World Journal of Engineering and Technology, 2024, 12, 65-79
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Enhanced Fuzzy Logic Control Model and Sliding Mode Based on Field Oriented Control of Induction Motor

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How to cite this paper: Tahhan, A. and Temurtaş, F. (2024) Enhanced Fuzzy Logic Control Model and Sliding Mode Based on Field Oriented Control of Induction Motor. *World Journal of Engineering and Technology*, **12**, 65-79.
https://doi.org/10.4236/wjet.2024.121004

Received: December16, 2023
Accepted: January 15, 2024
Published: January 18, 2024

Abstract

In the context of induction motor control, there are various control strategies used to separately control torque and flux. One common approach is known as Field-Oriented Control (FOC). This technique involves transforming the three-phase currents and voltages into a rotating reference frame, commonly referred to as the "dq" frame. In this frame, the torque/speed and flux components are decoupled, allowing for independent control, by doing so, the motor's speed can be regulated accurately and maintain a constant flux which is crucial to ensure optimal motor performance and efficiency. The research focused on studying and simulating a field-oriented control system using fuzzy control techniques for an induction motor. The aim was to address the issue of parameter variations, particularly the change in rotor resistance during motor operation, which causes the control system to deviate from the desired direction. This deviation implies to an increase in the magnetic flux value, specifically the flux component on the q-axis. By employing fuzzy logic techniques to regulate flux vector's components in the dq frame, this problem was successfully resolved, ensuring that the magnetic flux value remains within the nominal limits. To enhance the control system's performance, response speed, and efficiency of the motor, sliding mode controllers were implemented to regulate the current in the inner loop. The simulation results demonstrated the proficiency of the proposed methodology.

Keywords

Induction Motor, Vector Control, Fuzzy Logic Control, Sliding Mode

1. Introduction

An electrical motor transforms electrical input into mechanical output, providing energy to diverse kinds of loads. AC motors are classified into synchronous, induction, and specialized motors. Among them, three-phase induction motors find extensive application in industrial settings, due to their self-starting capability. The designation of a three-phase induction motor indicates that the rotor current is induced by magnetic fields rather than direct electrical connections. This design allows for the production of a rotating magnetic field, eliminating the need for electrical connections to the rotor.

Induction motors have many advantages, the most important of which are [1] [2] [3] [4] [5]:

- Self-starting.
- Explosion-proof (because to the lack of spark-producing brushes, commutators, or slip rings).
- Robust in its design.
- Inexpensive.
- Easier in maintaining up.

There are various methods available for controlling induction motors. Among these methods, V/f control stands as the oldest technique. However, this approach demonstrates limited dynamic performance due to its inability to achieve synchronized control over the amplitude, frequency, and phase of the stator current in induction motor drives. An alternative choice is vector control, widely recognized as field-oriented control [FOC], which offers superior dynamic performance despite the added complexities compared to scalar control systems. [5] [6] [7] [8]

FOC control of an induction motor can be likened to regulating a DC motor with separate excitation. In this comparison, the voltage vector applied to the motor is divided into two components. The first component is responsible for governing the magnetic flux, while the second component is responsible for controlling the motor's torque, thereby enabling adjustments to its speed.

Here, great importance should be given to the transition from a reference frame with three axes (abc) to a reference frame with only two axes (d, q). The rotation speed of the two axes must be calculated correctly in order to obtain the three components of the voltage vector applied to the motor for the sake of achieve robust dynamic performance and stability of the motor while maintaining at the appropriate flux value.

The main objective of using induction motor control systems, in addition to regulating the speed, is to maintain a constant value of the magnetic flux in the air gap, which allows the possibility of applying the full load of the machine on the one hand, and the absence of magnetic saturation on the other hand.

The importance of the research is in presenting an advanced driving system using Fuzzy logic technique, in which the rotor flux vector is regulated directly, as this contributes to reducing the effect of changing the rotor resistance value, which causes magnetic saturation. In the proposed drive system, the electric angular velocity (the voltage-frequency value (w_s)) is treated as a third control signal in addition to the two components of the voltage vector (V_d, V_q), where (w_s)

is the control effort for regulate the flux on q-axis. Also, a sliding mode technique was used to regulate currents in inner loop for the sake of enhancing the performance and stability of the motor despite the presence of external disturbances or change in parameter values.

The design of vector control for induction motor utilizing different PI controllers was described in depth in [9]. The use of anti-windup PI controllers helps to avoid deep saturation. As a result, speed and flux reactions respond more quickly and the system responds more dynamically. For the purpose of creating gating pulses to drive the induction motor, SVPWM is applied, which increases DC bus Utilization and removes harmonics. The speed of d, q reference frame (voltage frequency) was calculated according to the traditional relation of FOC control, the impact of parameter variations on motor performance was not assessed.

In [10], researchers introduced a control approach for regulating speed and flux in an induction motor drive, employing an adaptive back-stepping controller. This adaptive technique effectively addresses the system's nonlinearities in the control rule. The rotor flux is monitored using an adaptive sliding rotor flux observer, which includes an adaptive rotor resistance mechanism. The estimation of the rotor resistance is crucial for determining the applied voltage frequency to the motor.

The results of simulations and tests on a squirrel cage induction motor showed the viability and efficacy of the suggested course of action in regulating the speed and overcoming the load torque, as well as regulating the magnetic flux with a small error value when there is a change in the motor parameters (rotor resistance).

