

Article

IoT-Based Lithium-Ion Battery Safety Condition Monitoring Using Voltage and Temperature Parameters with Fuzzy Logic Method

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Abstract: The increasing number of vehicles in Indonesia has a negative impact if it is allowed to continue; one solution is to switch to environmentally friendly electric vehicles. One of the main components of electric vehicles is the battery. IoT-based battery monitoring is needed to check battery health using the fuzzy logic method with LED notification results. Notifications indicate whether the battery is in a safe, alert or dangerous condition. The results of battery monitoring in a discharge condition with a load of battery voltage decrease linearly compared to temperature, which changes according to the ambient temperature. In a charging condition, the battery voltage increases linearly, and the peak temperature is higher than when discharged with a load. When testing a load variation of 4 LEDs, the voltage decreases faster, and the temperature rises higher than with a load of 2 LEDs. With these various conditions, the application of fuzzy logic is used to monitor the condition of the battery in a discharge or charge. This study aims to develop IoT-based battery monitoring by implementing the use of fuzzy logic as a battery notification when the battery is in a safe, alert, or dangerous condition. Experimental testing was conducted under charging and discharging conditions with varying loads. The calibration results show that the voltage measurement using the INA219 sensor has an average error of 0.35% during discharge and 0.31% during charging, while the temperature measurement using the NTC thermistor shows an average error of 0.85%. The fuzzy logic system successfully classifies battery safety states based on voltage–temperature combinations, and the notification results are consistent with MATLAB-based fuzzy simulations. The proposed system demonstrates reliable real-time monitoring of lithium-ion battery safety conditions and can serve as an effective early warning mechanism to prevent unsafe battery operation.

Keywords: Battery Monitoring; Voltage; Temperature; Fuzzy Logic; IoT.

1. Introduction

Technological developments in Indonesia are developing very rapidly, one of which is in the transportation sector. There are various types of transportation in Indonesia; one of the most common types of vehicles is the private vehicle. The number of private vehicles in Indonesia is very large. According to the Central Statistics Agency (BPS), the number of motor vehicles in Indonesia in 2021 reached 141,992,573 units, and this number continues to grow. [1]. This increasing number of vehicles has a negative impact if left unchecked. The impact of fuel-powered vehicles can cause air pollution from exhaust emissions from motor vehicles [2]. A solution to this problem has been found: switching

to electric vehicles, which are more environmentally friendly because they do not produce exhaust gases. Automotive companies have also begun researching these electric vehicles [3].

One of the most important components of an electric vehicle is the battery as a power storage. To maintain the battery in good condition, a battery monitoring system was created [4]. The battery monitoring system used in this study is a lithium-ion battery [5]. This type of lithium-ion battery was chosen because it has several advantages, namely, stable voltage, relatively small size compared to other types of batteries, light weight, and relatively long battery life. Although lithium-ion batteries have many advantages, the electrochemistry of lithium-ion batteries is quite complex. Overcharging and discharging will reduce the performance and life of lithium-ion batteries, and even repeated excessive use can cause explosions. Therefore, a battery monitoring system is needed to determine the health of lithium-ion batteries. By monitoring the battery, the condition of the lithium-ion battery can be known when the electric power is running out, which can prevent over-discharge and extend the life of the lithium-ion battery. To facilitate monitoring of lithium-ion batteries, an IoT-based battery monitoring system was created. With the use of IoT, it is easy to find out the current, voltage, and temperature parameters that can be displayed on mobile devices. This IoT system utilizes an internet connection to send lithium-ion battery parameter data to a web server in the cloud, which then displays the data in the software [6]. In previous research, the characteristics of Lithium-Ion batteries were tested using the Fuzzy Method with Varying Loads using voltage and temperature parameters as variables in fuzzy logic[7]. The second previous study, the implementation of fuzzy logic for accurate measurement of the SoC of electric car batteries, used voltage, current, and temperature as fuzzy variables to estimate the state of charge of electric car batteries[8]. Fuzzy logic is used to generate notifications from battery monitoring results. From the monitoring results, two parameters are obtained: voltage and temperature, which are used to analyze the condition of the lithium-ion battery.

2. Materials and Methods

2.1. Materials

2.1.1. Lithium-Ion Battery



Figure 1. Lithium-Ion Batteries

This study used a secondary battery type, namely a lithium-ion battery. When used, it works as a voltaic cell: Lithium will deliver electrons from the anode to devices that require electrons, such as capacitors and processors in cellphones or laptops, then ending at the cathode. Meanwhile, protons from the cathode enter through the separator between the anode and cathode (intercalation process). This process continues continuously until the battery's capacity is exhausted (indicated by a line or percentage of battery capacity on the cellphone or laptop screen). When charged, it works as an electrolysis: Meanwhile, when the battery is recharged, electrons will return from the cathode to the

anode through the charger, and with the help of the incoming current from the charger, the protons will return to the cathode. So that the condition returns to its original state

2.1.2. NTC Thermistor



Figure 2. NTC thermistor

The NTC (Negative Temperature Coefficient) thermistor is a resistor whose value its resistance decrease when temperature increased. Due to its highly sensitive nature to change temperature, many NTC thermistors used as a temperature sensor in the circuit electronics.

