ANFIS-based optimisation for achieving the maximum torque per ampere in induction motor drive with conventional PI

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ABSTRACT

This research presents an innovative approach to controlling the speed of an induction motor drive by utilizing a combination of neural networks and fuzzy inference systems (ANFIS). The study focuses on computing the rotor's magnetic flux while considering different overshoot and settling criteria for torque and motor speed. The goal is to optimize torque per ampere and generate the necessary torque. The proposed ANFIS-based torque-per-ampere control technique offers a distinctive method applicable to a static induction motor model. This method allows for an increase in stator current while maintaining flexibility and individuality in motor control strategies. It compares various motor vector control methods, specifically focusing on strategies to reduce torque ripple. These strategies include adaptive ANFIS, fuzzy logic control (FLC), and proportional-integral (PI) control. The research highlights the effectiveness of an adaptive ANFIS controller in achieving the most significant reduction in torque ripple within the induction motor system. This proposed problem identification sets the stage for exploring and developing solutions to enhance the performance and efficiency of induction motor drives.

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1. INTRODUCTION

Induction motors offer essential operational characteristics such as reliability, robustness, and simplicity in control, making them a popular choice across various applications, from household appliances to industrial settings. Their speed control has traditionally relied on varying the frequency, and their operation is based on the fundamental principle of electromagnetic induction. As a result, 3-phase induction motors are known for their straightforward and sturdy construction, ease of maintenance, simple design, and cost-effectiveness. In such scenarios, conventional controllers have often struggled to deliver superior performance. Traditional controllers rely on precise mathematical models for the current system, whereas intelligent controllers have become prevalent in engineering applications, eliminating the need for exact mathematical approaches. These intelligent controllers, especially fuzzy artificial neural networks (ANN), excel in managing non-linearity and do not require mathematical modelling. the adaptive neuro-fuzzy inference system (ANFIS) is the superior method. ANFIS utilizes a hybrid learning technique that combines fuzzy logic and neural networks (NN) to handle imprecise methods effectively. Also, fuzzy and neural can reason and learn in traditional control systems. However, intelligent controllers, such as fuzzy logic controllers, operate without mathematical modelling.

One notable intelligent controller is the adaptive neuro-fuzzy inference system (ANFIS), which combines fuzzy logic and neural network techniques. ANFIS employs a hybrid learning algorithm that utilizes both neural networks and fuzzy logic. Unlike traditional proportional-integral-derivative (PID) and proportional-integral (PI) controllers, ANFIS doesn't require extensive mathematical modelling. In our proposed paper, we have developed and implemented ANFIS, PI, and fuzzy controllers to regulate the motor system. The research compares performance metrics based on experimental outcomes, including total harmonic distortion (THD), motor speed, and harmonics. This comparative analysis provides valuable insights into the effectiveness of ANFIS, PI, and fuzzy controllers in real-world applications. Like self-excited generators, induction machines are widely used to generate power from renewable energy sources [1]. However, they suffer a significant drawback: poor voltage regulation when subjected to varying loads and speeds. Saleeb *et al.* [2] proposed a solution by employing fuzzy control to adjust the coefficients of the conventional PI controller dynamically. This approach was anticipated to outperform traditional controllers, enhancing the system's overall performance. Cao *et al.* [3] introduced a PI controller for an induction motor to minimize output current ripples.

Moreover, Dynamina and Kakodia [4] that one of the main challenges in motor driving based on model predictive control (MTC) is dealing with ripples in the motor output. To mitigate this issue, researchers have explored various methods, with a significant approach involving the utilization of multilevel inverters to regulate flux, motor, and torque effectively. The research efforts have been directed towards comparing conventional controllers with their artificial intelligence counterparts. Utilizing ANFIS controllers and algorithms to optimize time and cost has proven superior in motor drive systems. A mechanism based on flux-switching to generate the phase back-EMF of the induction motor is introduce in this proposed paper. This innovative approach sheds light on addressing the challenges associated with voltage regulation in these machines. Al-Mahturi *et al.* [5] introduced an artificial neural network (ANN) aimed at minimizing losses in electric vehicles driven by direct torque-controlled induction motors (IM). Their proposed architecture and control strategies utilized ANN to regulate the amplitude of the starting current, resulting in significant power savings compared to traditional PID controllers. In this study, the researchers employed a fuzzy logic (FL) model, which relies on language regulations, to address the inherent non-linear nature of the problem. The primary objective of the research is to showcase improved motor speed control achieved through the implementation of an ANFIS controller. This approach enhances motor speed regulation and ensures stable motor performance even when subjected to varying loads. The study also delves into the intricacies of maximum torque control schemes, which are fundamental in regulating machines' electromagnetic torque and flux. The algorithms developed in this study assess the performance of induction motors under diverse operating conditions [6].