A hybrid PI-Fuzzy controller was used in [11]. To resolve the shortcomings of Fuzzy logic controller which related to the steady state error and PI controller, Integration of fuzzy logic and PI controller is initially researched for the speed control of induction motors (overshoot and undershoot). Simulation results demonstrated that hybrid controller offered better performance in terms of rise time, settling time, overshoot, and undershoot. The traditional equation was relied upon to calculate the voltages frequency, without the presence of an observer mechanism for any of resistance or flux the rotor.

Direct Field Oriented Control to control the speed was discussed in [12], the application of fuzzy logic was employed to regulate the speed of an induction motor, aiming to optimize torque while minimizing energy wastage. The fuzzy logic-based controller was implemented utilizing the FOC method, which allows for improved torque control and exceptional dynamic efficiency. The motor model was developed, and appropriate membership functions were selected based on the motor model's parameters to ensure optimal performance.

The estimation of the rotor flux was conducted utilizing an open-loop model, and the rotor flux angle needed to calculate the angle of the voltage vector supplied to the motor was then calculated.

The purpose of paper [13] was to introduce a novel method for controlling an induction motor with type-1 fuzzy logic. To retain the decoupling and solve the sensitivity to parametric variations issue, a new block control had been installed in place of the field oriented one. The inputs of the proposed fuzzy controller are: electromagnetic torque, rotor flux and rotational speed, while the outputs are frequency and stator voltage vector components V_{sd} and V_{sq}. The comparison was conducted between a fuzzy vector controller and a traditional vector controller. The simulation outcomes indicated that the proposed fuzzy controller achieves quicker speed regulation settling time and preserves the magnetic flux within optimal levels, even in the presence of variations in the rotor resistance value. However, it was observed that the currents applied to the motor exhibited a higher level of harmonic content.

In the previously mentioned studies, the focus was on simulating the motor's vector control system and addressing the issue of pulse width modulation, or estimating the rotor flux to complete the control system, while other research focused on improving the time response characteristics in terms of rise and stability time or clarifying the effect of the control system on the harmonic distortion content, without giving due importance to the issue of the occurrence of magnetic saturation when the value of the rotor resistance changes when applying the traditional winding vector control system, or improving the motor performance by adding an internal control loop to regulate the currents.

The research aims to develop a simplified vector control system for an induction motor based on the hybrid fuzzy PI logic technique for the sake of Enhancing the performance and stability of the motor despite the presence of external disturbances or change in the parameter values.

This issue can be done by providing a special controller to obtain the voltage-frequency value (w_s) and dispensing with the open-loop model used in traditional vector control for its computation, which tested by using MATLAB program [License No: 40692431].

This is expected to achieve greater motor performance and stability while maintaining rotor flux within the nominal values, also to have the ability to simplify the flux estimation process without the need for highly complex estimators.

2. Induction Motor Dynamic and Control Methods

2.1. The Dynamic Representation of the Induction Motor

The mathematical representation of a 3-phase induction motor in a dq frame is [10]:

$$\frac{\mathrm{d}i_{sd}}{\mathrm{d}t} = -a_5 i_{sd} + \omega_s i_{sq} + a_3 \Phi_{rd} + a_4 \omega \Phi_{rq} + b v_{sd} \tag{1}$$

$$\frac{\mathrm{d}i_{sq}}{\mathrm{d}t} = -\omega_s i_{sd} - a_5 i_{sq} - a_4 \omega \Phi_{rd} + a_3 \Phi_{rq} + b v_{sq} \tag{2}$$

$$\frac{\mathrm{d}\Phi_{rd}}{\mathrm{d}t} = a_2 i_{sd} - a_1 \Phi_{rd} + (\omega_s - \omega) \Phi_{rq} \tag{3}$$

$$\frac{\mathrm{d}\Phi_{rq}}{\mathrm{d}t} = a_2 i_{sq} - (\omega_s - \omega)\Phi_{rd} - a_1\Phi_{rq} \tag{4}$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{p}{J}\left(G\Phi_{rd} i_{sq} - G\Phi_{rq} i_{sd} - T_d\right) - \frac{f}{J}\omega \tag{5}$$

where:

$$a_1 = \frac{R_r}{L_r},\ a_2 = \frac{L_m R_r}{L_r},\ a_3 = \frac{L_m R_r}{\sigma L_s L_r^2},\ a_4 = \frac{L_m}{\sigma L_s L_r},\ a_5 = \frac{L_r^2 R_s + L_m^2 R_r}{\sigma L_s L_r^2},$$

$$b = \frac{1}{\sigma L_s},\ G = \frac{P L_m}{L_r},\ \sigma = 1 - \frac{L_m^2}{L_s L_r},\ \omega = P\Omega$$

where:

ω_s : synchronous speed

ω : electric speed

Ω: mechanical speed

v_{sq}, v_{sd} : Elements of stator voltage vector

i_{sq}, i_{sd} : Elements of stator current vector

Φ_{rq}, Φ_{rd} : Elements of rotor flux vector

P: pole pairs

L_m : magnetizing inductance

L_s : stator inductance

L_r : rotor inductance

J: rotor inertia

f: friction coefficient

T_d : load torque.

2.2. Field Oriented Control

The primary goal of FOC methodology is to make the relationship between the electromagnetic torque and flux linear, as is the case in DC motors with separate excitation, in order to open up the potential of decoupling flux control from torque\speed control.

