Adaptive Fuzzy Logic Control for Optimal Speed Regulation in Single Phase Induction Motors

Sumukh M S[a], Sumanth A R[b], Shree Harsha M Kalyanshetti[c], Shiva Prasad A[d] and Suganthi N[e]
Department of Electrical and Electronics Engineering, Dayananda Sagar College of Engineering, Kumaraswamy Layout, Bangalore, Karnataka, India

Keywords: Fuzzy-Logic, Inverter, Error.

Abstract:: The present work addresses the design of an intelligent controller for single-phase induction motors to achieve precise speed regulation. Due to their straightforward design and reliability, these motors are commonly used in both industrial and domestic applications. Traditional control methods often face challenges with nonlinearity and variations in load, which has led to the development of a fuzzy logic-based controller that offers better real- time adaptability. The proposed fuzzy logic controller enhances the motor's responsiveness, reduces overshoot, and minimizes steady-state errors, resulting in smoother and more efficient control. Simulations conducted in MATLAB/Simulink show significant improvements in speed control, stability, and efficiency, highlighting its potential for modern intelligent motor control applications.

1 INTRODUCTION

The necessity of the speed control of induction motor has increased due to increasing application of induction motor, hence finding efficient method to control the motor has become the at most need of the moment. In order to tackle this problem we have designed a robust and efficient control system to address precise speed regulation challenges in single-phase induction motors, which are widely used in both industrial and domestic settings due to their simple design and reliability. Achieving effective speed control however, is challenging because of inherent nonlinearities and load sensitivity. Traditional methods, such as basic PI controllers, often fall short in delivering the required stability and dynamic response. To overcome this, the project integrates fuzzy logic controller, creating a hybrid control system that can dynamically adjust parameters in real time. This integration makes the motor highly responsive to load changes while minimizing issues like overshoot and steady-state errors, leading to smoother, more accurate speed control even under fluctuating loads.

Previous studies have primarily focused on (Abdelwanis et al., 2023) fuzzy logic control using the dspic controller here we are using Atmega and esp32.

Fuzzy logic provides notable benefits compared to traditional control methods, especially when dealing with systems that involve uncertainty, complexity, and imprecision. Unlike conventional control techniques that depend on exact mathematical models, fuzzy logic accommodates "degrees of truth," allowing for more nuanced decision-making based on partial truth values. This flexibility makes it particularly effective in scenarios where human reasoning and expert knowledge play a crucial role. Moreover, fuzzy logic is resilient to noise and disturbances, enabling it to manage input variability without the need for complicated adjustments.

[a] https://orcid.org/0009-0004-2553-3345
[b] https://orcid.org/0009-0009-0151-2909
[c] https://orcid.org/0009-0003-4581-8332
[d] https://orcid.org/0009-0009-9594-2976
[e] https://orcid.org/0000-0003-2222-856X

M S, S., A R, S., M Kalyanshetti, S. H., A, S. P. and N, S.
Adaptive Fuzzy Logic Control for Optimal Speed Regulation in Single Phase Induction Motors.
DOI: 10.5220/0013652800004639
In *Proceedings of the 2nd International Conference on Intelligent and Sustainable Power and Energy Systems (ISPES 2024)*, pages 178-184
ISBN: 978-989-758-756-6