Numerous optimized control techniques have been applied to the management of induction motors [7], focusing on minimizing active power loss and improving power factors. This study aims to evaluate the effectiveness of the proposed algorithms by comparing the outcomes with conventional methods. Even with appropriate controllers, total harmonic distortion (THD) issues may arise, mainly when the load operates at maximum capacity, leading to significant fluctuations in THD. The modelling of the induction motor has been derived from (1) to (6).

- Maximum torque modelling

The calculated total magneto motive force (MMF) of the motor is as follows: $F_{total}=N_a I_a+N_f I_f$. N_a is the number of turns of the armature, N is the number of turns of the field armature, f is the number of turns of the field, and I_a is the R.M.S. current of the armature.

$$2I_a = (i_r^2 q_s + i_r^2 ds)\frac{1}{2} \tag{1}$$

Rearrange from (1) to be (2).

$$I_a + N_f N_a N_f = F_{total} N_a \tag{2}$$

$$T_e = \frac{3}{2} P L_f \sqrt{2} I_a \tag{3}$$

Substituting (2) into (3) and eliminating I_a yield.

$$F_{total} = N_a - N_f N_a I_f \quad (4)$$

By substituting ∂Te/∂ I_f = 0 for (4), the using I_a and I_f to determine maximum torque using (5).

$$I_f = F_{total} 2N_f \quad (5)$$

Combining (3) and (5) and eliminating F_{total} yield.

$$I_a = N_f N_a I_f \quad (6)$$

When the total magneto-motive force (MMF) remains constant, it is observed that the maximum torque occurs when the product of the number of turns (N_a) and current (I_a) equals the product of the number of turns (N_f) and field current (I_f). This relationship provides the motor's calculated torque about the ratio N_aI_a/N_f. This ratio holds regardless of the variations in F_{total} values. When N_aI_a/N_f equals 1, maximum torque consistently occurs for any F_{total} value. However, it's crucial to note that the saturation effect starts to impact F_{total} at 1350 Ampereturns (AT). As the currents continue to rise, the resulting torque increases rapidly within a short period.

2. THE METHODOLOGY OF THE SUGGESTED SYSTEM

In the context of Figure 1, a vector controller of the block diagram is employed to implement the maximum torque management technique for the induction motor. This diagram's symbol "m" represents the rotor's mechanical speed. The outer loop, dedicated to vector control, involves PI control and armature currents on the q-axis, influencing velocity accuracy (i_{rqs}). The d-axis armature current signal (i_{rds}) is initially set to zero. The internal loops regulate the armature current, with the synchronous frame current [8], [9] generating the armature current. This configuration ensures precise control over the motor's behavior, optimizing its performance based on the given inputs and control signals.

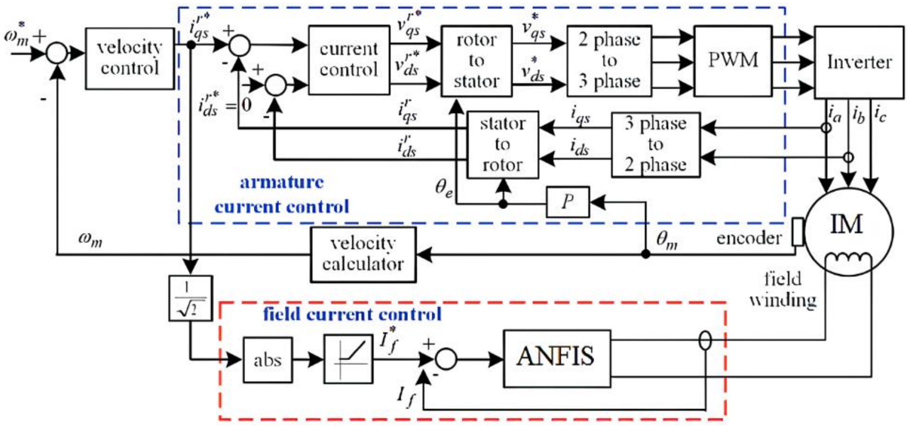

Figure 1. Maximum torque control of induction motor block diagram

Moreover, a hysteresis current controller is employed to address the situation where i_{rds} remains consistently zero, and i_{rqs} is equal to $2I_a$, ensuring a constant field current. The desired field current I_f is calculated at half of i_{rqs} to achieve the optimal torque. The design of the adaptive neuro-fuzzy inference controller (ANFIS) is shown in Figure 2. This approach guarantees the stability of the control system.