In order to achieve decoupling, the rotor flux vector is aligned with the d-axis, thereby ensuring that the rotor flux component Qrq remains consistently zero. This approach allows for independent control and manipulation of the rotor flux and the torque components in the motor, then [9] [10] [11]:

$$\underline{\Phi}_r = \Phi_{rd} \tag{6}$$

$$\Phi_{rq} = 0 \tag{7}$$

$$\frac{\mathrm{d}\Phi_{rq}}{\mathrm{d}t} = 0 \tag{8}$$

Based on the above, two outer control loops are used to implement the FOC scheme: one controls the rotor flux, and the other the motor's angular velocity. The motor speed is measured and the slip angular frequency is computed, then the sum of them determines the angle of the applied voltage vector.

2.3. FOC Control Using PI Controller

PI controller is a simply and easily, it is the most frequently used in driving the electrical machine and control systems. However, they have certain drawbacks include their sensitivity to changing system parameters, which can lead to unpredictable results. For the application of these controls, it is necessary to have a linearized model of the system.

Depending on Equations (1) and (3), it is possible, using Laplace transforms, to represent the induction motor model according to the d-axis, as in **Figure 1**, taking into account the neglect of internal disturbances. It is also possible with the same steps and by relying on Equations (2) and (5) the depiction of the induction motor model according to the q-axis as in **Figure 2**, taking into account the neglect of internal disturbances.

So, the controlling of Φ_{rd} is done through V_{sd} and the controlling of the speed is done through V_{sq}.

Relationship (4) can be set up to be as follows in order to obtain ω_s:

$$\omega_s = \omega + i_{sq} a_2 / \Phi_{rd} \tag{9}$$

Figure 3 illustrates the block diagram of the PI control system.

2.4. FOC Control Using Fuzzy Logic Controller

Fuzzy logic is a subdivision of artificial intelligence that emulates human thinking and endeavors to express thoughts using linguistic terms to facilitate decision-making. Its objective is to develop intelligent technologies that closely resemble human cognition.

In our system we added a special controller to enhance a simplified vector control system for an induction motor based on the hybrid fuzzy PI logic technique in order to improve the performance and stability of the motor despite the presence of external disturbances or change in the parameter values, rather than open-loop model closed-loop model used to obtain the voltage-frequency value (w_s) as shows in **Figure 4**.

The fuzzy logic controller is distinguished from other controllers by the ability to deal with the non-linear system, and its performance is less affected by the differences in the system parameters. Moreover, fuzzy techniques use a grammar base that is designed by taking advantage of qualitative aspects of the system and expert knowledge. These features eliminate the need for an accurate mathematical model of the studied system [12] [13] [14].

Figure 5 shows the structure of the proposed Fuzzy logic controller, while **Figure 6** shows the membership functions of both the input and output signal of the fuzzy controller shown in **Figure 5**.

Figure 4 presents the block diagram of the Fuzzy logic control system implementation.

Table 1 shows the experience rules for both the speed and flux regulator on the d-axis, while **Table 2** shows the experience rules for flux regulation on the q-axis.

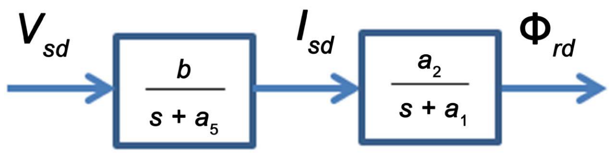

Figure 1. The motor's block diagram in relation to the d-axis.

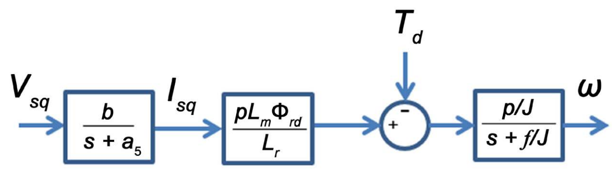

Figure 2. The motor's block diagram in relation to the q-axis.

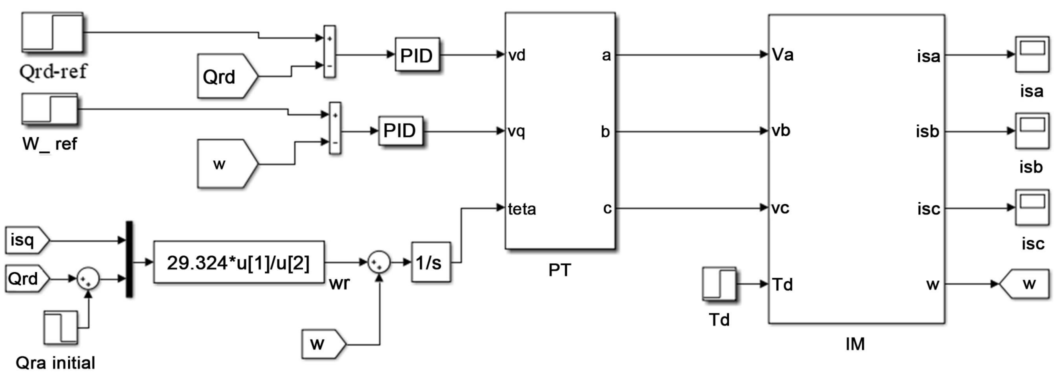

Figure 3. The block diagram of PI control system.