It also facilitates smooth, gradual transitions between states, which is particularly useful in applications that require fine-tuned control, such as regulating temperature or speed. The straightforward design of fuzzy systems and their wide-ranging applicability from consumer electronics to automotive systems further highlight their versatility. The adaptability, robustness, and simplicity of fuzzy logic position it as a strong alternative and complement to traditional methods in various practical applications.
The system also utilizes IGBTs, providing efficient and rapid switching from a DC source, which reduces power losses and enhances overall system performance. MATLAB/Simulink simulations confirm improvements in speed control, stability, and energy efficiency. By allowing real-time adjustments, this fuzzy logic-based controller maintains stable motor performance amid unpredictable load changes, making it especially useful in industrial contexts. This approach not only extends motor life and reduces mechanical stress but also optimizes power utilization, offering practical solutions for advancing motor control. The design of fuzzy membership functions, and rules were made by referring (Alwadie, 2018) and (El Ouanjli et al., 2019a), in the hardware implementation of the controller the tachometer was designed by referring (El Ouanjli et al., 2019b) and lastly the single phase full bridge inverter, gate driving SPWM circuitry were all designed by referring to (Firdaus, 2019). The main reason we have opted for fuzzy control is due to its abilities of providing adaptive control over the speed drive under non-linear conditions caused by sudden application or removal of mechanical shaft loads, unlike the PI or PID controller where one has to determine the controller constants that are prone to vary for non-linear loads. In this project, we have chosen to use V/F as our speed control method, under open-loop conditions this method is used to change the output voltage and frequency of the inverter according to set speed. This method is suitable for changing speed and can obtain high speeds. Simply when speed regulation with varying load regulations will not so much of a concern. In closed loop V/F drives, the torque is constant for a given constant V/F ratio, however, the lower the speed is, the more difficult in keeping the input impedance of the induction motor with change in f. Therefore, to obtain a torque that is constant from low speed to high speed it is necessary to adjust V/F ratio at low speed in accordance to characteristics of the motor. Emerging trends in fuzzy logic-based speed control for single-phase induction motors involve the incorporation of machine learning algorithms to improve adaptability and performance across various operating conditions. `
With the advent of IoT-enabled controllers, there will be opportunities for real-time monitoring and remote optimization of motor functionality. Improvements in hardware, including high-speed processors and affordable sensors, will support quicker and more efficient fuzzy controller implementations. Furthermore, investigating hybrid intelligent systems that combine fuzzy logic with neural networks or evolutionary algorithms could lead to greater precision and resilience in motor control.

2 SYSTEM CONFIGURATION

This block diagram represents a control system for a single-phase induction motor using a fuzzy logic controller. The fuzzy controller adjusts the motor's frequency to control its speed based on the error between reference speed and actual speed. The system employs SPWM (Sinusoidal Pulse Width Modulation) for driving the IGBT gates to control the inverter's output.

2.1 Speed Control of Single-Phase Induction Motors:

Single-phase induction motors (SPIMs) have been widely known due to their simple structure, robustness, and relatively low production costs. However, the variation of parameters of SPIMs and nonlinear behaviour pose big challenges to SPIM control. Moreover, conventional control methods cannot provide stable and efficient operation under variations; thus, there is a great interest in advanced techniques, like FLCs, to maximize the operation of SPIM.

2.2 Fuzzy Logic Control in Motor Drives

Fuzzy logic controllers are robust in handling the nonlinear character of a motor drives, and that property makes them extremely useful for an application like SPIM even without a good mathematical model. That further enhances dynamic response and stability. The tools in MATLAB/Simulink make them a preferred platform for designing and simulating FLCs.

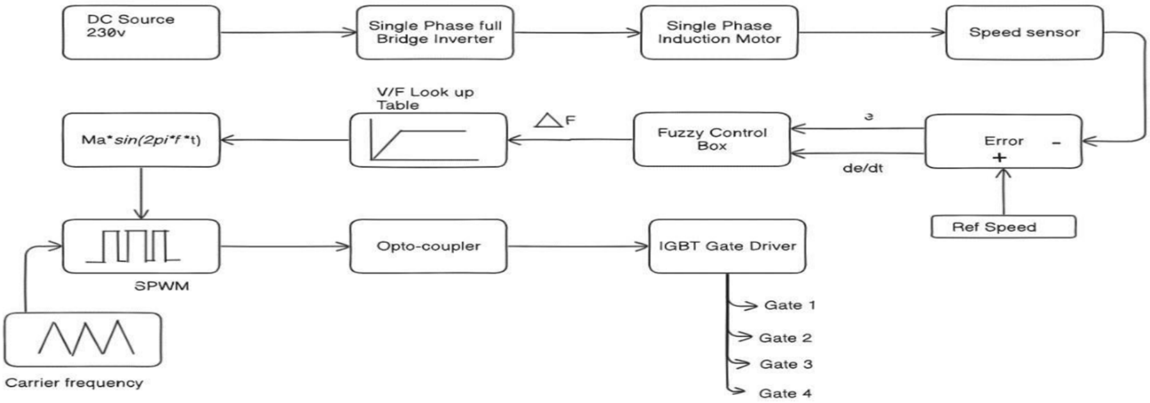

Figure 2.1: Block Diagram.

