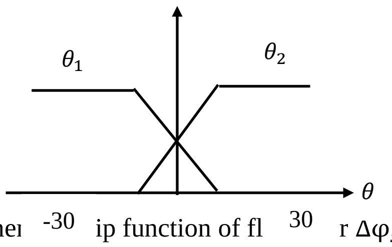


Figure 5. The me ip function of fl r $\Delta\varphi_s$

➢ The output variable of the fuzzy controller is the commutation state (S_a, S_b, S_c). They are used to define the appropriate active inverter voltage vectors two linguistic variables can be described by: open (O), closed noted (C).As shown in Figure. 6.

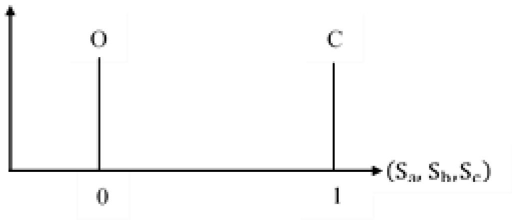


Figure 6. The membership Function of switching state (1, 0).

C. Fuzzy inference engine

The inference method utilized in this study is the mamdani method, which relies on min-max decision criteria. The factor $\propto_i$ for the i th rule can be expressed as:

$$\propto_i = \min\left(\mu_{\varphi i}(\Delta\varphi), \mu_{Tei}(\Delta T_{em}), \mu_{\theta i}(\theta)\right) \tag{11}$$

By fuzzy reasoning, the minimum process of Mamdani gives:

$$\mu_{Vi}(n) = \min\left(\alpha_i, \mu_{Vi}(n)\right) \tag{12}$$

The membership function μ_V of the return n is given by:

$$\mu_V(n) = \max_{i=1}^{22}\left(\mu_{Vi}(n)\right) \tag{13}$$

The value corresponding to $\mu_V(n)$ should then be converted to reality into a vector of voltage.

By the same reasoning we find the set of control rules presented by Table 2.

Table 2. Fuzzy switching logic rule base.

	θ_1				θ_2		
$\Delta T_{em}/\Delta\varphi_s$	P	Z	N	$\Delta T_{em}/\Delta\varphi_s$	P	Z	N
PB	V_2	V_2	V_3	PB	V_2	V_3	V_3
MP	V_1	V_2	V_3	MP	V_1	V_3	V_4
Z	-	-	-	Z	-	-	-
NB	V_6	-	V_4	NB	V_6	-	V_5
MN	V_6	V_5	V_4	MN	V_6	V_6	V_5

The control rules are expressed as a function of the input and output variables as follows:

- If (θ is θ_1) and (ΔT_{em} is PB) and ($\Delta\varphi_s$ is P) then (S_a is C) and (S_b is C) and (S_c is O) ($V_i = V_2$).
- If (θ is θ_2) and (ΔT_{em} is MP) and ($\Delta\varphi_s$ is P) then (S_a is C) and (S_b is O) and (S_c is O) ($V_i = V_1$).

D. Defuzzification

The process involves combining the rules of the fuzzy controller and converting the resulting fuzzy sets into real values. The Small of Maximum (SOM) method is utilized, which calculates the value of the membership functions. The fuzzy controller outputs voltage vectors V_i, represented by the membership functions shown in Fig 6. These voltage vectors are then converted into commutation signals (S_a, S_b, S_c) for the inverter using a Boolean expression that results in a binary value (0 or 1).

V. Speed Control of DFIM: Robust Fuzzy Gains for PI Controller with Fuzzy DTC

The Proportional-Integral (PI) controller is a linear control system widely used in mechanical operations due to its simplicity, ease of implementation, and ability to achieve satisfactory performance. Adaptive control has seen significant advancements in recent years, and the field of PI control has integrated artificial intelligence to improve performance and address a wider range of issues. Fast computing resources and increased memory capacity have made it possible to implement high-performance adaptive control algorithms [2, 33-34].