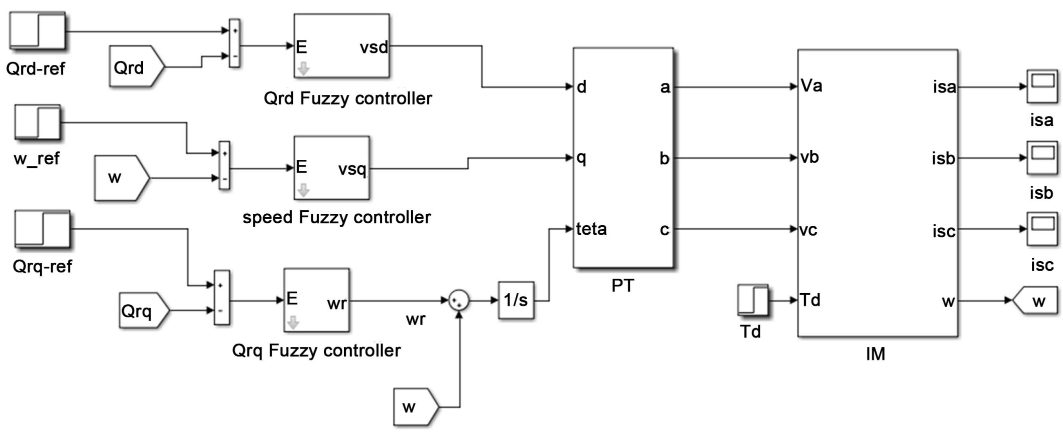

Figure 4. The block diagram of the Fuzzy logic control system.

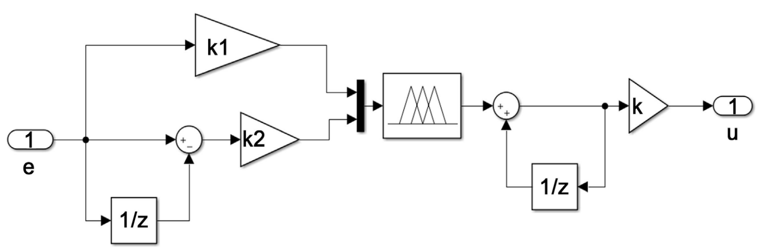

Figure 5. Structure of the fuzzy controller.

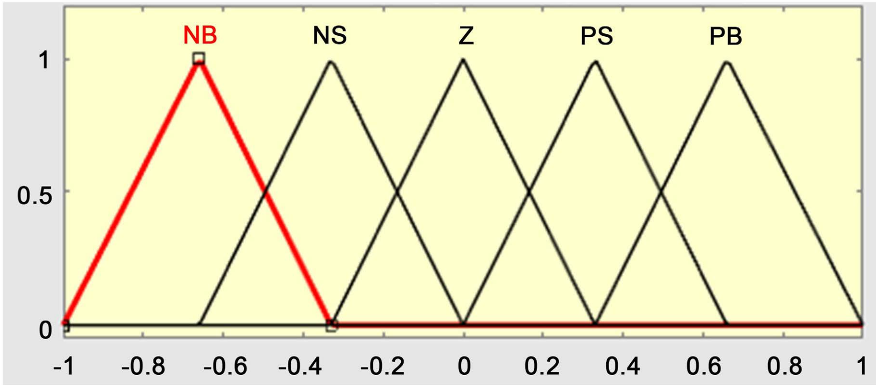

Figure 6. The membership functions of input and output signal of the fuzzy controller.

Table 1. Rule base for speed and Qrd fuzzy controllers.

Δe/e	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

Table 2. Rule base for Qrq fuzzy controller.

Δe/e	NB	NS	Z	PS	PB
NB	PB	PB	PB	PM	Z
NS	PB	PS	PS	Z	NS
Z	PB	PS	Z	NS	NB
PS	PS	Z	NS	NM	NB
PB	Z	NS	NB	NB	NB

2.5. Sliding Mode Controller of Current

The sliding mode was studied for the first time in the former Soviet Union, it is characterized by its durability, its ability to resist changes in machine parameters, its relative ease of application, and its high dynamic performance [15] [16] [17].

- **regulation i_{sd} current**

The switching surface of i_{sd} current-regulating loop can be written as:

$$S_{id} = I_{sd-ref} - I_{sd} \tag{10}$$

By deriving the previous relationship, we find:

$$\dot{S}_{id} = \frac{\mathrm{d}I_{sd-ref}}{\mathrm{d}t} - \frac{\mathrm{d}I_{sd}}{\mathrm{d}t} \tag{11}$$

Based on **Figure 1**, we get:

$$\dot{S}_{id} = \frac{\mathrm{d}I_{sd-ref}}{\mathrm{d}t} + a_5 i_{sd} - bV_{sd} \tag{12}$$

In order for the current to be compelled to move toward the sliding surface, $\dot{S}_{id}$ must be compensated for by an appropriate law of attraction:

$$\dot{S}_{id} = -K_1 \operatorname{sig} S_{id} - Q_1 S_{id} \tag{13}$$

By equating relations (18) and (14), we get:

$$V_{sd} = \frac{1}{b}\left(\frac{\mathrm{d}I_{sd-ref}}{\mathrm{d}t} + a_5 i_{sd} + K_1 \operatorname{sig} S_{id} + Q_1 S_{id}\right) \tag{14}$$