2.3 Simulation of MATLAB Fuzzy Logic Controllers

MATLAB is a very good tool for implementation of fuzzy logic controller design. MATLAB Fuzzy Logic Toolbox allows a direct way of creating the FIS with predefined membership functions and rule base. Also, upon there are ways to convert the FIS file into the Arduino IDE compatible *.ino* file using online converters. For SPIM-based speed control, FIS can be defined using Mamdani or Sugeno methodologies, while inputs are defined by examples similar to error in speed affecting output signals like voltage. A rule base is generated from expert knowledge in the form of if-then rules for computing the outputs of the controller.

2.4 Role of IGBTs in Motor Drives

IGBTs play a very important role in motor drives. Its high switching time, high efficiency, and high power-handling capabilities improve the use with low losses during switching. Since the losses associated with SPIMs' switching are greatly reduced, more detail can be taken into the control of motor speed and torque. In addition, the implementation of a fuzzy logic controller with IGBTs improves efficiency and quick response.

2.5 Optocoupler

An optocoupler isolates the control circuitry from the high-power section and utilizes light to transmit signals. It ensures safe and noiseless communication between sinusoidal pulse width modulation generator and gate driver.

2.6 Gate Driver

The gate driver boosts the low-power control signals from the optocoupler to effectively drive the gates of the IGBTs. It supplies the necessary power and timing to switch the IGBTs in the inverter, ensuring proper control of the motor. In practical implementation either TLP250 or IR21101 can be used for the building the gate driving circuit, TLP250 is an optocoupler with high frequency operating characteristics that can be controlled by a microcontroller , or the IR21101 can also be used as Mosfet/IGBT gate driver.

3 METHODOLOGY

Our speed control system is based on v/f(voltage/frequency) control of the single-phase induction motor. In v/f control, the applied voltage to the motor is varied in proportion to the frequency of the ac supply to maintain a constant flux in the motor. This approach ensures that the motor operates efficiently across different speeds. Since the system assumes a constant load torque, the torque demand remains steady, and the control focuses on maintaining the appropriate balance between voltage and frequency to achieve the target speed.

3.1 Fuzzy Logic Controller

Fuzzy logic control (FLC) provides a practical method for managing the speed of induction motors, particularly in situations characterized by nonlinear dynamics, varying loads, and uncertain conditions.
In contrast to traditional control techniques that depend on exact mathematical models, FLC mimics

human decision-making through linguistic rules, allowing it to effectively manage the intricate behaviour of motors. The process starts by gathering inputs like the speed error (the difference between the desired speed and the act. The linguistic variables are explained as follows: “NL” is “Negative and Large”, “NM” is “Negative and Medium”, “NS” is “Negative and Small”, “ZZ” is “Zero”, “PS” is “Positive and Small”, “PM” is “Positive and Medium” and “PL” is “Positive and Large”. The membership range is normalized to [-1, 1] by dividing the error of speed before giving it to for the fuzzification, as illustrated in Fig. 3.1.1.Fuzzy rules can be processed based on knowledge about the control process, which is dealt with linguistically in an "if-then" form. It eliminates detailed knowledge of the mathematical model that represents the control plant. Whose first three fuzzy rules are represented as follows: If (speed error is NL), and (speed error variation is NL), Then (frequency change is NL) If (speed error is NM) and (speed error variation is NL) Then (frequency variation is NL) If (speed error is PM) and (speed error variation is NL) Then (frequency variation is NS) as shown in table 3.1.1

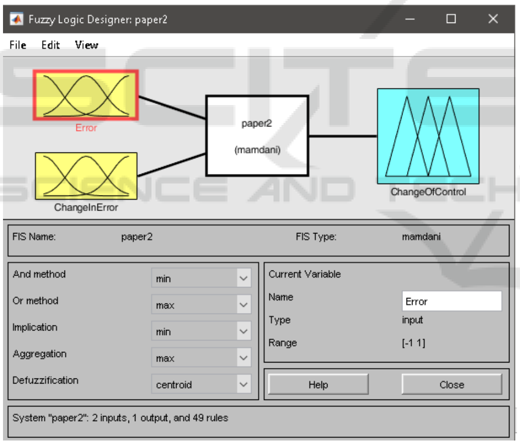

Figure 3.1.1 Fuzzy membership function.

