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Speed control of induction motor using fuzzy logic based on internet of things

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ABSTRACT

The aim of this research was to propose an innovative method of controlling the speed of an induction motor (IM) using fuzzy logic, integrated with internet of things (IoT). To achieve this aim, fuzzy logic was used to increase the performance of IM in order to obtain stable speed and high system response even in the presence of disturbances. Moreover, fuzzy logic relied on rules that used linguistic variables, and its main advantage was simple yet highly accurate, enabling the system to be efficient for determining parameters compared to the time-consuming and inefficient trial-and-error method. In this research, IoT implementation used Blynk platform to control and monitor IM speed remotely. Additionally, the components used in this research included an inverter, gate driver, Arduino Mega 2560, and NodeMCU ESP8266. Pulse width modulation (PWM) was required to obtain rotational speed of the motor through MOSFET switching process. The gate driver amplified PWM signal from Arduino Mega 2560, allowing MOSFET to operate. As a result, IM achieved a stable speed, and the system response followed the reference using fuzzy logic. In addition to this process, the system could be controlled and monitored remotely. Finally, the control system was successful, and the results were presented to show the viability of the proposed method.

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1. INTRODUCTION

The use of induction motor (IM) is rapidly expanding across various scales, from household applications to large industries, with a notable presence in electric vehicles [1], [2]. Generally, IM offers both technical and economic advantages but also has a significant drawback because the rotation speed remains constant despite load changes. To address this limitation and achieve highly stable speed and improved system response, IM speed controllers are essential [3], [4]. This research focuses on implementing IM speed control system using fuzzy logic controller (FLC), enhanced by the integration of internet of things (IoT) technology for remote monitoring and control via smartphone. FLC method was adopted due to the ability to handle uncertainty caused by unclear input values through fuzzy logic-based rules. This method allows for effective management of inputs and outputs without relying on complex mathematical models to obtain optimal IM performance. FLC's superiority over traditional trial-and-error methods lies in three-step processes, namely fuzzification, fuzzy inference, and defuzzification. This process enables FLC to control motor speed with high stability and good system response. Moreover, trial-and-error methods often struggle to achieve optimal results and can be laborious and time-consuming [5], [6].

IoT technology enables remote control and monitoring of IM in real-time, increasing operational efficiency and system flexibility [7]. The research uses Blynk platform to implement a hardware control system through mobile and web applications. Moreover, NodeMCU ESP8266 microcontroller is used as hardware connected with Blynk platform through the internet network. The process allows sensor data to be sent to Blynk server and receive commands from users to implement remote control of IM speed. Consequently, controlling the speed of IM can be done remotely in real-time.

Many investigations discuss the control of IM speed using FLC based on IoT. Rajpoot *et al.* [8] proposed FLC for IM speed control, implemented in MATLAB software. Additionally, the research results show dynamic motor speed despite load changes. Shuraiji and Shneen [9] proposed a comparison between proportional, integral, and derivative (PID) controllers and FLC, concluding that fuzzy controllers are superior in producing system response parameters. According to Talib *et al.* [10], this result leads to good IM performance, with no change after simplifying the rules. Vo *et al.* [11] proposed research on controlling sensor less IM using FLC in a current-based model reference adaptive system (CB-MRAS). In addition, IM produces better performance than a conventional CB-MRAS system. Hartono and Nizar [12] proposed speed control for mobile robots using fuzzy controllers. The results shown in this research signify that the application of fuzzy controllers enable robots to move stably in uneven environments with variations in loading.

Based on previous investigations, FLC has been widely implemented to control the speed of electric motor, with good results. Earlier research was conducted through simulations using MATLAB software or IoT-based IM control, performed through an open loop. Therefore, the process did not produce a speed response in the form of a step and disturbance response, as IM control system using an IoT-based FLC is designed.

The research discovers a new IoT-based IM speed control model using FLC that produces a speed response following its ideal characteristics, both in step and disturbance response. This research follows the pattern of the previous investigation by using a closed-loop system, causing the speed of IM to be monitored and controlled remotely with ease. When IM experiences a disturbance, it can be resolved because IoT monitors the model remotely. This method is more effective and efficient than monitoring directly using measuring instruments, such as tachometers. Industrial activities that use IM can run well because the motor speed can be controlled and monitored remotely with the system. This method is expected to improve the shortcomings of previous investigations by enabling real-time IM control and monitoring.