- **regulation i_{sq} current**

The switching surface of i_{sq} current-regulating loop can be written as:

$$S_{iq} = I_{sq-ref} - I_{sq} \tag{15}$$

By deriving the previous relationship, we find:

$$\dot{S}_{iq} = \frac{\mathrm{d}I_{sq-ref}}{\mathrm{d}t} - \frac{\mathrm{d}I_{sq}}{\mathrm{d}t} \tag{16}$$

Based on Figure 7 we get:

$$\dot{S}_{iq} = \frac{\mathrm{d}I_{sq-ref}}{\mathrm{d}t} + a_5 i_{sq} - bV_{sq} \tag{17}$$

In order for the current to be compelled to move toward the sliding surface, $\dot{S}_{id}$ must be compensated for by an appropriate law of attraction:

$$\dot{S}_{iq} = -K_2 \operatorname{sig} S_{iq} - Q_2 S_{iq} \tag{18}$$

By equating relations (18) and (14), we get:

$$V_{sq} = \frac{1}{b}\left(\frac{\mathrm{d}I_{sq-ref}}{\mathrm{d}t} + a_5 i_{sq} + K_2 \operatorname{sig} S_{iq} + Q_2 S_{iq}\right) \tag{19}$$

Figure 7 illustrates the block diagram of the Fuzzy logic sliding mode (SM) control system.

3. Simulation Results

The motor's rotational velocity is controlled at 282.7 rad/sec, and a load torque is imposed after 1 second, while maintaining the motor parameters at their designated values.

Figure 8 illustrates the motor's response to speed regulation, Figure 9 demonstrates the motor's response to magnetic flux Φ_{rd} regulation, and Figure 10 exhibits the motor's response to magnetic flux Φ_{rq} regulation.

Figure 8 shows the efficiency of the Fuzzy SM control system compared to the other two systems in terms of tracking accuracy and rapid response, as well as in terms of the motor's ability to overcome the applied load torque, as it is noted that the speed decreases to 253 rad/sec for Fuzzy controller and to 278 rad/sec for PI controller and Fuzzy SM controller, but it returns to the reference signal in shorter time.

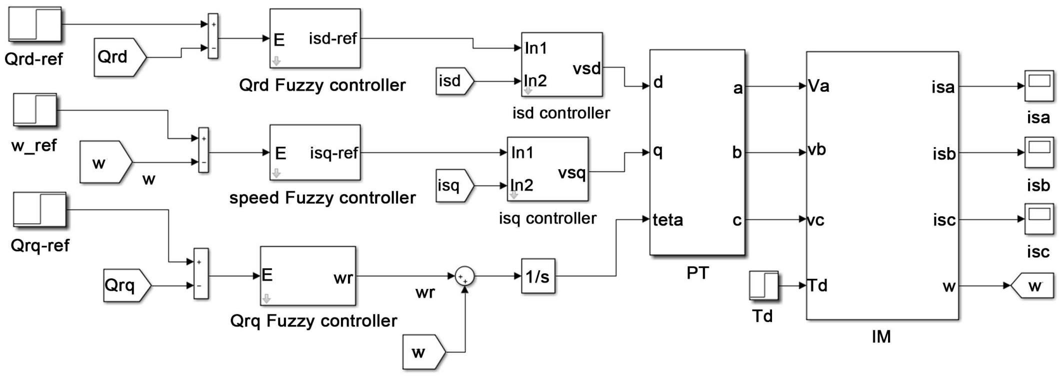

Figure 7. The block diagram of the Fuzzy logic SM control system.

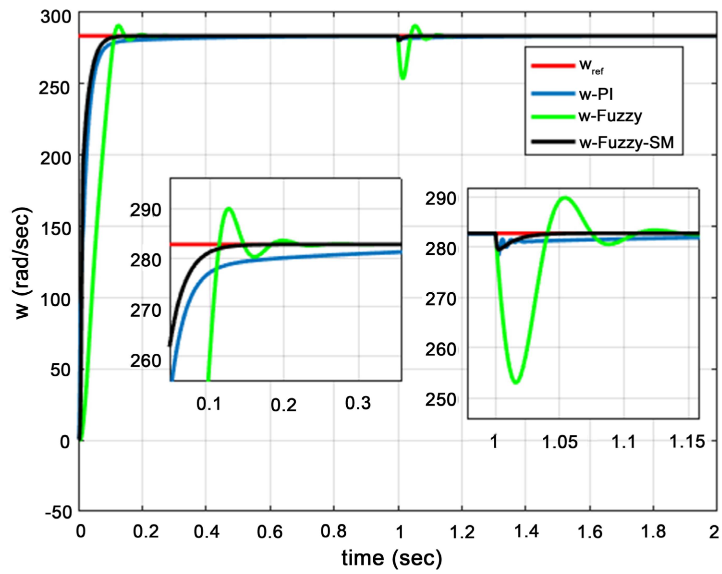

Figure 8. Shows the response of the motor to speed regulation.