Table 1: Membership Table.

e/de/dt	NL	NM	NS	ZE	PL	PM	PS
NL	NL	NL	NL	NL	ZE	PS	NM
NM	NL	NL	NL	NM	PS	ZE	NS
NS	NL	NL	NM	NS	PM	PS	ZE
ZE	NL	NM	NS	ZE	PL	PM	PS
PL	ZE	PS	PM	PL	PL	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PS	NM	NS	ZE	PS	PL	PL	PM

The surface plot's shape illustrates the fuzzy rules used in the controller, demonstrating its response to various combinations of error and change in error. When both error and change in error are significant, the controller enacts a stronger corrective action, which is depicted by the peaks or dips in the plot. As these values get closer to zero (the centre of the plot), the output also approaches zero, signifying that the system is nearing the desired state. The smooth gradient across the surface showcases the fuzzy controller's gradual response, preventing sudden changes and ensuring a more fluid control action. This visualization is helpful for fine-tuning the fuzzy rules, enabling adjustments for either more aggressive or more gradual responses to error, based on the specific needs of the application.

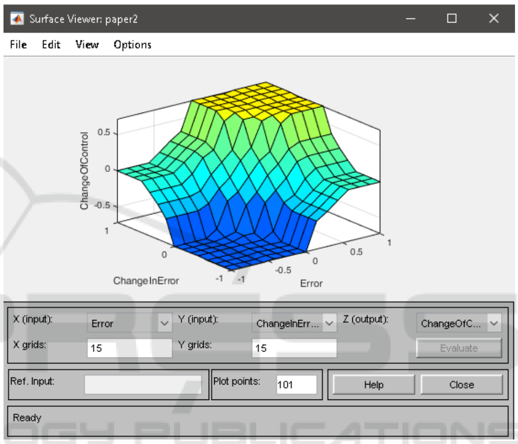

Figure 3.1.2 Fuzzy logic surface plot.

3.2 Working

The 4 IGBTs in our circuit serve as the switches in a full-bridge inverter, converting the DC input voltage (230V) into single-phase AC voltage. This AC voltage, with a frequency controlled by the PWM signals, drives the motor at the desired speed based on the V/f control strategy. In our circuit, the control system is designed to compare the actual speed of the motor with are reference speed. The reference speed is the desired output speed that the motor should be driven to. In the first diagram Fig.3.2.1, we notice the control section of the system. The process of controlling begins with an input reference signal indicating the desired speed of the motor. This signal is compared with the actual speed of the motor to produce an error signal, which indicates a difference in desired and the actual speeds. The error is downscaled for easier processing, probably to get it

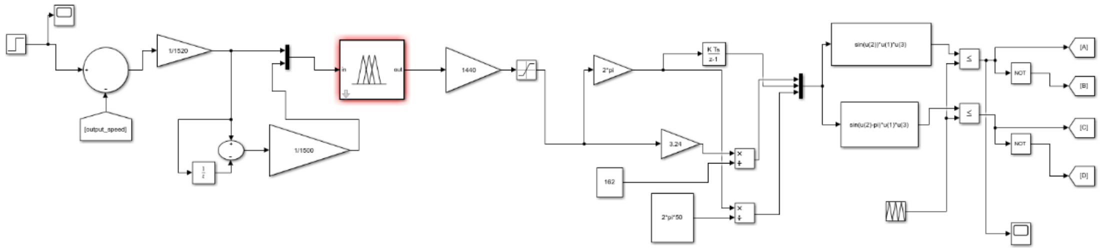

Figure 3.2.1: Fuzzy logic control circuit.