A fuzzy controller is integrated with the typical setup of an induction motor operating under load. This controller establishes connections between input variables and the properties of the output model [10]. It optimizes K_p and K_i by considering relevant factors, ensuring efficient motor performance from (7) and (8). The membership functions have been shown in Table 1 for easy understanding of the minimization of error. The fuzzy inference system (FIS) is essential to the MAX-MIN design process [11]. The inference process is crucial in real-time applications because it converts imprecise control results into precise actions. To do this, the center of gravity (C.G.) technique is used to defuzzify the fuzzy variable, after which it is transformed into physical values.

$$K_p = K_p^* + \frac{\sum_{j=1}^{n} \mu_j(e,e_c)\Delta K_{pj}}{\sum_{j=1}^{n} \mu_j(ee_c)} \tag{7}$$

$$K_i = K_i^* + \frac{\sum_{j=1}^{n} \mu_j(e,e_c)\Delta K_{ij}}{\sum_{j=1}^{n} \mu_j(ee_c)} \tag{8}$$

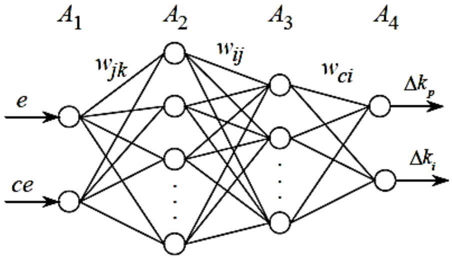

Figure 2. The construction of ANFIS

Table 1. Fuzzy logic rule base membership system

$E(pu)$ / $CE(pu)$	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NL	NL	NL
NM	NL	NL	NL	NM	NM	ZE	PS
NS	NL	NL	NM	NS	ZE	PM	PM
ZE	NL	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	NS	PS	PS	PL	PL	PL	PL

The process of designing the controller (ANFIS) involves two crucial steps: comprehending the mathematical arrangement of the induction motor and creating the controller mathematical model [12]–[15]. Simulation techniques are employed to streamline and ease the analysis of the controller's design. According to (3), integrated into the Simulink model, serves as the mathematical representation of the torque within the system. The block diagram of the induction motor system is depicted in Figure 1. The error and the change in error are represented using (9) and (10) have been recognized as inputs to the ANFIS controller.

$$e(k) = \omega_{ref} - \omega_r \tag{9}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{10}$$

Here ω_{ref} is the reference speed, ω_r is the actual rotor speed, e(k) is the error, and Δe(k) is the change in error. The torque equation of the induction motor is shown in (11).

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\lambda_r I_{qs} \tag{11}$$

The fuzzy system is critical in converting discrete data into verbal variables, which is vital for generating inputs for rule-based membership systems 49 rules are formulated based on previously acquired knowledge or understanding. These rules are integrated with well-designed rule-based membership functions connected to neural networks [16]. The neural networks utilize back-propagation to select the proper rule base by this method [17], [18].

3. RESULTS AND DISCUSSIONS

In contrast to a single-step method, the fuzzy logic control evaluates torque and flux in multiple processes, which minimizes torque ripples up to 1.44% when compared to the PI, as shown in Figures 3 and 4 [19]. However, minimizing torque ripple and improving torque reference were two of the study's goals. The analysis of expected MTC involves considering the frequency-angle and DC link voltage ratio in both the transient and stable regions. This system has been designed in Simulink to assess the recommended PI controller. PI control without a nonlinear disturbance observer serve as two comparative methods implemented on the motor to illustrate the effective control and superior disturbance attenuation achieved by the developed ANFIS controller. In Figure 5, the speed response waveforms for these three strategies are depicted across a range of 0 to 1000 r/min. The same figure also displays the speed response waveforms under abrupt load disruption. The curves based on PI undergo sudden changes and overlap with each other. In contrast, the ANFIS design showcases a reduced speed loss compared to the aforementioned methods. Figures 5, 6, and 7 compare the toque for proportional-integral (PI), fuzzy systems, and ANFIS controllers.