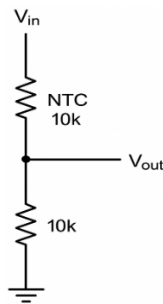


Figure 3. Voltage Divider Schematic

For read change NTC resistance, used voltage divider circuit, where the NTC 10K is in series with a 10K ohm resistor. The voltage at the point middle divider voltage connected to the analog input of the microcontroller. The voltage divider circuit formula is as follows:

$$V_{out} = V_{cc} \times \frac{R_2}{R_1 + R_2} \quad (1)$$

Information:

- R1 (NTC) varies in accordance temperature
- R2 (10k ohm)
- Vout will increase as the temperature decreases (because R1 increases)
- Vout will decrease as temperature increases (because R1 decreases)

2.1.3 INA219

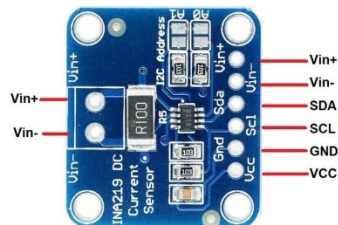


Figure 4. INA219

The INA219 is a sophisticated electronic sensor module that can monitor current and voltage. With a little multiplication, we can even measure power. The INA219 can monitor voltages up to 26 volts DC. Its current measurement range, +/- 3.2A, is suitable for most small measurements. In other

words, this module can measure power above 75 watts. Texas Instruments introduces the INA219 shunt current sensor module. This module is a bidirectional, driftless power monitor that measures shunt voltage, bus voltage, current, and power. This module communicates with a microcontroller through a built-in interface that supports I2C and SMBus.

2.2. Design Battery Monitoring System

In the research This battery tested in Charging and discharging conditions. Current sensors, voltage sensors, and temperature sensors detect how much battery value is being monitored. Then the data value from each sensor enters the ESP8266 microcontroller and the data is processed to be displayed via TFT LCD and IoT system that can be seen in the blynk software. Before the data is displayed, the data goes through a fuzzy logic process with predetermined variables. The data results displayed are the status of current, voltage, temperature and notification in the form of LEDs with statuses that have been determined through the fuzzy logic process.

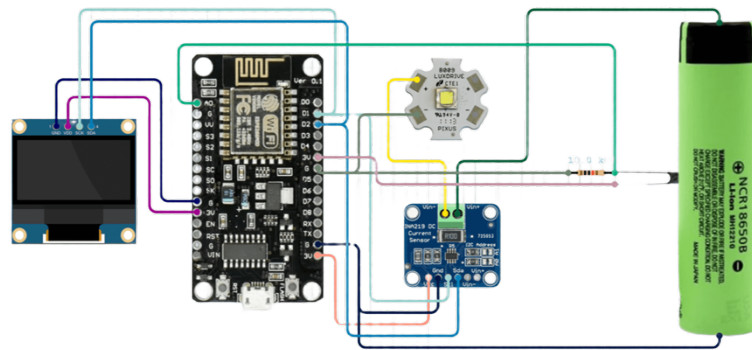


Figure 5. Design Battery Monitoring System

2.3. Fuzzy Logic

Fuzzy logic is an approach to variable processing that allows multiple possible truth values to be processed through the same variable. Fuzzy logic attempts to solve problems with an open and imprecise spectrum of data and heuristics, allowing for a range of accurate conclusions. Fuzzy logic is designed to solve problems by considering all available information and making the best decision based on that input. Fuzzy logic was first proposed by Lotfi Zadeh in a 1965 paper for the journal Information and Control. In his paper, "Fuzzy Sets," Zadeh attempted to reflect on the types of data used in information processing and derive elemental logic rules for such sets.

In the experiment This done simulation For get results notification with enter mark voltage and temperature battery during the charging and discharging process to in system fuzzy logic that has been prepared. For make system notification with fuzzy logic, need made function membership function and rules logic (rule based) based on the data obtained from voltage sensor and temperature sensor as input while the output in the form of led notification as output.

Table 1. Fuzzy variables

No	Function	Variables	Fuzzy Set	Domain
1	Input	Temperature	Cold	[26, 27, 28]
2			Normal	[27, 30, 33]
3			Hot	[32, 35, 39]
4	Input	Voltage	Very Low	[2.5, 2.8, 3.0]
5			Low	[2.8, 3.1, 3.4]
6			Normal	[3.3, 3.6, 3.9]
7	Output	Notification	Tall	[3.7, 4, 4.2]
8			Safe	[0, 1, 3]
9			Alert	[3, 5, 7]

In this study, a battery monitoring system monitors the current, voltage, and temperature of a lithium-ion battery using a fuzzy system and the Mamdani fuzzy method. The input to the fuzzy controller is voltage and temperature data, while the output is a notification in the form of an LED light.