2. METHOD

The process described the design and implementation of hardware and software used to control and monitor the speed of an IM with an IoT-based fuzzy logic controller (FLC). The system comprised both hardware and software components for motor control, programming, and monitoring. Furthermore, a detailed description of each component and the development process discussed in the subsequent section.

2.1. Block diagram of the proposed system

After conducting a literature review on IM speed research, control and monitoring of IM speed using FLC method based on IoT was designed as Figure 1 shows the block diagram of the proposed system. The system required a direct current (DC) power source to supply the inverter and gate driver circuits. Moreover, output of the inverter was used as input for IM, whose voltage was increased using a step-up transformer. Rotation speed of the motor was detected using LM393 speed sensor, and the current was discovered using ACS712. Following the process, the data was processed using Arduino Mega 2560 microcontroller programmed with pulse width modulation (PWM) and FLC. The Arduino mega 2560 sent sensor data to Blynk through NodeMCU ESP8266 connected to Wi-Fi, enabling remote control and monitoring of IM speed using Blynk application.

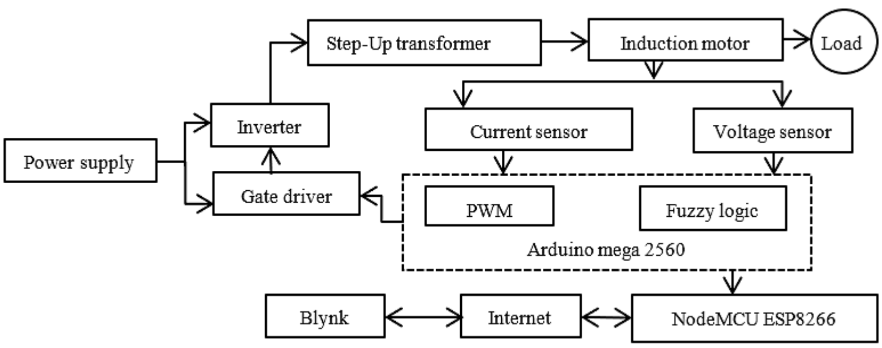


Figure 1. Hardware block diagram

2.2. Induction motor

IM functioned by converting electrical energy into mechanical energy consisting of rotor and stator. This research used a three-phase IM with a squirrel cage rotor type, which had a simple and solid construction [13], [14]. Table 1 shows the specifications of the three-phase IM used in the research.

IM speed testing was done by installing an encoder and LM393 speed sensor on a DC generator coupled with IM. The DC generator served as a load for the system during the test. This test was conducted to ensure each frequency used for inverter switching produced speeds that matched the setpoints, namely 600 RPM, 900 RPM, and 1,200 RPM, obtained from (1).

$$Ns = \frac{120.f}{P} \tag{1}$$

Where Ns represents the speed (RPM), f denotes the frequency (Hz), and P refers to the number of poles.

2.3. Fuzzy logic controller

Implementing control to overcome the problem of unstable motor speed was attempted. This research used a closed-loop system with fuzzy control method that could handle error values when a disturbance or speed change occurred, ensuring the speed remained stable. Moreover, FLC was designed to address problems of ambiguity, uncertainty, and lack of information [3], [15]. The advantage of using this model included better results compared to other control methods [6], [16]. Figure 2 shows the fuzzy reasoning process known as fuzzy inference system (FIS), consisting of the fuzzification process, inference with a rules base, and defuzzification [17].

The research incorporated two inputs into the fuzzy system, namely setpoint value and error value, as shown in Figures 3(a) and 3(b). This process was called fuzzification, where the precise inputs were converted into linguistic variables. The next step was the inference process, consisting of a knowledge base, a core part of fuzzy logic. Additionally, fuzzy inputs were represented in rules, typically in IF-THEN format, using membership functions. The inference process converted fuzzy inputs into outputs by following the rules in the knowledge base. Several inference system models existed, a part of Mamdani model used in this research [18], [19]. The final step was defuzzification using the center of area method by converting fuzzy output obtained from inference into a precise value through membership functions [20]. In this research, the production of FLC was an accurate value, specifically delay, as shown in Figure 3(c).

Table 2 shows 49 system rule bases of FLC used in the research, expressed in if-then logic. Defuzzification results were used to adjust the inverter output frequency. During this process, input and output values were entered into source code in Arduino IDE programming, which was sent to Blynk cloud server using NodeMCU ESP8266, enabling control and monitoring via smartphone.

