Journal of Optimization of Soft Computing (JOSC)

Vol. 3, Issue 1, pp: (55-62), Spring-2025
Journal homepage: https://sanad.iau.ir/journal/josc

Paper Type (Research paper)

Fuzzy Logic-Based Vector Control Method for Induction Motors

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Article Info

Article History:
Received: 2025/03/15
Revised: 2025/06/08
Accepted: 2025/06/12

DOI:

Keywords:
Fuzzy logic, Speed control, Torque control, Induction motors, Motor performance optimization.

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Abstract

Vector control methods in induction motors based on proportional-integral (PI) and proportional-integral-derivative (PID) controllers with fixed gains are not effective against changes in system parameters, load changes, temperature changes, magnetic saturation, and other disturbances due to their strong dependence on machine parameters.

In vector control systems, motor flux and torque control are performed by determining the currents and spatial angles of the vectors, which are not very accurate due to instantaneous oscillations in the load and changes in rotor resistance. In many industrial applications, the stable and precise performance of these controllers is challenged. To deal with these problems, there is a need for an adaptive control system that can dynamically adjust the controller gains. The use of fuzzy logic controllers (FLC) due to their high flexibility, adaptability to different operating conditions, and improved dynamic response, without the need for a precise mathematical model of the system, can adjust of control strategies based on linguistic rules and fuzzy sets. In this paper, an induction motor indirect vector control method is replaced with a fuzzy logic controller. The results of simulation and evaluation of the method in different conditions show that the use of fuzzy control leads to improved stability, reduced speed, and torque oscillations, reduced system response delay, and increased control accuracy and can be a suitable alternative to classical controllers in industrial applications in systems requiring precise and stable performance.

1. Introduction

AC motor drives require high-efficiency performance due to their numerous industrial applications. In these drives, the motor speed must follow the desired reference speed trajectory with less influence from load changes, parameter changes, and motor model estimation errors. For this purpose, the vector control method was proposed. In this method, the design of an appropriate controller plays a decisive role in the drive performance.

Unfortunately, there are problems such as high sensitivity to machine parameters such as rotor time constant, and the need for accurate flux measurement and estimation in the vector control method.

The fixed-gain PI and PID controllers, which are commonly used in speed control drives, are very sensitive to changes in parameters and load changes, so the parameters of these controllers must be continuously adapted to the prevailing environmental and load conditions. This problem can be solved to some extent by various techniques such as Model Reference Adaptive Control (MRAC)[1][1], Sliding Mode Control (SMC)[2][2], Variable Structure Control (VSC)[3][3], Self-Tuning PI Controllers[4][4] and some other methods.

Controller design in all the above methods requires a more accurate mathematical model of the system, but determining the exact mathematical model of the system

[1] Model Reference Adaptive Control
[2] Sliding-Mode Control
[3] Variable Structure Control
[4] Self - tuning PI controller

is often difficult due to reasons such as uncertain load changes and uncertain changes in parameters due to conditions such as temperature changes and system disturbances [5, 6].
To overcome these problems, fuzzy logic controllers (FLC)[5] can be used [7-10].
In a general comparison between classical PI and PID controllers and adapted fuzzy controllers, the following advantages are observed [11, 12]:
1. These controllers do not require an accurate mathematical model of the system.
2. They are easy to implement in systems with nonlinear and complex behavior.
3. The structure of this type of controllers is based on the linguistic rules common among humans and can be implemented through "IF-Then" statements, which itself expresses the proximity of this logic to life in human societies.
In order to achieve better performance, the indirect vector control method is simulated with the help of a fuzzy controller, and its results are presented.

2. Indirect Vector Control of Induction Motors

The stages of vector control at induction motor by indirect method and by precise tracking of the rotor field are given below [13, 14]:
First step) Sampling of a stator and Calculating the real value of Longer and Transverse Components of Stator current in rotor flow Coordinates:

$$\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{SA} \\ i_{SB} \\ i_{SC} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} = \begin{bmatrix} cos\theta_e & sin\theta_e \\ -sin\theta_e & cos\theta_e \end{bmatrix}\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \quad (2)$$