In the time domain, a classical PI controller can be defined as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{14}$$

The fuzzy controller fine-tunes the parameters of the PI controller and produces fresh parameters tailored to varying operational conditions. This is accomplished by taking into account the error and its derivative as inputs. Figure 7 illustrates the block diagram of the adaptable fuzzy gain for the PI controller

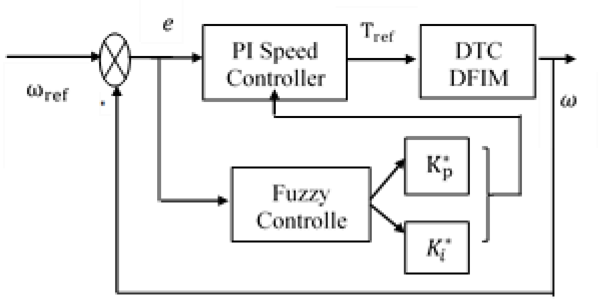


Figure 7. Adaptive fuzzy gain of PI controller

The inputs of the FLC fuzzy controller are: error (e) and the derivative of the error (Δe) the outputs are: the normalized value of the proportional action K_p^* and the normalized value of the integral actionK_i^*.

The normalization PI parameters are given by [35–36]:

$$\begin{cases} K_p^* = \dfrac{K_p - K_{pmin}}{K_{pmax} - K_{pmin}} \\ K_i^* = \dfrac{K_i - K_{imin}}{K_{imax} - K_{imin}} \end{cases}$$

The inputs of fuzzy controller are: error (e) and derivative (Δe) of error are designed as in Figure 8

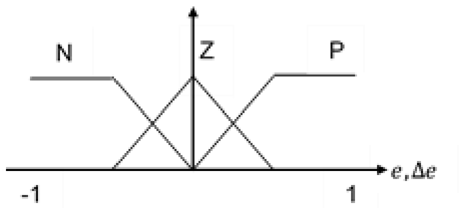


Figure 8. Membership functions the inputs (e) and Δe

The membership functions the outputs K_p^* and K_i^* gain of the speed controller are designed as in Figure. 9, Figure. 10.Which: Negative noted N; Zero noted Z; Positive noted ; Positive Small noted PS; Positive Medium noted MP; Positive Big noted PB.

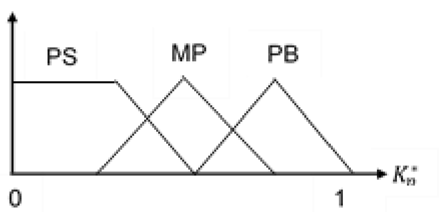


Figure 9. Membership functions the output K_p^*

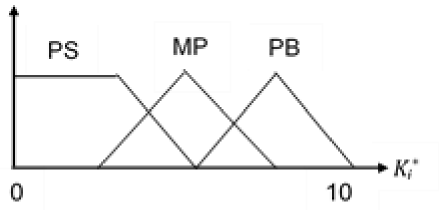


Figure 10. Membership functions the output K_i^*.

Table 3 show the tuning rules for K_p^* and K_i^*:

Table 2. Fuzzy switching logic rule base.

	e					
Δe	N		Z		P	
	K_p^*	K_i^*	K_p^*	K_i^*	K_p^*	K_i^*
N	PS	PB	PB	PS	PS	PB
Z	PB	PS	MP	MP	PS	PB
P	PB	PS	PS	PB	PB	PS

VI. RESULTS AND DISCUSSION

An evaluation of conventional DTC and Fuzzy-DTC for doubly fed Induction machine with an adaptive fuzzy-PI speed controller is showcased in MATLAB/Simulink. The machine parameters employed in the simulation are based on Table 4 from reference [37].

The simulation tests were carried out for a 10 N.m load disturbance applied at time 1s with speed reference of magnitude 100 rad /s and flux reference $\varphi_{s-ref} = 1.2\text{Wb}$.

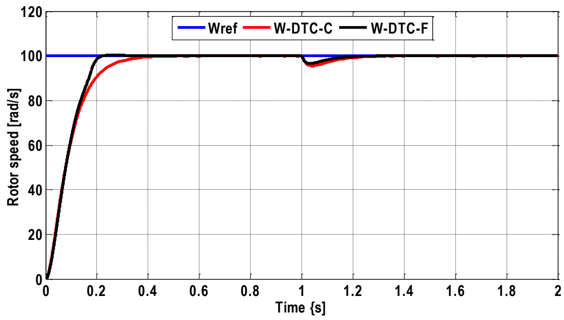


Figure 11. Mechanical speed.