Applying ANFIS to regulate the MTC for the 3-phase induction motor (IM) enabled the evaluation of PI controller responses [20]–[22]. This research highlighted the reduced sensitivity of the system to abrupt changes in both ripple amount and sensitivity. Consequently, users of the controller benefited from empirical speed, successfully achieving the desired objective. The empirical study results demonstrated improved drive performance during short periods of acceleration, ensuring the attainment of maximum torque. ANFIS performance was evaluated using platforms like Simulink and MATLAB. The different speed variations of FLC controllers are shown in Figure 8. Specifically, at a speed of 1000 rpm at 2 seconds and a load torque of 0.25 N.m., varying between 0.4 seconds and 4 seconds, Figures 5 to 7 illustrate how the characteristics shift with load torque changes in different controllers. Figure 8 illustrates speed estimation concerning the FLC controller [23]. Further insights from Figure 9 distinguished the THD of ANFIS controller, and it is observed that the THD of ANFIS is reduced up to 3.46%; hence, it is proved that the ANFIS controllers are superior to the Induction motor [24]. This study highlights that the proposed ANFIS controller promptly stabilizes speed, outperforming the standard PI controller, which exhibits a minor overshoot.

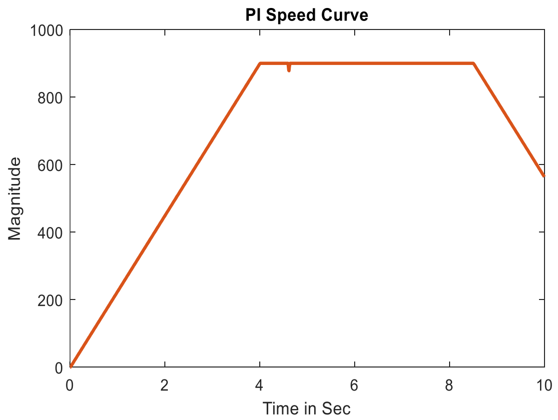

Figure 3. Reference and actual speed of conventional PI

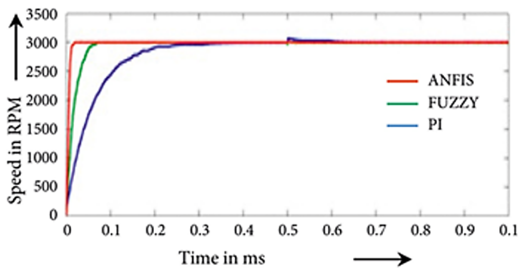

Figure 4. Reference speed and actual speed of ANFIS

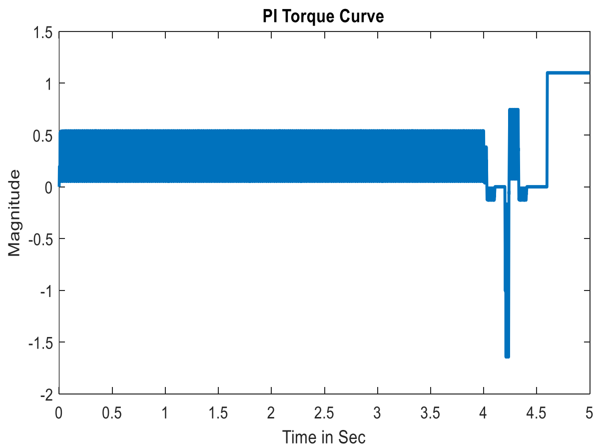

Figure 5. PI controller torque

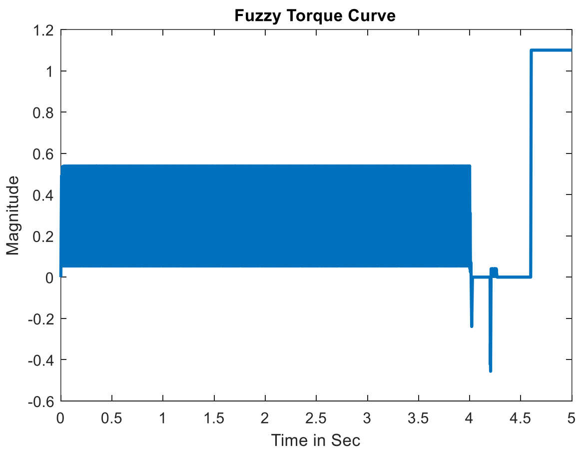

Figure 6. Torque of fuzzy logic system

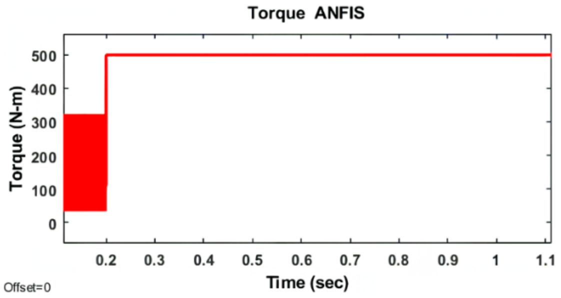

Figure 7. ANFIS-based torque

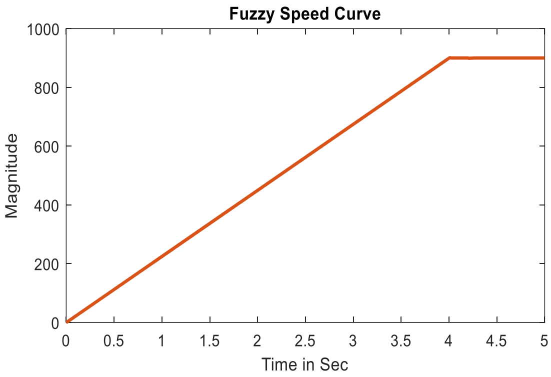

Figure 8. FLC controller speed variations

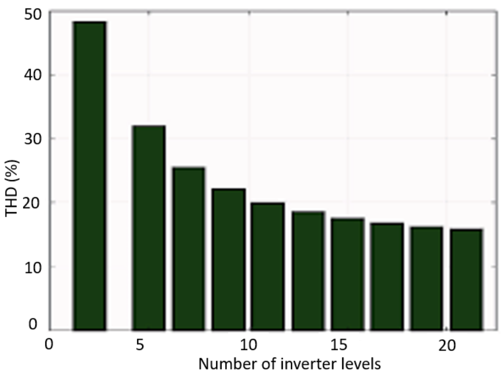

Figure 9. THD (3.46%) for ANFIS controller of induction motor