Second step) Calculate the amount of the rotor flux linkage by estimated $\left|\overline{\psi}_r\right|_{est}$, angular slip angle frequency ω_{sl} , and rotor angle position θ_e . For ω_{sl} :

$$\omega_{sl} = \frac{L_m}{\left|\overline{\psi}_r\right|_{est}} \cdot \left(\frac{R_r}{L_r}\right) i_{qs} \quad (3)$$

$$\theta_e = \int \left(\omega_m + \omega_{sl}\right) dt \quad (4)$$

And for the rotor flux linkage, we can write:

$$\left|\overline{\psi}_r\right|_{est} = \frac{L_m i_{ds}}{1 + T_R S} \quad (5)$$

Third Step) Determine the Reference Current i_{ds}^{*} :
The speed control in this study is below the base speed ω_b . Therefore, i_{ds}^{*} is calculated using the following relationship:

$$i_{ds}^{*} = \frac{\left|\overline{\psi}_r\right|^{*}}{L_m} \quad (6)$$

Where $\left|\overline{\psi}_r\right|^{*}$ is the reference value of the rotor flux space phasor and its nominal value can be obtained through the steady-state model of the induction machine in the constant torque region of the induction machine's speed-torque curve.

Fourth Step) Determine the Reference Current : i_{qs}^{*}
The torque-producing component in an induction motor is the reference current, i_{qs}^{*} , and can be calculated from T_e^{*} as follows:

$$i_{qs}^{*} = \frac{2}{3P} \cdot \frac{L_r}{L_m} \cdot \frac{T_e^{*}}{\left|\overline{\psi}_r\right|_{est}} \quad (7)$$

In Equation (7), T_e^{*} , represents the reference electromagnetic torque, P, denotes the number of pole pairs in the machine, and i_{qs}^{*} corresponds to the reference value of the transverse (quadrature-axis) component of the stator current."

To achieve T_e^{*} , the motor speed is initially sampled. Then, the error between the desired reference speed and the actual motor speed is processed through a proportional-integral (*PI*) speed controller, which generates the reference torque T_e^{*} .

Fifth Step) Converting reference currents i_{ds}^{*} and i_{qs}^{*} into three-phase currents i_a^{*}, i_b^{*}, and i_c^{*} through equations (8) and (9):

$$\begin{bmatrix} i_{ds}^{s*} \\ i_{qs}^{s*} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix}\begin{bmatrix} i_{ds}^{e*} \\ i_{qs}^{e*} \end{bmatrix} \quad (8)$$

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[5] Fuzzy Logic Controller

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ds}^{s*} \\ i_{qs}^{s*} \end{bmatrix} \quad (9)$$

Sixth Step) Applying three-phase reference currents to a current-controlled PWM inverter:
At this stage, the current error resulting from the three-phase reference currents and the sampled currents is applied to a hysteresis controller with a specific hysteresis band to generate the necessary pulses for the inverter.
The general block diagram of indirect control of an induction motor using the FOC method based on the above six steps with Current-controlled VSI voltage source inverter will be as shown in Figure (1).
In this block diagram, the speed controller is of the PI type and its role is to keep the actual speed of the motor equal to the reference speed in both steady-state and transient states with good dynamic response.