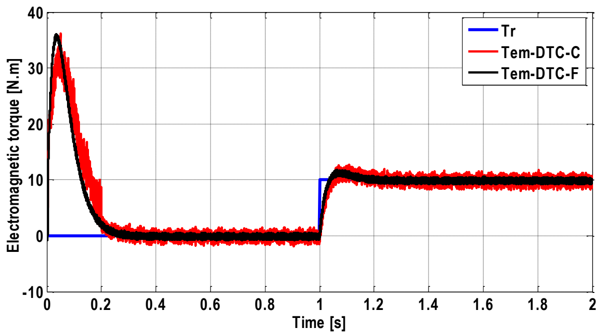


Figure 12. Electromagnetic torque

Figure 11 shows that the rotation speed has reached the reference value and stabilized at a constant 100 rad/s, with a small response time and reduced rise time. Additionally, the electromagnetic torque quickly follows the load instructions introduced. It is worth noting that there is less overshoot and fewer ripples in the fuzzy DTC control compared to the conventional DTC, as shown in Figure 12

Figure 13 and Figure 14 demonstrate a fast transient response of the stator flux modulus, exhibiting a perfectly circular shape without any steady-state ripple.

Additionally, the stator current exhibits good response to variations imposed by the torque, and its value remains close to the sinusoidal waveform depicted in Figure 15. These results indicate that the DTC with fuzzy logic and fuzzy gains of the PI controller for speed control of the DFIM is highly efficient in minimizing torque and flux ripples when compared to conventional DTC methods.

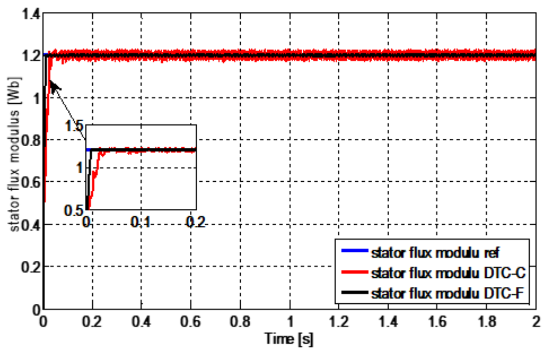


Figure 13. Stator flux.

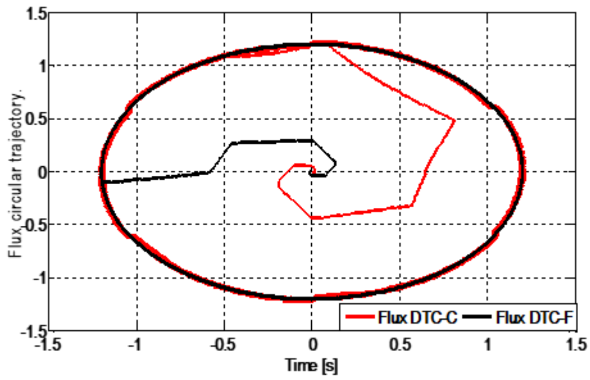


Figure 14. Flux circular trajectory.

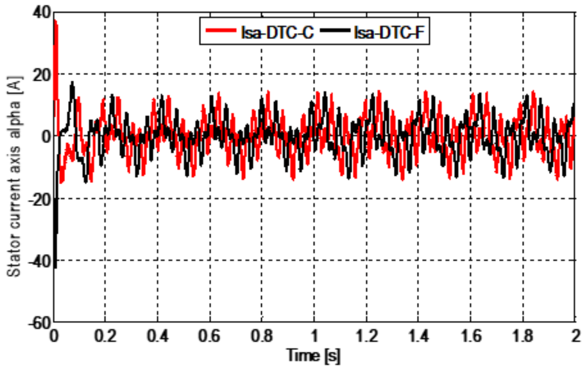
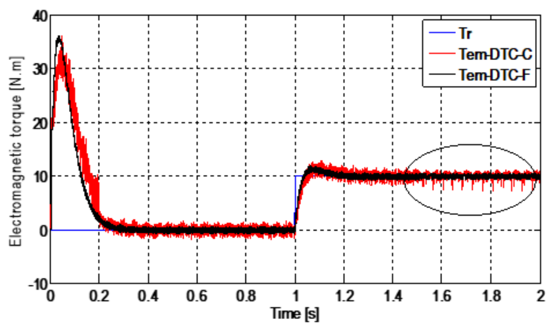


Figure 15. Stator current of phase α.