Analysis: In Table 2, a comparison with other artificial intelligence (AI) controllers reveals that the ANFIS controller exhibits the lowest percentage of overshoot and the shortest settling time for both the dynamic speed response and dynamic torque response of the induction motor [25]. Where the ZC represents the zero controller, Table 3 provides data on the reference speed with the combination of the load torque at different levels, set at 150 radians per second. Tables 2 and 3 will give a simulation analysis of the ANFIS controller.

Table 2. Induction motor speed analysis of comparative system with multiple AI controllers at magnetizing inductance: 34.7e-3 H

S. No	Type	% Overshoot	Settling time (Ts)	Total harmonic distortion (THD)
1	ZC	20.1	2.13	46.91
2	PI	12.3	1.83	26.72
3	FLC	11.1	1.65	7.92
4	ANFIS	8.9	0.85	3.46

Table 3. Finding the induction motor's setting time under different load conditions with a 150 rad/sec reference speed

Type of controller	Different loads/sec	Type of controller	Different loads/sec	Type of controller
1	0 Nm (Tm)	20.1	0 Nm (Tm)	46.91
PI	2.27	PI	2.27	PI
FLC	0.71	FLC	0.71	FLC
ANFIS	0.23	ANFIS	0.23	ANFIS

4. CONCLUSION

The primary finding objective of this innovative research approach is to introduce a distinct design methodology that combines a linear induction motor drive with an ANFIS controller. The study begins by conceptualizing and developing the entire drive system using MATLAB software. By integrating ANFIS controllers into the induction motor drive, the research aims to significantly reduce speed and torque fluctuations during startup, load disturbances, and speed problems. This reduction is achieved due to the ANFIS controller's robust and rapid response. Furthermore, the research evaluates the ANFIS torque controller's performance, considering it a potential replacement for the traditional PI controller. The goal is to achieve excellent decoupling and improved flux reactivity within the motor drive system using the proposed ANFIS controller.

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