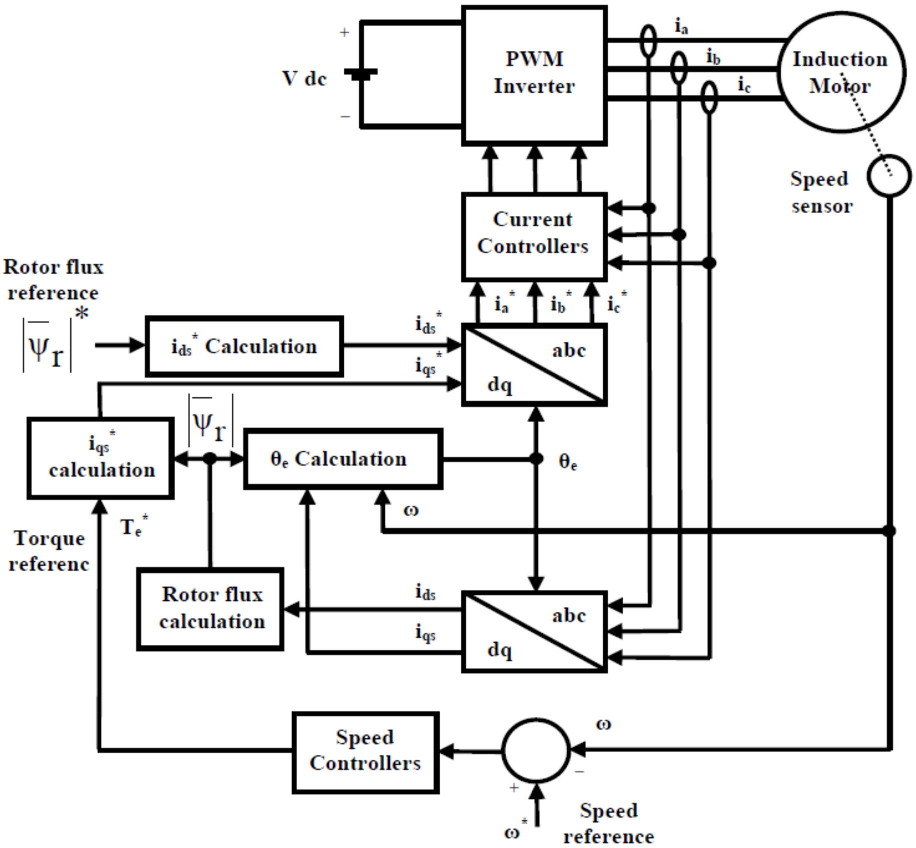


Figure 1. General block diagram of indirect vector control of an induction motor using the FOC method

The curves related to the start-up of a three-phase squirrel cage induction motor sample without load and at a speed lower than the rated speed are shown in Figure (2). As can be seen, the motor speed has reached the reference speed after approximately 1.9s. The results of the study of the dynamic behavior with respect to changes in load torque and reference speed are also shown in Figure (3). In this figure, the reference speed of the running motor has increased to 150 radians/second, which is the rated speed of the motor. Also, after a certain period of time, a load torque of 100 N.m has been applied to the motor.

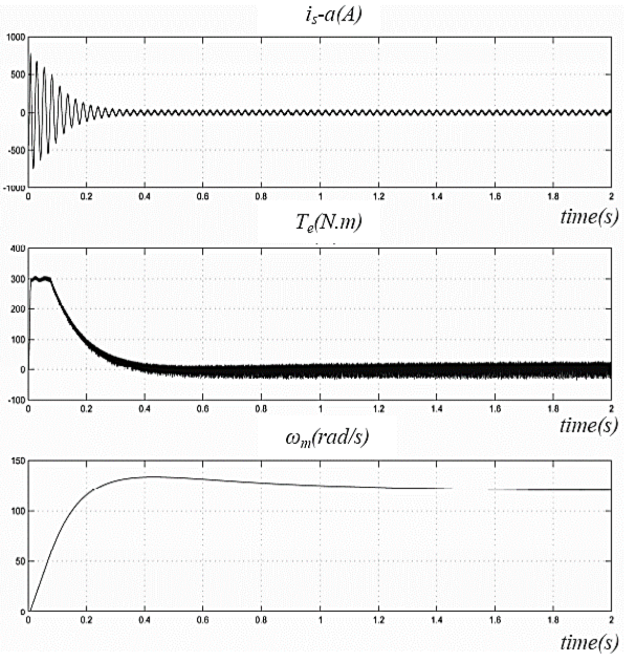


Figure 2. The curves related to the start-up of a three-phase squirrel cage induction motor sample without load and at a speed lower than the rated speed

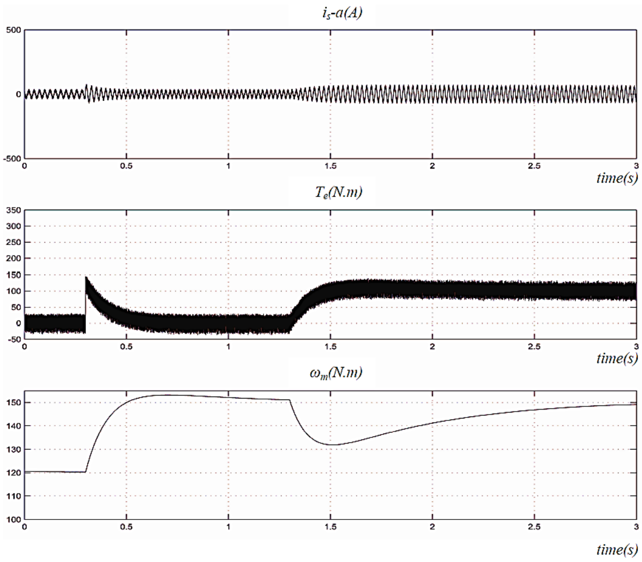


Figure 3. dynamic behavior with respect to changes in load torque and reference speed