A. Stator Resistance Variation

Misinterpretation of stator resistance can result from various factors, such as inaccurate machine parameter identification, load fluctuations, or changes in ambient temperature. An incorrect stator resistance value can introduce errors in estimating both the magnitude and position of the stator flux. Therefore, it is imperative to ensure accurate estimation of both the magnitude and position of the stator flux for the proper functioning of the control system.



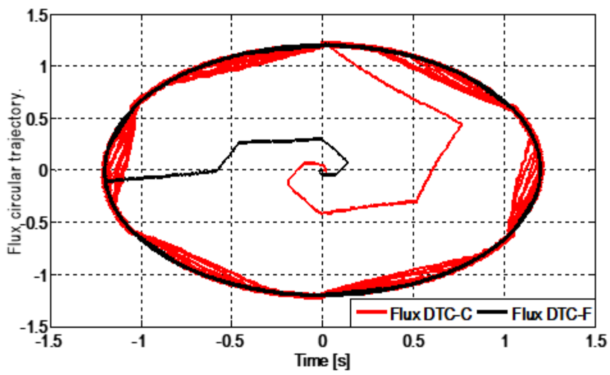


Figure 16. Electromagnetic torque.

Figure 17. Flux circular trajectory.

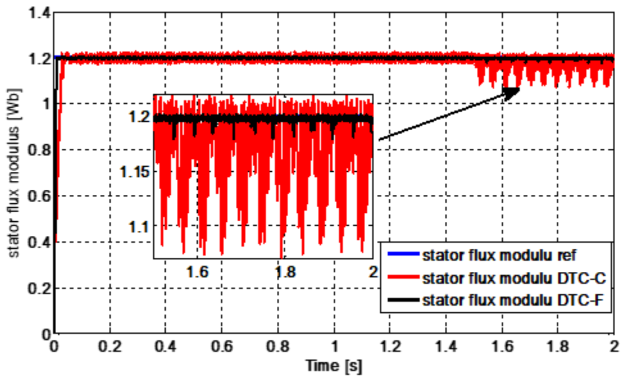


Figure 18. Stator flux.

To evaluate the robustness of the fuzzy DTC control performance to parameter uncertainty, we carried out simulations by varying the stator resistance. We simulated an increase in resistance up to twice the ideal value (2*Rs). The results, illustrated in Figure. 16, Figure. 17, and Figure. 18, show oscillations in torque and flux as stator resistance increases. However, Fuzzy DTC shows a reduction in the amplitude of the transient oscillations.

VII. CONCLUSION

The incorporation of fuzzy logic into classical control systems provides an interesting solution to achieve optimal regulation that can meet user requirements even in challenging and variable environments. This paper proposes a direct torque control method for the doubly fed induction motor using a fuzzy logic controller. The method replaces hysteresis comparators and switching tables with a fuzzy logic controller. Additionally, for speed control, a combination of a fuzzy controller and a conventional PI controller is proposed to overcome the limitations of PI controllers. This combination allows for adaptive gains of the PI controller. The DTC-Fuzzy method presented in this work for DFIM outperforms conventional DTC. It improves response time and reduces torque and flux ripples, making it suitable for electrical traction applications that have specific requirements. Based on these results, it can be concluded that both fuzzy logic-based techniques offer an attractive solution for direct torque control of doubly fed induction motor.

APPENDIX

Table 4. Parameters of DFIM.

Parameters	Values
Nominal power P_n Voltage	4 kW 220/380 V
Frequency	50 Hz
P	2
R_s	1.2 Ω
R_r	1.8 Ω
L_s	0.158 H
L_r	0.156 H
M	0.15 H
J	0.07 Kgm^2

NOMENCLATURE

$V_{s\alpha}$, $V_{s\beta}$ Stator voltages in the reference (α, β).

$V_{r\alpha}, V_{r\beta}$ Rotor voltages in the reference (α, β).

$\varphi_{s\alpha}, \varphi_{s\beta}$ Stator flux in the reference (α,β).

$I_{s\alpha}, I_{s\beta}$: Stator currents in the reference (α,β).

R_s, R_r: Stator and rotor resistance.

L_s, L_r Stator and rotor inductance.

M Mutual inductance .

P Number of pole pairs

J The moment of inertia,

σ: The leakage coefficient.

ω The machine speed ($\omega = p.\Omega$).

θ_s Position of the stator flux.

T_s, T_r Stator and rotor time constants.

T_{em} The electromagnetic torque,

T_r The load torque.

f The friction coefficient

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