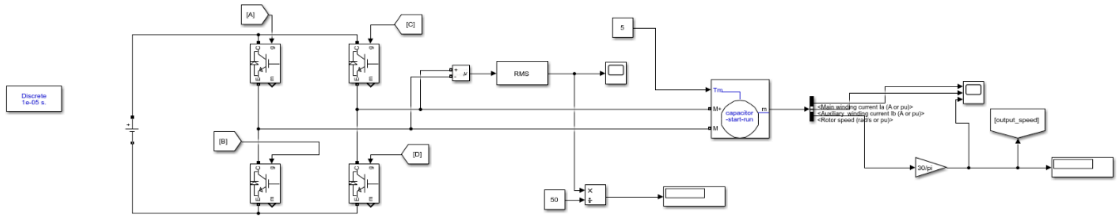

Figure 3.2.2: Motor driving circuit.

within the range expected by the fuzzy logic controller. The fuzzy logic controller uses this error, and possibly the rate of change in error, to determine the necessary adjustments to the control signals. These controller elements, in turn, dynamically adjust the frequency and voltage parameters according to the error to ensure that the V/F ratio achieves the desired motor speed. Signal processing blocks and trigonometric functions further refine the signals to give single phase AC outputs that have been correctly shifted to make them suitable for their role of driving the motor.

The second diagram Figure 3.2.2, illustrates the power circuit and motor model. A full bridge inverter, made up of switches like IGBTs, receives the adjusted frequency and voltage signals from the control section and converts them into a single phase AC output to power the motor. The inverter is managed by signals labelled [A], [B], [C], and [D], which correspond to the switching states required to create a rotating magnetic field. This single phase output is then applied to the induction motor model, which simulates real motor behaviour with parameters such as resistance, inductance, and back-EMF, providing a realistic depiction of motor dynamics under varying load conditions. The system features a feedback loop where the motor's actual speed and current are measured and sent back to the controller. RMS blocks assess the motor output characteristics, which can be used for monitoring and control purposes. Additionally, capacitors and filters are likely included to stabilize and smooth the motor voltage, ensuring that the AC supply to the motor remains steady. The feedback loop enables continuous adjustments based on realtime motor performance, and the output speed is displayed as [output speed], confirming that the motor is operating at the intended speed. Matlab tools specification table: Most of the tools used are the built-in functions/blocks. The tools used in the Matlab are listed as following:

Table 2: Matlab tools used.

Sl No	Tools
1	Fuzzy Control Toolbox
2	Saturation limit box
3	Discrete time integrator
4	Repeating sequence block
5	Relation operator block
6	Asynchronous Single Phase machine

3.2.1 SPWM Working

The repetitive sequence block here generates a triangular waveform, given certain time and output values. These time values are [0 1 2] * (1/10000), which set the timing for the triangular carrier waveform. Now, by multiplying these values by1/10000, you create a time interval of 0.1milliseconds corresponding to a frequency of 10kHz. The output values are [-1 1 -1], which means that the triangular waveform has oscillations between -1 and 1, and it generates a repeating triangular shape.

Basically, the logical operator blocks help in comparing the carrier waveform with the time varying sinusoidal signal generating the Sinusoidally pulse width modulated signals for the gates of IGBT.

3.2.2 Logical Operator for SPWM

The sequence block here produces a triangular waveform provided you have this set of time and output values. These time values are [0 1 2] *(1/10000), which determines the time on or off for the triangular carrier waveform. By multiplying these by 1/10000, you then get a time interval of 0.1milliseconds corresponding to a frequency of 10kHz. The output values are [-1 1 -1], which means that the triangular waveform has the oscillations between -1 and 1, and it generates a repeating triangular shape.

4 RESULT

The image shows the speed and electromagnetic torque characteristics of a single-phase induction motor controlled using a fuzzy controller. The graph represents Fig 4.1, the output voltage for controlling the speed of a single-phase induction motor using pulse-width modulation (PWM). The horizontal axis represents time, ranging from approximately 0.9 to 1.7 seconds. The vertical axis represents voltage, with values ranging from -325 to 325 units. The consistent voltage pulses demonstrate how varying the duty cycle controls the power delivered to the motor, ensuring precise speed regulation.