3. Fuzzy vector control

Fuzzy logic techniques are of significant use in solving many problems in various sciences [15-17]. These techniques play a particularly important role in the control of engineering processes. Fuzzy logic controllers (FLC) allow the setting of control strategies based on linguistic rules and fuzzy sets, due to their high flexibility, adaptability to different operating conditions, and improved dynamic response, without the need for an accurate mathematical model of the system.

Due to the high sensitivity of the vector control method to machine parameters such as the rotor time constant, the need for accurate flux measurement and estimation, etc., classical PI controllers are not very suitable for this method. For this reason, the controller in the vector control method is replaced by a fuzzy PI controller.

PI controllers are used as one of the most important controllers due to their simple structure and robust performance. The transfer function of these controllers is as follows:

$$G = k_p + \frac{k_i}{s} \qquad (10)$$

The success of a PI controller depends on the appropriate choice of its gains, A and B. In practice, determining the PI gains that will provide optimal efficiency is not a simple task and must be derived with the help of expert experience and based on a number of general rules.

In a speed control system, the goal is to achieve a fast rise time with the least overshoot.

Therefore, the set of rules of the fuzzy control system is obtained empirically and based on the step response. Figure (4) shows a typical response of a process to a step input.

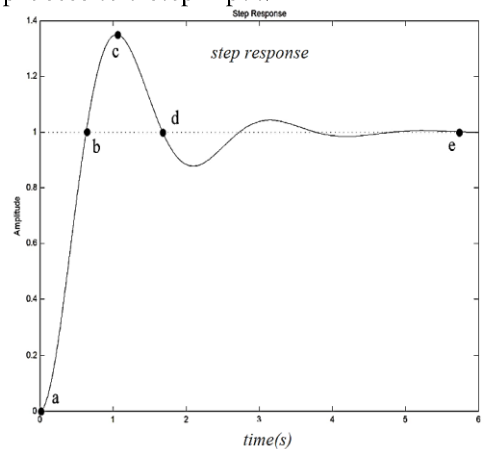


Figure 4 A typical response of a process to a step unit input

Around point "*a*", a large control signal is needed, so we can say: If the error between the reference speed and the actual speed of the motor is large, then k_p should be large and k_i, small.

At points "*b*" and "*d*", the speed changes with respect to time are large and the error between the reference speed and the actual speed is small, so we can write: If the speed changes with respect to time (acceleration) are large and the speed error is small, Then k_p and k_i are both small because large k_p causes large overshoot and large k_i causes the system to oscillate.

At point *e*, the error between the reference speed and the actual speed is zero and the speed changes with respect to time are also almost zero, so we have: If the speed error is zero and the acceleration is also zero, then k_p should be small and k_i, large So that the steady-state error in the system is reduced. A similar behavior to point "a" can also be proposed for "c" point.

Based on the above expressions, the desired fuzzy controller can be prepared for replacement in the vector control method. For this purpose, one fuzzy controller is considered for determining the value and another fuzzy controller is considered for determining.

The fuzzy inference system used in this paper is of the Mamdani type. This system has features such as its efficiency in ambiguous environments, the use of human knowledge, and the ability to find the optimal solution to the problem from a large number of available solutions.

The membership functions used in these controllers are trapezoidal and triangular, which are defined as follows:

$$f(x;\ a,b,c,d) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \dfrac{d-x}{d-c} & c \le x \le d \\ 0 & x \ge d \end{cases} \quad (11)$$

In the above expressions, if b = c, the triangular membership function will be obtained.