Table 2. Fuzzy Rules

No	Input 1 (Voltage)	Input (Temperature)	Output (Notification)
1	Very low	Cold	Alert
2	Very low	Normal	alert
3	Very low	Hot	Danger
4	Low	Cold	Alert
5	Low	Normal	Safe
6	Low	Hot	Danger
7	Normal	Cold	Safe
8	Normal	Normal	Safe
9	Normal	Hot	Alert
10	Tall	Cold	Safe
11	Tall	Normal	Alert
12	Tall	Hot	Danger

2.4 IoT

The term IoT, or Internet of Things, refers to the collective network of connected devices and the technologies that facilitate communication between them and the cloud, as well as between the devices themselves. Thanks to the advent of inexpensive computer chips and high-bandwidth telecommunications, a wide variety of devices are now connected to the internet. Examples include toothbrushes, vacuum cleaners, cars, and machines that use sensors to collect data and intelligently respond to users.

The Internet of Things (IoT) is integrating everyday objects with the internet. Computer engineers have been adding sensors and processors to everyday objects since the 1990s. However, progress was initially slow because the chips were large and took up a lot of space. Low-power computer chips called RFID tags were first used to track expensive equipment. As computer devices have shrunk, these chips have become smaller, faster, and smarter over time.

3. Results

3.1. Battery Monitoring System Design Using Fuzzy Logic

This battery monitoring system uses several components, such as voltage sensors and temperature sensors, and an ESP8266 microcontroller. The output is displayed on a TFT LCD and through IoT-based Blynk software. The design is shown in Figure 6 below.

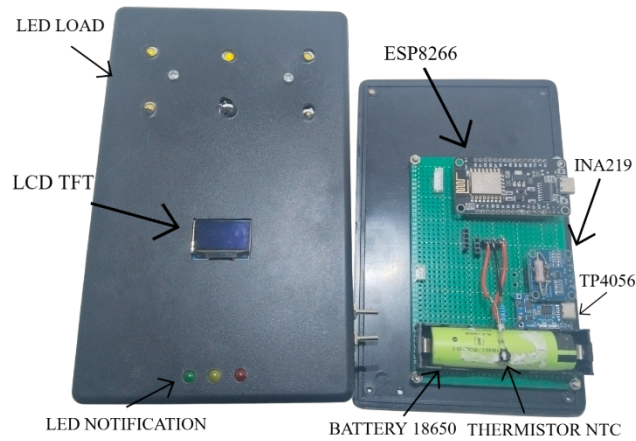


Figure 1. Battery Monitoring System Implementation

The hardware made in the picture is composed of a battery, a voltage sensor, a temperature sensor, an ESP8266 microcontroller, a TFT LCD, Blynk software, and an LED notification using the fuzzy logic method.

3.2. Prototype Implementation

3.2.1. Hardware Design Flowchart

The following is a flowchart for designing the hardware of the tool, which can be explained in the image below.