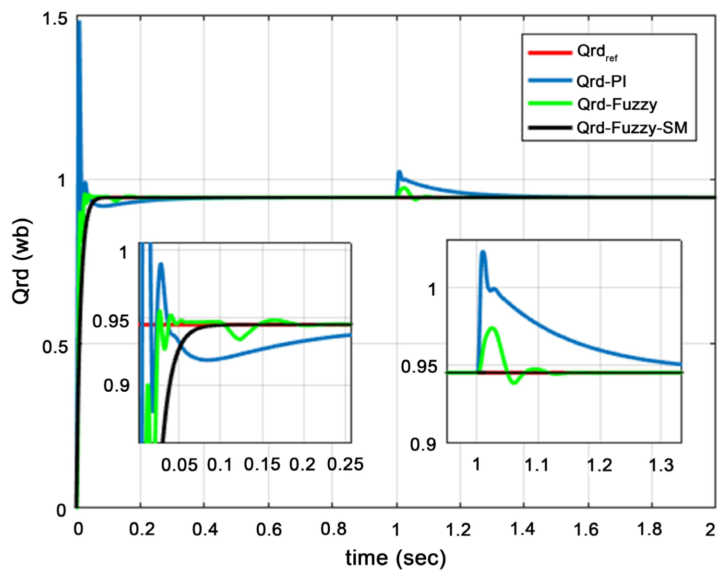

Figure 9. The response of regulating the magnetic flux Φ_{rd}.

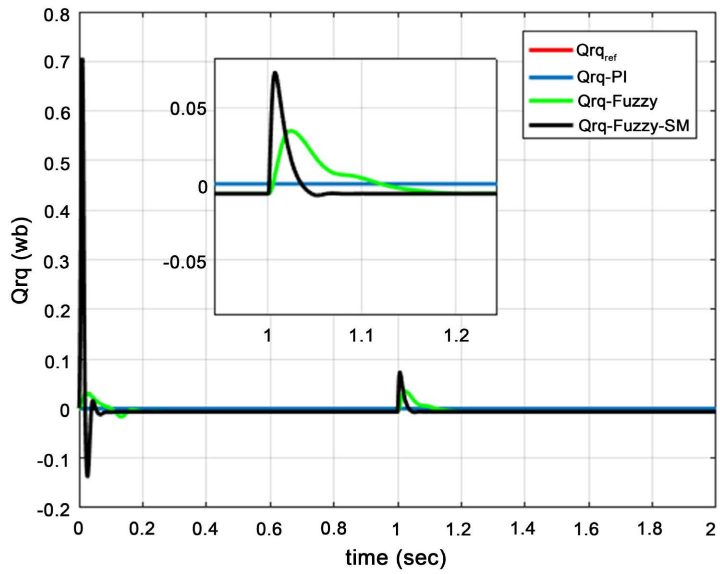

Figure 10. The response of regulating the magnetic flux Φ_{rq}.

In order to regulate the two components of the rotor magnetic flux, **Figure 8** and **Figure 9** also show the efficiency of the Fuzzy SM control system in tracking accuracy and response speed in both the motor's starting and load torque application states, where it is always less overshoot and less settling time.

So, we can say here that both the traditional (PI controllers) and proposed (Fuzzy SMC) control methodologies achieve the desired goal in terms of regulating the speed at the required reference value and the flux at the nominal value in the steady state, with the proposed methodology superior in transient case, taking into account that the comparison was made for nominal values of motor's parameters, but what if the values of these parameters change, this is what will be discussed in the following paragraph.

In the next paragraph, the effectiveness of the control systems is retested for an increase in the rotor resistance value of 40% and an increase in the stator resistance value of 20%.

Figure 11 displays the motor's response to speed regulation, while **Figure 12** exhibits the response of magnetic flux Φ_{rd} regulation. Lastly, **Figure 13** demonstrates the motor's response to magnetic flux Φ_{rq} regulation.

Figure 11 shows the efficiency of the Fuzzy SM control system compared to the other two systems in terms of tracking accuracy and fast response, as well as in terms of the ability of the motor to overcome the applied load torque, despite the change in the motor parameters.

In order to regulate the two components of the magnetic flux of the rotor, **Figure 12** also shows the efficiency of Fuzzy SM control system in tracking accuracy and response speed in both cases of application of motor torque and load, where it is always less than overshoot and less settle time, noting that all control systems achieve error static is equal to zero, while it is noted from **Figure 13** that the flux Φ_{rq} is not equal to zero, and reaches a value of 0.36 wb, which means

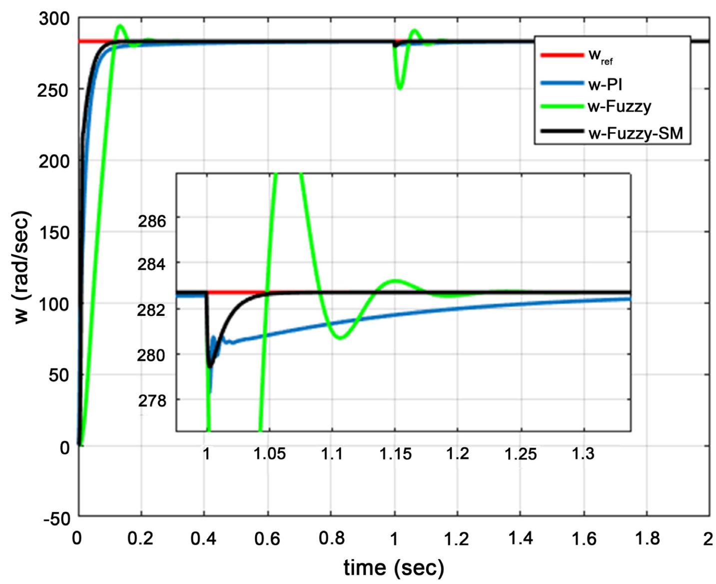

Figure 11. The response of regulating the speed after changing motor's parameters.