The methods used for combining and summing the rules are also in accordance with the following relation expressions:

min	:	And Method
max	:	Or Method
min	:	Implication
max	:	Aggregation
center of gravity	:	Defuzzification

The defuzzification method used is the center of gravity method, which is defined as follows:

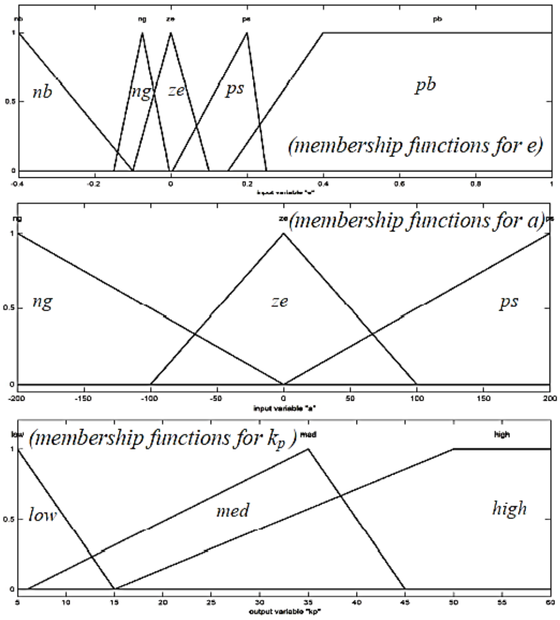
$$output\ i = \frac{\sum_{k=1}^{N} i\mu_{c(k)}(i)}{\sum_{k=1}^{N} \mu_{c(k)}(i)} \quad (12)$$

Where N is the number of fuzzy rules used and $\mu_{c(k)}(i)$ is the membership degree of the output for the *k*th rule.

Figure (5) shows the membership functions and fuzzy rules related to the k_p fuzzy controller. In this figure, the first input of the fuzzy controller is the error of the reference speed and the measured speed, which is represented by "*e*", and the second input is the acceleration or change in speed with respect to time, which is represented by "*a*".

$$e = \omega_{ref} - \omega \quad (13)$$

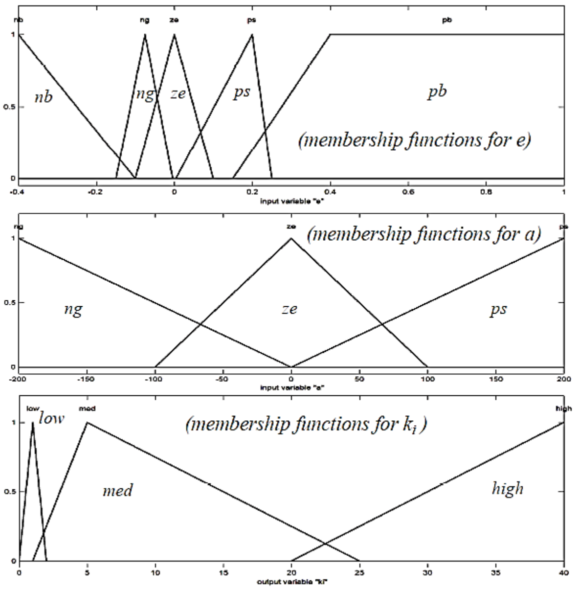
$$a = \frac{d\omega}{dt} \quad (14)$$



a \ e	nb	ng	ze	ps	pb
ng	high	med	low	high	high
ze	high	med	low	med	high
ps	high	high	low	med	high

Figure 5. membership functions and fuzzy rules related to the k_p fuzzy controller

Figure (6) shows the membership functions and fuzzy rules related to the k_i fuzzy controller. The inputs of this controller are the velocity error "*e*" and acceleration "*a*" and its output is the desired numerical value for k_i according to the fuzzy rules used.



a \ e	nb	ng	ze	ps	pb
ng	low	med	high	low	low
ze	low	low	high	low	low
ps	low	low	high	med	low

Figure 6. membership functions and fuzzy rules related to the k_i fuzzy controller

By replacing the block corresponding to the classical controller in the conventional vector control method with the blocks of fuzzy controllers and the necessary sections, the fuzzy vector control method was simulated on a motor with the same specifications and under similar transient conditions. The simulation results are shown in Figures (7), (8), and (9).