Testing phase was conducted by operating the system and then providing a disturbance when the system was controlled at each setpoint value. FLC was successfully implemented when a decrease in speed occurred due to disturbance, and the system quickly returned to its ideal reference value. As membership function was used frequently, the performance of the system in responding to changes and disturbances became better.

Table 1. Specifications of the three-phase IM

Voltage rating	400 V(Y)/230 (Δ)
Current rating	0.45 A(Y)/0.78 A(Δ)
Power rating	0.12 kW
Frequency rating	50 Hz
Speed rating	1380 U/min
Cos φ	0.67

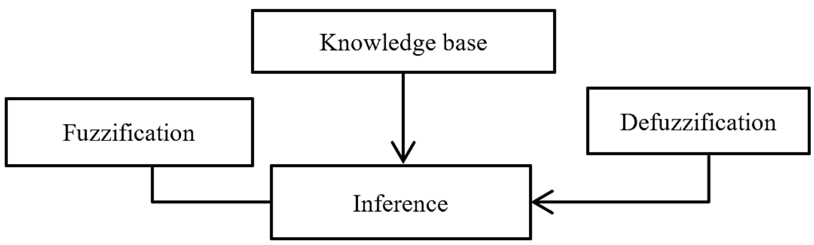
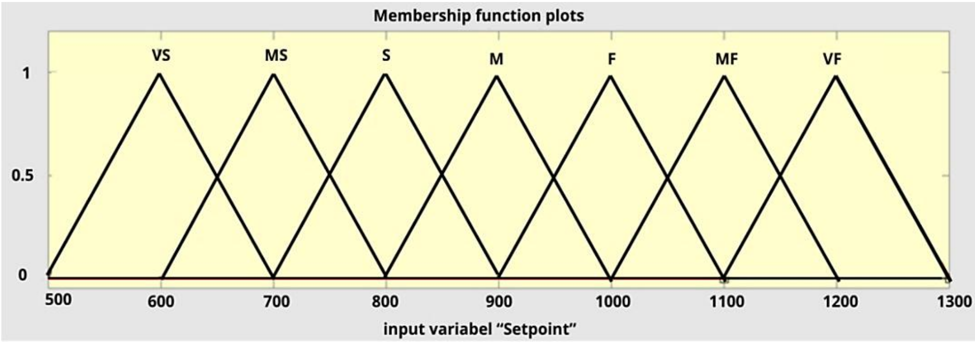
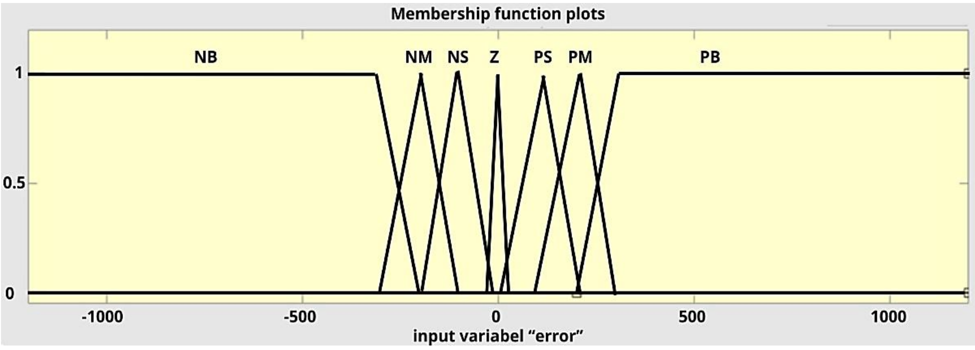


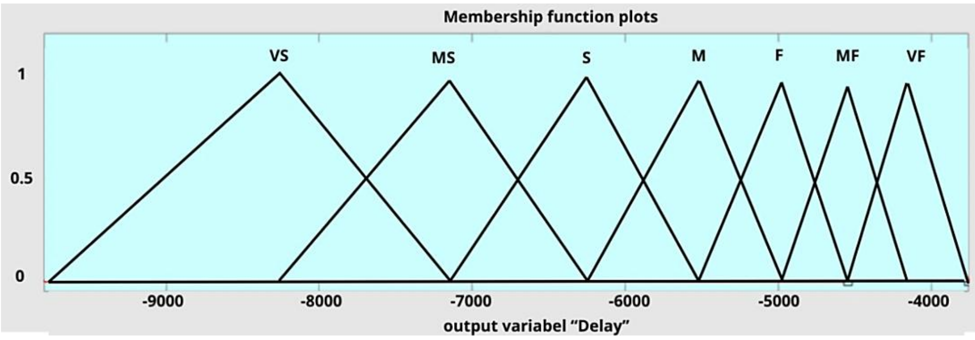
Figure 2. Structure of FLC



(a)