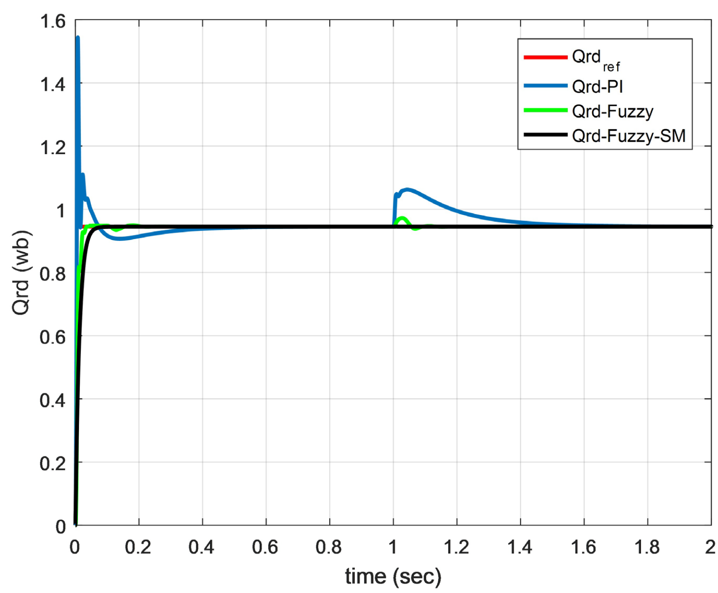

Figure 12. The response of regulating Φ_{rd} after changing motor's parameters.

magnetic saturation, an increase in thermal heating and a decrease in motor efficiency.

As a result of the previous discussion, it can be said that the proposed methodology achieves the desired goal, as the speed is precisely regulated while the flux values are maintained within the nominal limits despite the change in the motor parameter values.

4. Conclusions

In the realm of electrical motor control, achieving precise regulation of torque

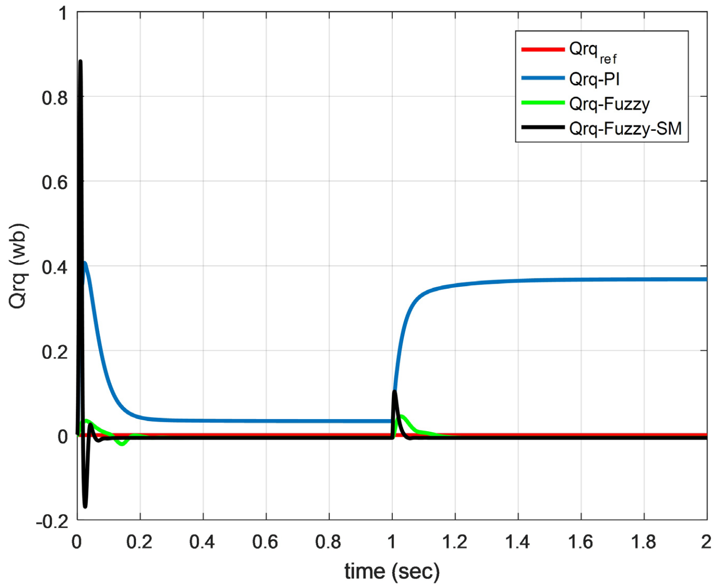

Figure 13. The response of regulating Φ_{rq} after changing motor's parameters.

and flux is imperative for optimal performance. This study delves into the application of a field-oriented control system for an induction motor, integrating fuzzy control techniques. The primary focus lies in addressing the formidable challenge posed by parameter variations, particularly fluctuations in rotor resistance during motor operation. Such variations can lead to deviations in the control system, manifesting as undesired increases in magnetic flux, with the flux component on the q-axis deviating from its intended zero value.

To surmount this challenge, the research employs fuzzy logic techniques to regulate the components of the flux vector in the dq frame. This nuanced approach proves to be highly effective in mitigating deviations and ensuring that the magnetic flux remains within the specified nominal values. Beyond addressing parameter variations, the study also seeks to enhance the overall performance of the control system, emphasizing response speed and motor efficiency, especially in transient scenarios.

To bolster the control system's robustness and adaptability, sliding mode controllers are introduced to govern the current in the inner loop of the control system. This methodology, combining fuzzy control for flux regulation and sliding mode controllers for inner loop current regulation, is meticulously simulated to validate its effectiveness. The results of these simulations unequivocally demonstrate the prowess of this proposed control strategy in achieving precise and stable motor control, showcasing improved performance and efficiency in dynamic operating conditions.

In a future work, we can focus on studying and improving the pulse width modulation phase using direct drive methods, or go towards estimating the rotor flux using sliding mode observe (SMO), as this is necessary to complement the vector control system.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Horch, M., Boumédiène, A. and Baghli, L. (2019) Direct Torque Control of Induction Machine Drive Based on Sliding Mode Controller and a Stator Resistance Compensator with a New Hybrid Observer. *International Journal of Digital Signals and Smart Systems*, **3**, 60-78. https://doi.org/10.1504/IJDSSS.2019.103384

[2] Diyoke, G.C., Okeke, C. and Aniagwu, U. (2016) Different Methods of Speed Control of Three-Phase Asynchronous Motor. *American Journal of Electrical and Electronic Engineering*, **4**, 62-68.