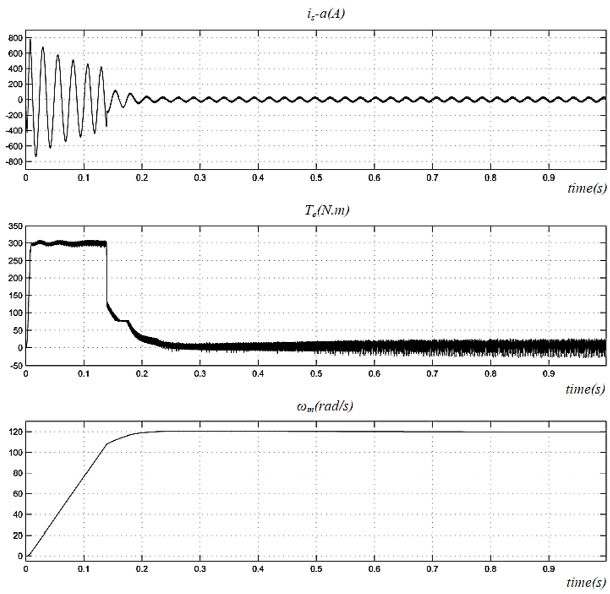


Figure 7 . The curves related to the start-up of a induction motor sample without load and at a speed lower than the rated speed with fuzzy logic controller

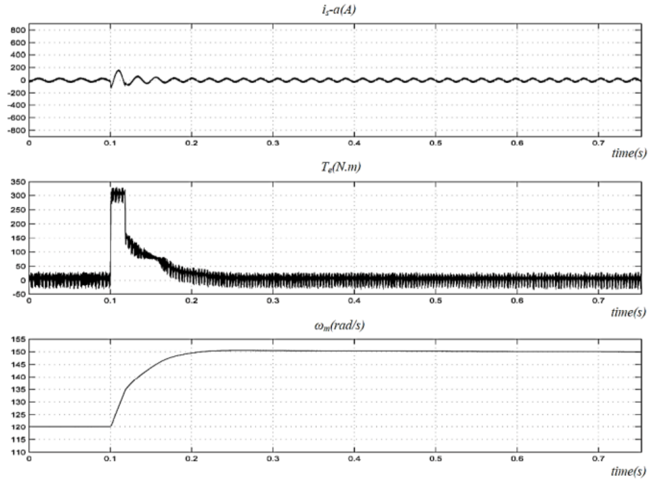


Figure 8. dynamic behavior with respect to the reference speed increase with fuzzy logic controller

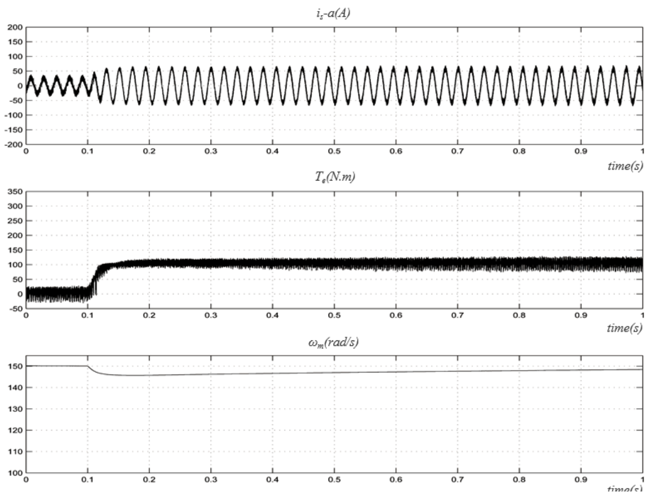


Figure 9. Dynamic behavior with increasing motor load using a fuzzy logic controller

The curves related to the changes in the k_i *and* k_p gains and the ratio of the speed change curve are presented in Figure (10). By observing this figure and the previously presented fuzzy rules, the result of applying fuzzy rules and using fuzzy controllers can be seen.