(b)



(c)

Figure 3. Membership function FLC: (a) input setpoint, (b) input error, and (c) output delay

Table 2. Rules membership function

E/SP	VS	MS	S	M	F	MF	VF
NS	VF	VF	VF	VF	MF	F	M
NM	VF	VF	VF	MF	F	M	S
NF	VF	VF	MF	F	M	S	MS
Z	VF	MF	F	M	S	MS	VS
PS	MF	F	M	S	MS	VS	VS
PM	F	M	S	MS	VS	VS	VS
PF	M	S	MS	VS	VS	VS	VS

2.4. Three-phase inverter

Inverter circuit worked by converting DC into alternating current (AC) source [21]. Frequency was needed to control speed of IM obtained from MOSFET switching process in inverter circuit [22]. Switching process requires a PWM signal to trigger the gate pin, and the signal was generated by Arduino mega 2560 microcontroller, which was insufficient to drive MOSFET gate pin. Following this discussion, a gate driver circuit was needed to amplify PWM signal. This driver circuit consisted of HCPL 3120 IC, 0.1 μF mylar capacitor, 47 Ω resistor, and 220 Ω resistor. The driver had six output pins supplying the inverter circuit, which consisted of six MOSFETs and 2200 μF ELCO capacitor. Figure 4 shows the schematic of inverter circuit created using easyEDA software, which was implemented on the hardware.

The research used an inverter with a 180° conduction method because it produced an output resembling sine wave [23]. When an electric motor was supplied with a non-sinusoidal waveform, the process could decrease power quality and cause overheat of equipment, causing damage to the electric motor [24]. The switching sequence of the inverter using 180° conduction method is shown in Table 3.

During this research, the following tests were performed on the inverter component. The first test was PWM wave testing, which was needed to ensure the waveform, voltage, and duty cycle. This test aimed to ensure that the PWM wave did not contain harmonics affecting inverter performance and system reliability. The examination was conducted on R, S, and T phases using an oscilloscope measuring instrument. The second test was inverter voltage testing, where the inverter output voltage was used to supply IM, which had previously increased voltage using a step-up transformer. Following the discussion, the voltage was balanced to produce optimal motor performance. This voltage testing was alternately conducted at R, S, T, and ground phase points.