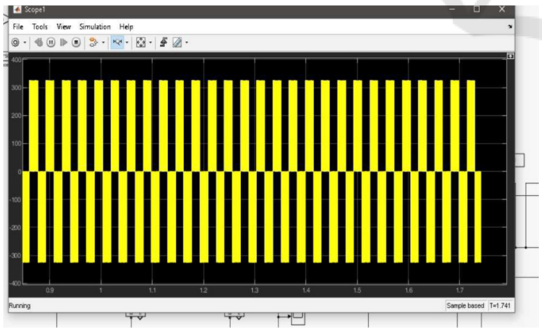

Figure 4.1: Output Voltage Graph

The graph displays Fig 4.2, the output current for the speed control of a single-phase induction motor. The x-axis represents time, ranging from approximately 1.6 to 2.2 seconds, while the y-axis represents current, with values from -20 to 40 units. The waveform is oscillatory, indicating fluctuating current over time. These fluctuations correspond to the motor's response to speed control inputs, essential for maintaining desired speed and ensuring efficient operation. Even though the output voltage waveform appears to be in the form of square wave in the simulation, in practical implementation it will appear as sinusoidal in shape which can further be filtered for harmonics using capacitors and inductors.

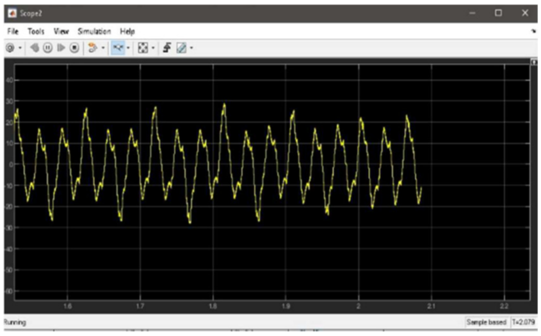

Figure 4.2: Output current graph.

The speed response Figure 4.3 of the single-phase induction motor starts at zero and quickly increases within the first second. Once it reaches about 900units in RPM, the speed levels off with minor oscillations. This pattern shows that the controller successfully brings the motor to its target speed, though there are slight variations in the steady state as the system works to maintain that speed. The torque varies around an average value, indicating dynamic adjustments to keep the desired speed efficiently. These variations are crucial for ensuring stable and effective motor operation.

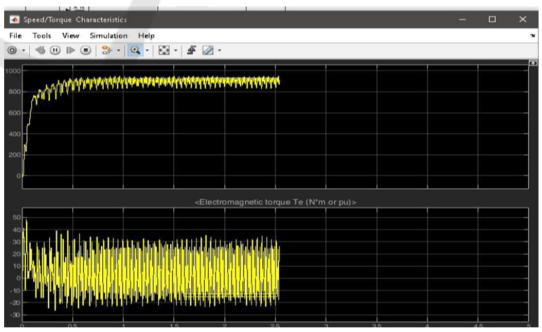

Figure 4.3: Output speed and Torque.

The most important thing to note in this configuration of speed control is that we have not included any kind of inner control loop for controlling the current which is often times a good practice to ensure the safety of the motor's windings, however the single Fuzzy logic controller is enough to implement both the outer speed and inner current loop

REFERENCES

Abdelwanis, M. I., Fayez F. M. El-Sousy, & Ali, M. M. (2023). A Fuzzy-Based Proportional–Integral–Derivative with Space-Vector Control and Direct Thrust Control for a Linear Induction Motor. *Electronics*, *12*(24), 4955–4955. https://doi.org/10.3390/electronics12244955

Alwadie, A. (2018). A Concise Review of Control Techniques for Reliable and Efficient Control of Induction Motor. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, *9*(3), 1124. https://doi.org/10.11591/ijpeds.v9.i3.pp1124-1139