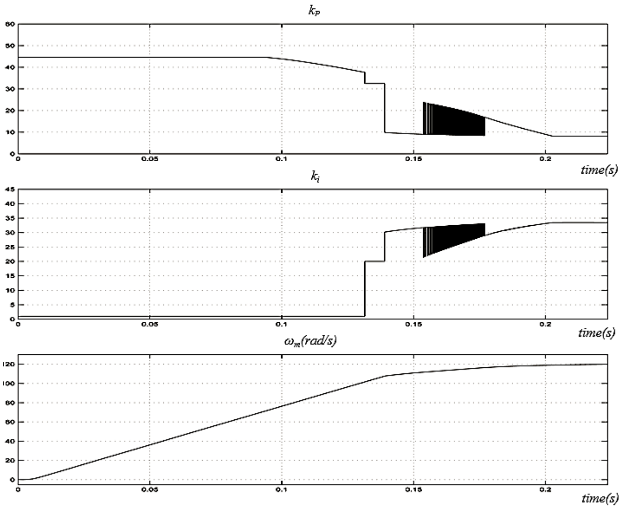


Figure 10.

Figure (11) presents the simultaneous response of the induction motor starting curves using the classical vector control method and the fuzzy vector control method.

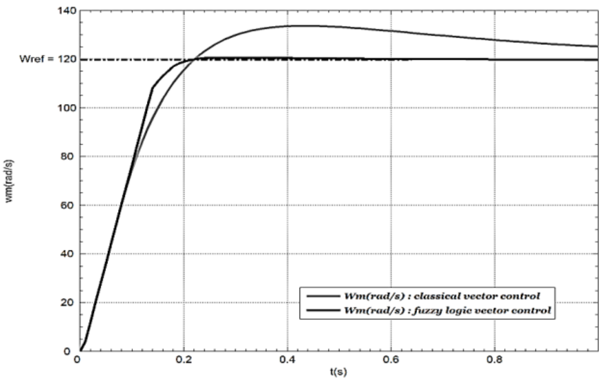


Figure 11.

As can be seen in Figure (11), in the fuzzy method, the speed of the induction motor will reach the desired reference speed in less time. Also, the steady state error in this case is almost zero.

The rate of speed overshoot from the desired reference speed is very small and can be reduced further by better and more appropriate selection of membership functions and their parameters and the use of fuzzy rules.

However, the fuzzy vector control method is one of the reliable application method of speed control of induction motors, which in addition to its simplicity increases the speed and accuracy of the system response under variable environmental conditions and motor parameters. Of course, the practical implementation of this method is possible using fast digital signal processors (DSP[6]).

4. Specifications of the squirrel cage induction motor used in the simulations

The specifications of the induction motor used in the simulations are as follows:

Table 1. Specifications of the induction motor

Parameter	Nominal value
P_n	50 HP (37kW)
V_n	400 V
f_n	50 Hz
N_n	1480 rpm
R_s	0.08233 Ω
L_{ls}	0.724 mH
R'_{rs}	0.0503 Ω
$L_{,lr}$	0.724 mH
L_m	27.11 mH
J	0.37 kg.m^2
f	0.02791 N.m.s
P	2 (Pair of poles)

5. Conclusion

Using the fuzzy vector control method, on the one hand, improves the speed and accuracy of the system's response to sudden changes in the load torque or the applied reference speed, and on the other hand, by using a fuzzy controller instead of a classic controller, the high sensitivity of the control system to changes in environmental conditions and changes in engine parameters is reduced. So that changing the proportional and integral gains of the controller during system operation tries to create a desired response in following the desired reference speed and responding to changes in the load torque in loads that have uncertain behavior.

The fuzzy control method in determining the controller gains compared to fixed-gain controllers includes other advantages such as simplicity, no need for an accurate mathematical model of the system, and faster response to unwanted changes in the load characteristics and engine model.

References

[1] R. Kumar, S. Das, P. Syam, and A. K. Chattopadhyay, "Review on model reference adaptive system for sensorless vector control of induction motor drives," IET Electr Power Appl, vol. 9, no. 7, pp. 496–511, Aug. 2015, doi: 10.1049/iet-epa.2014.0220.

[2] S. Di Gennaro, J. Rivera Dominguez, and M. A. Meza, "Sensorless High Order Sliding Mode Control of Induction Motors With Core Loss," IEEE

[6] Digital signal Processing

Transactions on Industrial Electronics, vol. 61, no. 6, pp. 2678–2689, Jun. 2014, doi: 10.1109/TIE.2013.2276311.

[3] V. V. Alekseev, A. P. Emel'yanov, and A. E. Kozyaruk, "Analysis of the dynamic performance of a variable-frequency induction motor drive using various control structures and algorithms," Russian Electrical Engineering, vol. 87, no. 4, pp. 181–188, Apr. 2016, doi: 10.3103/S1068371216040027.