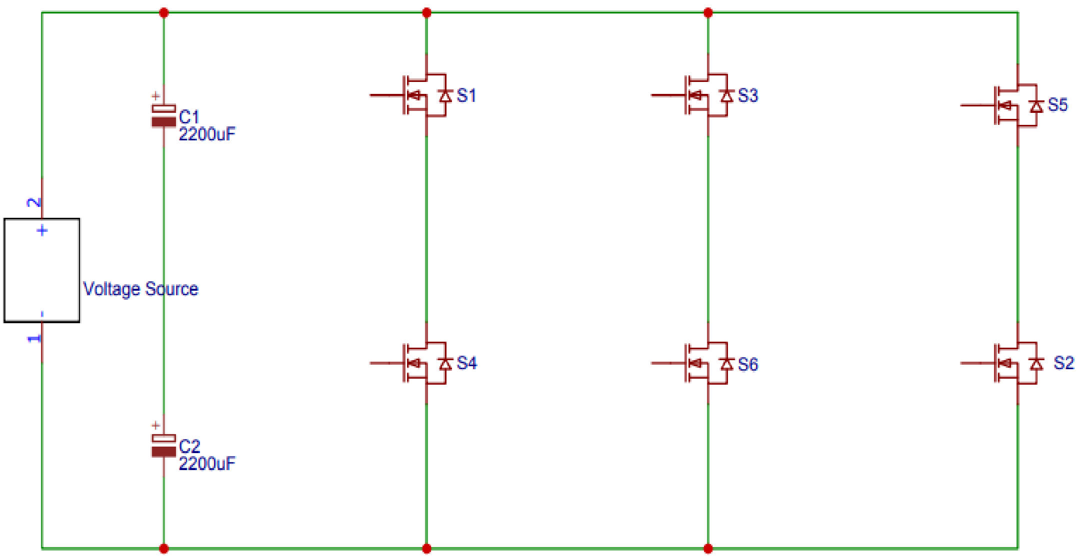


Figure 4. Three-phase inverter circuit schematic

Table 3. The switching sequence of 180° conduction inverter

Interval	Switch on	Phase voltage (Vdc)			Line voltage		
		R	S	T	V_{RS}	V_{ST}	V_{TR}
0°-60°	1,6,5	1/3	-2/3	1/3	Vdc	-Vdc	0
60°-120°	1,6,2	2/3	-1/3	-1/3	Vdc	0	-Vdc
120°-180°	1,3,2	1/3	1/3	-2/3	0	Vdc	-Vdc
180°-240°	4,3,2	-1/3	2/3	1/3	-Vdc	Vdc	0
240°-300°	4,3,5	-2/3	1/3	1/3	-Vdc	0	Vdc
300°-360°	4,6,5	-1/3	-1/3	2/3	0	-Vdc	Vdc

2.5. Internet of things (IoT)

IoT was used to control hardware systems in this research remotely. The model implemented the concept where various devices and objects were interconnected and communicated using the internet network [25]. The application of IoT used Blynk platform, which was accessed through both smartphone applications and web for simpler procedures [26], [27]. In addition, the general architecture of the IoT system for IM speed control is shown in Figure 5(a), and the hardware architecture is in Figure 5(b). During this research, sensors were used as the physical layer, LM393 was used to detect speed, and ACS712 was used to read current. The data was then sent to the hardware layer, consisting of Arduino mega 2560 and NodeMCU ESP8266 microcontrollers. These two microcontrollers communicated using serial communication and were programmed in Arduino IDE.

Downloading Blynk library onto each hardware device was essential for connecting to Blynk server [7], [28]. Data was immediately sent to the cloud server NodeMCU ESP8266, connected to the internet. Additionally, the token was obtained after the data was entered into Arduino IDE programming, ensuring that the data appeared on Blynk screen.

A stable internet network was necessary during IoT testing for the speed of the system in processing data operating in real-time. All setpoints were tested to ensure that the commands functioned properly as the test progressed. Moreover, a gauge widget was used to show current and speed values on Blynk screen. Segmented switch widget functioned as a push button for movement to the desired setpoint and used a graph widget to show the system response steps.

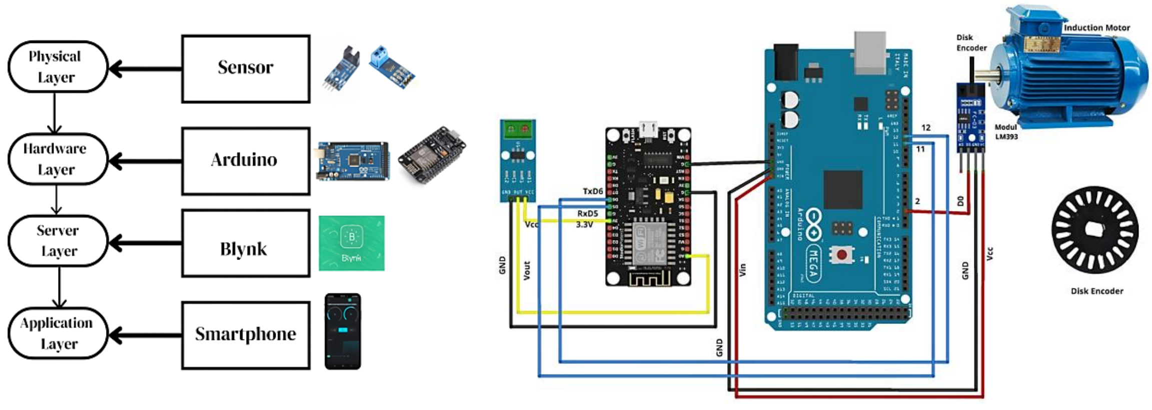


Figure 5. IoT: (a) general IoT architecture and (b) complete IoT hardware configuration

3. RESULTS AND DISCUSSION

After designing, manufacturing, and testing, this section described the results obtained from IoT-based IM speed control system. Figure 6(a) shows the complete circuit of the system, consisting of step-down transformer, power supply, gate driver, inverter, microcontroller, step-up transformer, and ACS 712 current sensor. Meanwhile, Figure 6(b) shows IM coupled to DC generator, where the output of the generator was used to supply three lamps with a total power of 15 W. In addition, LM393 speed sensor with encoder was installed in the gap between transmitter and sensor receiver to monitor the rotation speed of the motor.