[3] Chen, M.X. and Zhang, W.D. (2015) H2 Optimal Speed Regulator for Vector-Controlled Induction Motor Drives. *The 27th Chinese Control and Decision Conference* (2015 *CCDC*), Qingdao, 23-25 May 2015, 1233-1236. https://doi.org/10.1109/CCDC.2015.7162106

[4] Sudaryanto, A., *et al.* (2020) Design and Implementation of SVPWM Inverter to Reduce Total Harmonic Distortion (THD) on Three Phase Induction Motor Speed Regulation Using Constant V/F. 2020 3*rd International Seminar on Research of Information Technology and Intelligent Systems* (*ISRITI*), Yogyakarta, 10-11 December 2020, 412-417. https://doi.org/10.1109/ISRITI51436.2020.9315353

[5] Karthik, D. and Chelliah, T.R. (2016) Analysis of Scalar and Vector Control Based Efficiency-Optimized Induction Motors Subjected to Inverter and Sensor Faults. 2016 *International Conference on Advanced Communication Control and Computing Technologies* (*ICACCCT*), Ramanathapuram, 25-27 May 2016, 462-466. https://doi.org/10.1109/ICACCCT.2016.7831682

[6] Liu, P. and Hao, L. (2006) Vector Control-Based Speed Sensorless Control of Induction Motors using Sliding-Mode Controller. 2006 6*th World Congress on Intelligent Control and Automation*, Dalian, 21-23 June 2006, 1942-1946. https://doi.org/10.1109/WCICA.2006.1712695

[7] Bharti, R., Kumar, M. and Prasad, B.M. (2019) V/F Control of Three Phase Induction Motor. 2019 *International Conference on Vision towards Emerging Trends in Communication and Networking* (*ViTECoN*), Vellore, 30-31 March 2019, 1-4. https://doi.org/10.1109/ViTECoN.2019.8899420

[8] Peña, J.M. and Díaz, E.V. (2016) Implementation of V/f Scalar Control for Speed Regulation of a Three-Phase Induction Motor. 2016 *IEEE ANDESCON*, Arequipa, 19-21 October 2016, 1-4. https://doi.org/10.1109/ANDESCON.2016.7836196

[9] Divyasree, P. and Binojkumar, A.C. (2017) Vector Control of Voltage Source Inverter Fed Induction Motor Drive Using Space Vector PWM Technique. 2017 *International Conference on Energy, Communication, Data Analytics and Soft Computing* (*ICECDS*), Chennai, 1-2 August 2017, 2946-2951. https://doi.org/10.1109/ICECDS.2017.8389996

[10] Trabelsi, R., Khedher, A., Mimouni, M.F. and M'sahli, F. (2012) Backstepping Control for an Induction Motor Using an Adaptive Sliding Rotor-Flux Observer. *Electric Power Systems Research*, **93**, 1-15. https://doi.org/10.1016/j.epsr.2012.06.004

[11] Deshpande, G.V. and Sankeshwari, S.S. (2013) Speed Control of Induction Motors Using Hybrid Pi plus Fuzzy Controller. *International Journal of Advances in Engineering & Technology*, **6**, No. 5.

[12] Elabed, H.S., Ali, M.M. and Jamal, S.A. (2013) Indirect Field Oriented Control of Induction Motor (IM) Drive Using Fuzzy Logic Controller (FLC). 2013 *IEEE* 8*th Conference on Industrial Electronics and Applications* (*ICIEA*), Melbourne, 19-21 June 2013, 1914-1917.

[13] Rafa, S., Larabi, A., Barazane, L., Manceur, M., Essounbouli, N. and Hamzaoui, A. (2014) Implementation of a New Fuzzy Vector Control of Induction Motor. *ISA Transactions*, **53**, 744-754. https://doi.org/10.1016/j.isatra.2014.02.005

[14] Uddin, M.N., Radwan, T.S. and Rahman, M.A. (2002) Performances of Fuzzy-Logic-Based Indirect Vector Control for Induction Motor Drive. *IEEE Transactions on Industry Applications*, **38**, 1219-1225. https://doi.org/10.1109/TIA.2002.802990

[15] Parvat, B.J., Jadhav, V.K. and Lokhande, N.N. (2012) Design and Implementation of Sliding Mode Controller for Level Control. *IOSR Journal of Electronics and Communication Engineering* (*IOSR-JECE*), **2**, 51-54.

[16] Sebaaly, F., Vahedi, H., Kanaan, H.Y., Moubayed, N. and Al-Haddad, K. (2016) Design and Implementation of Space Vector Modulation-Based Sliding Mode Control for Grid-Connected 3L-NPC Inverter. *IEEE Transactions on Industrial Electronics*, **63**, 7854-7863. https://doi.org/10.1109/TIE.2016.2563381

[17] Gadgune, S. and Joshi, P.M. (2021) Control of Three-Phase PWM Rectifier as Virtual Synchronous Machine Using an Integral Sliding Mode Controller. *Journal of The Institution of Engineers* (*India*): *Series B*, **102**, 193-201. https://doi.org/10.1007/s40031-020-00523-z