[4] S. Yaacob and F. A. Mohamed, "Real time self tuning controller for induction motor based on PI method," in SICE '99. Proceedings of the 38th SICE Annual Conference. International Session Papers (IEEE Cat. No.99TH8456), Soc. Instrum. & Control Eng, pp. 909–914. doi: 10.1109/SICE.1999.788670.

[5] F. N. Sarapulov, V. E. Frizen, E. L. Shvydkiy, and I. A. Smol'yanov, "Mathematical Modeling of a Linear-Induction Motor Based on Detailed Equivalent Circuits," Russian Electrical Engineering, vol. 89, no. 4, pp. 270–274, Apr. 2018, doi: 10.3103/S1068371218040119.

[6] M. Konuhova, "Induction Motor Dynamics Regimes: A Comprehensive Study of Mathematical Models and Validation," Applied Sciences, vol. 15, no. 3, p. 1527, Feb. 2025, doi: 10.3390/app15031527.

[7] C. W. de Silva, Intelligent Control. CRC Press, 2018. doi: 10.1201/9780203750513.

[8] Y. A. Almatheel and A. Abdelrahman, "Speed control of DC motor using Fuzzy Logic Controller," in 2017 International Conference on Communication, Control, Computing and Electronics Engineering (ICCCCEE), IEEE, Jan. 2017, pp. 1–8. doi: 10.1109/ICCCCEE.2017.7867673.

[9] L. A. Zadeh, "Fuzzy Logic," 2009, pp. 19–49. doi: 10.1007/978-1-0716-2628-3_234.

[10] A. Sagdatullin, "Improving Automation Control Systems and Advantages of the New Fuzzy Logic Approach to Object Real-Time Process Operation," in 2019 1st International Conference on Control Systems, Mathematical Modelling, Automation and Energy Efficiency (SUMMA), IEEE, Nov. 2019, pp. 256–260. doi: 10.1109/SUMMA48161.2019.8947538.

[11] M. Masoumi, S. Hossani, F. Dehghani, and A. Masoumi, THE CHALLENGES AND ADVANTAGES OF FUZZY SYSTEMS APPLICATIONS A PREPRINT. 2020. doi: 10.13140/RG.2.2.22310.96328.

[12] A. G. M. A. Aziz, A. Y. Abdelaziz, Z. M. Ali, and A. A. Z. Diab, "A Comprehensive Examination of Vector-Controlled Induction Motor Drive Techniques," Energies (Basel), vol. 16, no. 6, p. 2854, Mar. 2023, doi: 10.3390/en16062854.

[13] A. Mishra and P. Choudhary, "Speed control of an induction motor by using indirect vector control method," International Journal of Emerging Technology and Advanced Engineering, vol. 2, no. 12, pp. 144–150, 2012.

[14] G. Satyanarayana, M. Karthikeyan, R. Mahalakshmi, and T. Vandarkuzhali, "Vector Control of an Induction Motor for Speed Regulation," in 2023 7th International Conference on Computing Methodologies and Communication (ICCMC), IEEE, Feb. 2023, pp. 1621–1625. doi: 10.1109/ICCMC56507.2023.10084248.

[15] F. Kiyoumarsi and B. Zamani, "Extending the Lifetime of Wireless Sensor Networks Using Fuzzy Clustering Algorithm Based on Trust Model," Journal of Optimization of Soft Computing (JOSC), vol. 1, no. 1, pp. 12–22, Sep. 2023, doi: 10.82553/josc.2023.14020714783332.

[16] A. Banitalebidehkordi, "Using the fuzzy methods to examine changes in brain lesions and atrophy from MRI images for rapid diagnosis of MS," Journal of Optimization of Soft Computing (JOSC), vol. 2, no. 1, pp. 19–25, Jun. 2024, doi: 10.82553/josc.2024.140302141118861.

[17] A. Jahanbakhsh and M. Jahangiri, "Bridging Technology and Language: Exploring Soft Computing Solutions for Effective English Language Teaching in Iran,"Journal of Optimization of Soft Computing (JOSC), vol. 2, no. 3, pp. 1–6, Nov. 2024, doi: 10.82553/josc.2024.140305181128542.