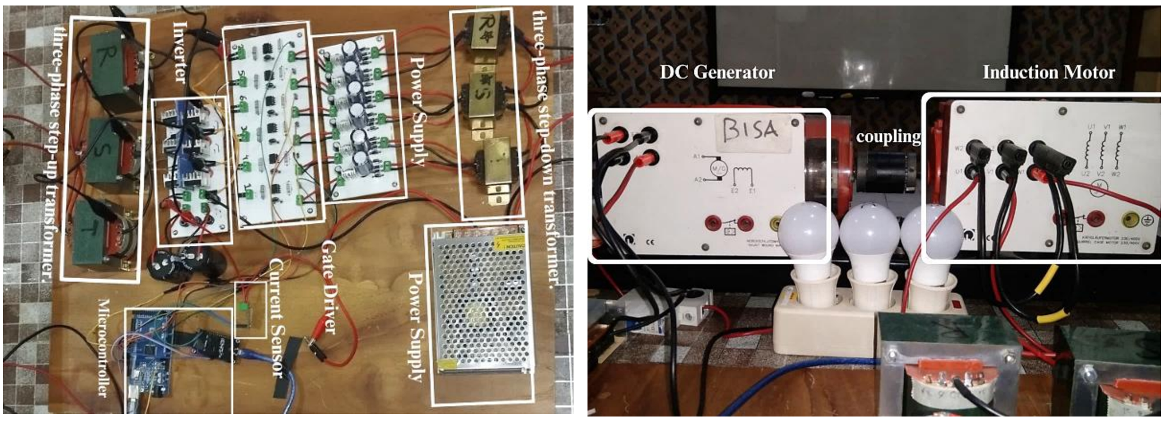


Figure 6. Total system circuit: (a) entire system and (b) IM coupled with a load

3.1. Pulse width modulation result

The purpose of testing PWM waveforms was to ensure the resulting waveforms were free of harmonics that could disrupt system stability. Harmonics caused deviations in frequency, current, or voltage, significantly affecting the output performance of the inverter. During this research, tests were conducted using an oscilloscope to monitor the voltage, frequency, and duty cycle values generated in inverter circuit with frequency variations of 20 Hz, 30 Hz, and 40 Hz. Figure 7(a) shows PWM waveform at a frequency of 20 Hz, Figure 7(b) at 30 Hz, and Figure 7(c) at 40 Hz. This test ensured that the waves obtained did not contain harmonics that could affect the performance of the inverter, providing stable, and optimal operation.

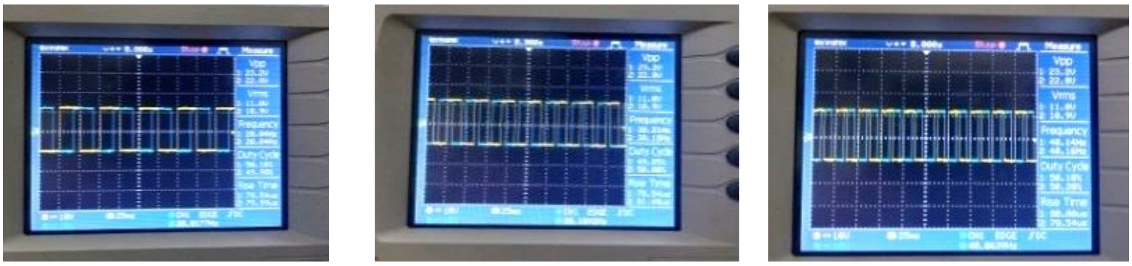
3.2. Fuzzy logic controller result

FLC was tested to observe the system response in terms of IM speed. The tests were conducted under two conditions, namely when the motor was with and without loaded, at setpoints of 600 RPM, 900 RPM, and 1,200 RPM. Figures 8(a)-8(c) show the results of the system response using FLC at three setpoints without load. Based on the tests conducted, the parameters of rise time, settling time, and overshoot were obtained, as shown in Table 4.