El Ouanjli, N., Derouich, A., El Ghzizal, A., Motahhir, S., Chebabhi, A., El Mourabit, Y., & Taoussi, M. (2019). Modern improvement techniques of direct torque control for induction motor drives - a review. *Protection and Control of Modern Power Systems*, *4*(1). https://doi.org/10.1186/s41601-019-0125-5

El Ouanjli, N., Derouich, A., El Ghzizal, A., Motahhir, S., Chebabhi, A., El Mourabit, Y., & Taoussi, M. (2019). Modern improvement techniques of direct torque control for induction motor drives - a review. *Protection and Control of Modern Power Systems*, *4*(1). https://doi.org/10.1186/s41601-019-0125-5

Firdaus, A. Z. A. (2019). Design and Simulation of Fuzzy Logic Controller for Variable Frequency Drive of Three Phase AC Induction Motor. *Journal of Advanced Research in Dynamical and Control Systems*, *11*(12-SPECIAL ISSUE), 834–842. https://doi.org/10.5373/jardcs/v11sp12/20193283

Guiza, D., Djamel Ounnas, Youcef Soufi, & Naoual Tidjani. (2023). Design and Real Hardware Implementation of Fuzzy Logic Controller for DC-DC Boost Converter. *PRZEGLĄD ELEKTROTECHNICZNY*, *1*(7). https://doi.org/10.15199/48.2023.07.19

Hannan, M. A., Ali, J. A., Mohamed, A., & Hussain, A. (2018). Optimization techniques to enhance the performance of induction motor drives: A review. *Renewable and Sustainable Energy Reviews*, *81*, 1611–1626. https://doi.org/10.1016/j.rser.2017.05.240

Hannan, M. A., Ali, J. A., Mohamed, A., & Hussain, A. (2018). Optimization techniques to enhance the performance of induction motor drives: A review. *Renewable and Sustainable Energy Reviews*, *81*, 1611–1626. https://doi.org/10.1016/j.rser.2017.05.240

Maghfiroh, H., Saputro, J. S., Adriyanto, F., Sujono, A., & Lambang, R. L. (2021). Performance Evaluation of Fuzzy-PID in Speed Control of Three Phase Induction Motor. *IOP Conference Series: Materials Science and Engineering*, *1096*(1), 012071. https://doi.org/10.1088/1757-899x/1096/1/012071

Maghfiroh, H., Wahyunggoro, O., Cahyadi, A. I., Lian, K. L., & Ke, B. R. (2016). Speed Control of a Single Taipei Mass Rapid Transit System Train by Using a Single Input Fuzzy Logic Controller. International Journal of Electrical and Computer Engineering (IJECE), 6(2), 621. https://doi.org/10.11591/ijece.v6i2.8123

Overview of advanced control strategies for electric machines. (2017). *Chinese Journal of Electrical Engineering*, *3*(2), 53–61. https://doi.org/10.23919/cjee.2017.8048412

Plamena Dinolova, Vyara Ruseva, & Ognyan Dinolov. (2023). Energy Efficiency of Induction Motor Drives: State of the Art, Analysis and Recommendations. *Energies*, *16*(20), 7136–7136. https://doi.org/10.3390/en16207136

Rekha Tidke, & Chowdhury, A. (2024). An experimental analysis of fuzzy logic-sliding mode based IFOC controlled induction motor drive. *AIMS Electronics and Electrical Engineering*, *8*(3), 340–359. https://doi.org/10.3934/electreng.2024016

Sahoo, A. Ku., & Jena, R. Ku. (2022). Improved DTC strategy with fuzzy logic controller for induction motor driven electric vehicle. *AIMS Electronics and Electrical Engineering*, *6*(3), 296–316. https://doi.org/10.3934/electreng.2022018

Shaikh, A. (2014). *Speed Control of Induction Motor by V/F Method Using Fuzzy Technique, IJSR, Call for Papers, Online Journal*. International Journal of Science and Research (IJSR). https://www.ijsr.net/getabstract.php?paperid=ART20197800

Suwongsa, T., Areerak, K., Areerak, K., & Pakdeeto, J. (2021). Energy Saving Approach for an Electric Pump Using a Fuzzy Controller. *Energies*, *14*(11), 3330. https://doi.org/10.3390/en14113330