Figure 9(a) shows the system response based on testing at a setpoint of 1,200 RPM conducted for 50 seconds and given a disturbance at the 30th second. This test achieved a rise time of 1.81 seconds, a settling time of 3.81 seconds, and an overshoot of 1%. Figure 9(b) shows the test performed using 600 RPM setpoint, and at the 23rd second, the speed was changed to 1,200 RPM setpoint. Following this discussion, a load was applied, causing interference at the 30th second. However, the speed decreased due to the addition of load, which could be corrected through FLC. The decrease in speed was effectively managed by using FLC to address the disturbance in 5 seconds.

3.3. Internet of things result

Blynk IoT test results showed the various widgets for monitoring and controlling the system, as shown in Figure 10. On the left side, a gauge widget showed current value, while on the right, widget presented the motor speed value. In addition, a segmented switch widget for setpoint switching and a graph widget were used to visualize the system response graph in IM speed control using FLC.



(a) (b) (c)

Figure 7. PWM wave: (a) frequency 20 Hz, (b) frequency 30 Hz, and (c) frequency 40 Hz

(a)
(b)
(c)

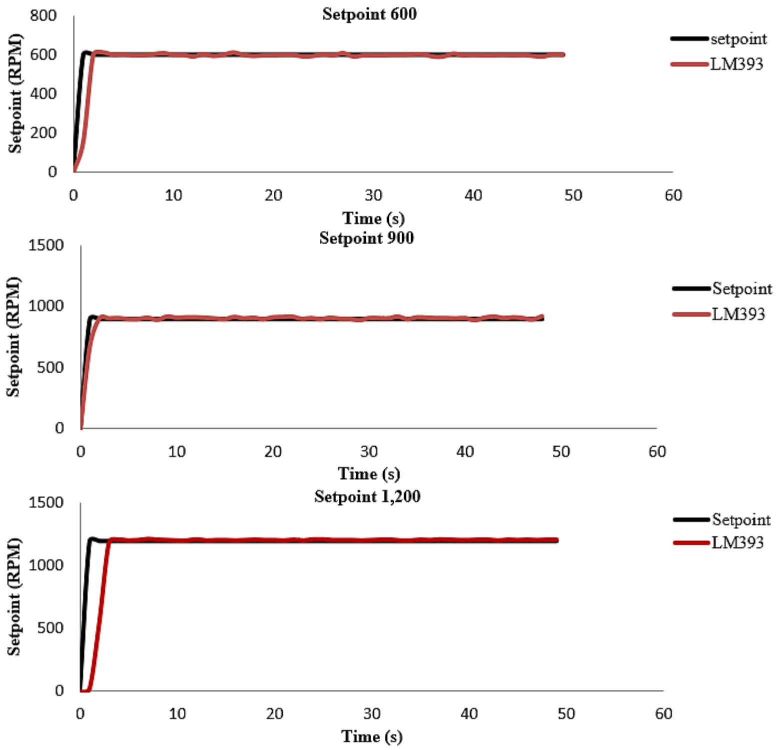


Figure 8. Speed response of IM: (a) setpoint 600 RPM, (b) setpoint 900 RPM, and (c) setpoint 1,200 RPM

Table 4. Test results of the system response using FLC

Setpoint	Rise time (s)	Settling time (s)	Overshoot (%)
600	1.48	2.97	1.5
900	1.46	2.92	2
1,200	1.65	3.98	1
Average	1.53	3.29	1.5

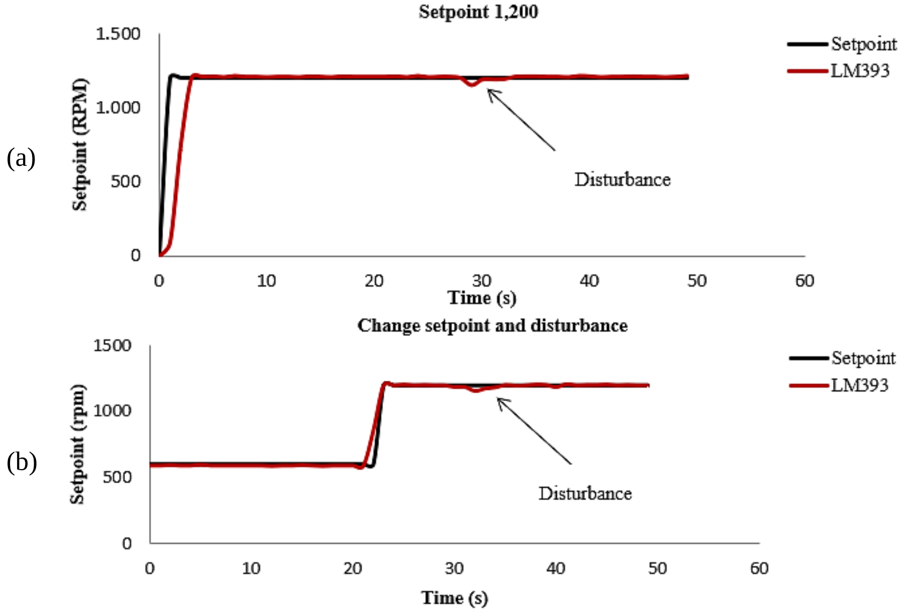


Figure 9. Speed response of motor with disturbances: (a) single setpoint and (b) setpoint changes

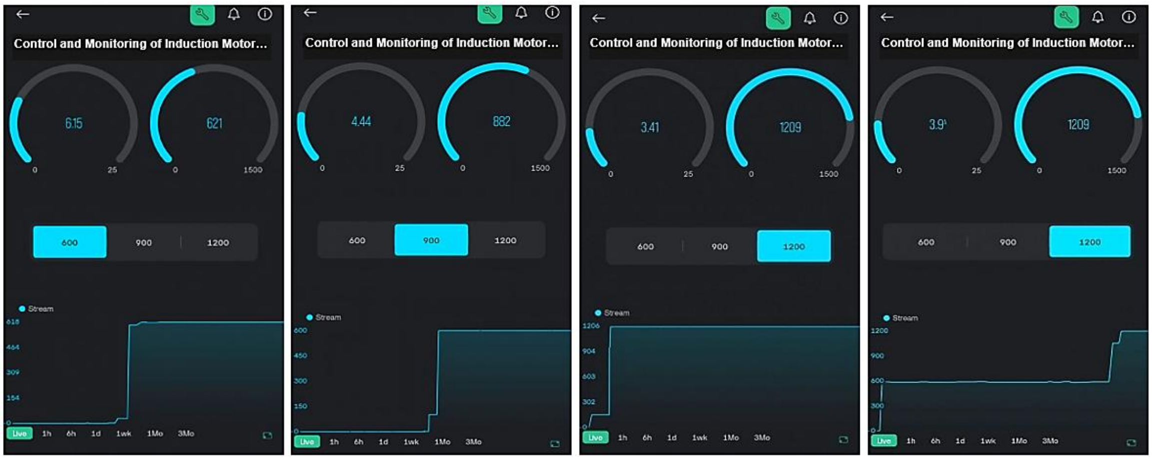


Figure 10. IoT interface during testing

4. CONCLUSION

In conclusion, the research successfully implemented a fuzzy logic-based IM speed control system with the support of IoT technology. This system showed the ability to maintain motor speed stably in no-load conditions and when facing load disturbances. The test results signified that the average rise time was 1.5 seconds, with 3.29 seconds of settling time and 1.5% overshoot under no-load conditions. Meanwhile, when given a disturbance, the time required to return the motor speed to the reference value was faster, with a rise time of 1.81 seconds and a settling time of 3.81 seconds. IoT technology implemented using Blynk platform enabled real-time, remote control and monitoring of the system, increasing efficiency as well as flexibility in IM operations. Moreover, the fuzzy logic method combined with IoT provided advantages concerning system stability and ease of monitoring directly from mobile devices compared to traditional control methods.

The research added new contributions to the development of IM control, especially in applying FLC and IoT. The system showed improvement from previous investigations that primarily operated in open-loop mode. This research ensured better speed response to load changes and improved the ability to monitor the motor directly and responsively when faults occurred. For future research, the model can be improved on sensor accuracy, faster IoT data processing, and fuzzy algorithm optimization by combining several methods, such as vector control, neural network, and PI, to reduce system recovery time when facing disturbances. In addition, further research can also explore the incorporation of artificial intelligence (AI) technology and fuzzy logic to improve the adaptability of the control system to more complex load variations.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Charles Ronald Harahap	✓	✓	✓	✓	✓		✓	✓		✓		✓	✓	✓
F.X. Arinto Setyawan		✓		✓	✓			✓		✓		✓	✓	
Desi Budiati	✓	✓	✓			✓	✓		✓	✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest

DATA AVAILABILITY

The data presented in this paper is newly obtained during the research and is not yet publicly available. Data is contained within the article.

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