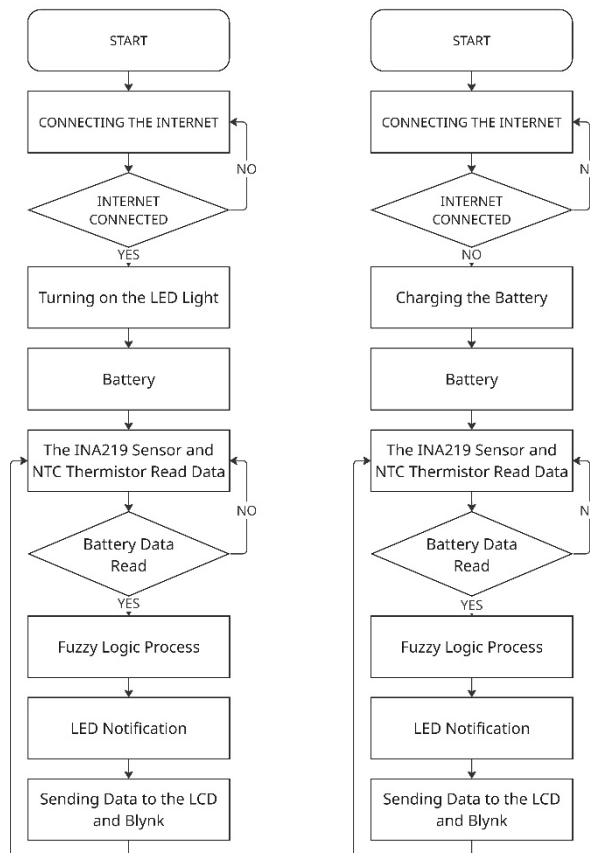


Figure 2 Battery Monitoring System Flowchart

In the first stage, the ESP8266 connects to the internet to be able to send data. After successfully connecting to the internet, then 2 tests will be carried out, namely discharge by connecting the LED light load to the battery, then the second test charge by charging the battery. After that, the sensor reads the battery, namely the voltage sensor and the temperature sensor. If the voltage and temperature data have not been read, the sensor will re-read the battery. Then the data from the INA219 sensor and the NTC Thermistor sensor will be processed into fuzzy logic, which first goes through the fuzzyfication process. After that, it enters the inference stage based on the fuzzy rules that have been created, and then the defuzzification process to make the right decision. The results of the fuzzy logic process will turn on 3 LED lights in green, yellow, and red, used as notifications, meaning green as safe, blue as alert, and red as danger. Finally, the data read from the INA219 sensor and the NTC Thermistor sensor will be displayed on the TFT LCD and the Blynk software connected to the internet.

3.2.2. INA219 Sensor Calibration

This battery voltage test compares the results from a multimeter with the test equipment that has been made. Battery voltage data is taken per hour, the data in table 3 shows the battery in a discharge condition with a load of 2 3-watt LED lights with the initial condition of the battery being fully charged until the LED lights are lit in a dim condition. The results of the test comparing the discharge voltage data obtained from the voltage sensor and multimeter show an average error of 0.36%.

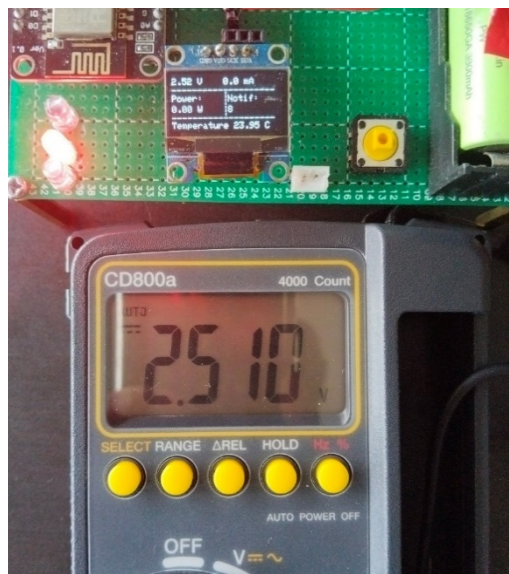


Figure 3. Calibration of Sensors and Multimeter Measurement Tools

Table 3. Calibration of the voltage sensor with a discharge condition measuring instrument

Tool Test Voltage (Volt)	Multimeter (Volt)	Error (%)
4.03	4.04	0.24
3.8	3.81	0.26
3.71	3.72	0.26
3.56	3.58	0.55
3.45	3.46	0.28
3.37	3.38	0.29
3.15	3.16	0.31
2.86	2.88	0.69
2.68	2.69	0.37
2.5	2.51	0.39
Average error		0.36

3.2.3. NTC Thermistor Sensor Calibration

Battery monitoring testing uses an INA219 sensor and an NTC thermistor sensor. The INA219 sensor is used to measure voltage, and the NTC thermistor sensor is used to measure battery temperature. This temperature sensor circuit consists of a 10k NTC thermistor and a 10k resistor connected in series. This test was conducted to compare the measurement results of the test equipment that has been made with a temperature multimeter. Battery temperature data was taken hourly in a discharged battery condition with a load of two 3-watt LED lights. In Table 4, the comparison of test equipment data with a temperature multimeter shows results that are not much different, with an average error of 0.85%.

Table 4. Temperature Sensor Calibration with Measuring Instruments

Temperature (Test tool)	Temperature (Celsius)	Error (%)
28.93	29	0.24
35	35.78	2.17
36.02	36	0.05
34.87	35	0.37
32.84	33	0.48
30.54	30	1.8
Average error		0.85

3.3. System Testing

3.3.1. Battery Testing under Discharging and Charging Conditions

Testing the battery in discharge condition using a load of 2 3 watt LED lights. Battery testing uses an INA219 sensor. In Figure IV.5, the graph of the discharge battery voltage is at 3.92 volts and the load power of 2 LED lights is at 4.02 watts. The battery capacity is discharged with a load until the LED lights are dim, after several battery tests the lower limit of the voltage is at 2.5 volts and the upper limit of the discharge load voltage is at 4 volts. Temperature sensor testing uses an NTC thermistor sensor, monitoring the battery temperature by bringing the thermistor close to the battery being tested. The temperature is at its peak in the first 60 minutes of testing at 38o Celsius, then the

temperature decreases over time until the light load is dim and the battery voltage is at the cut-off limit.

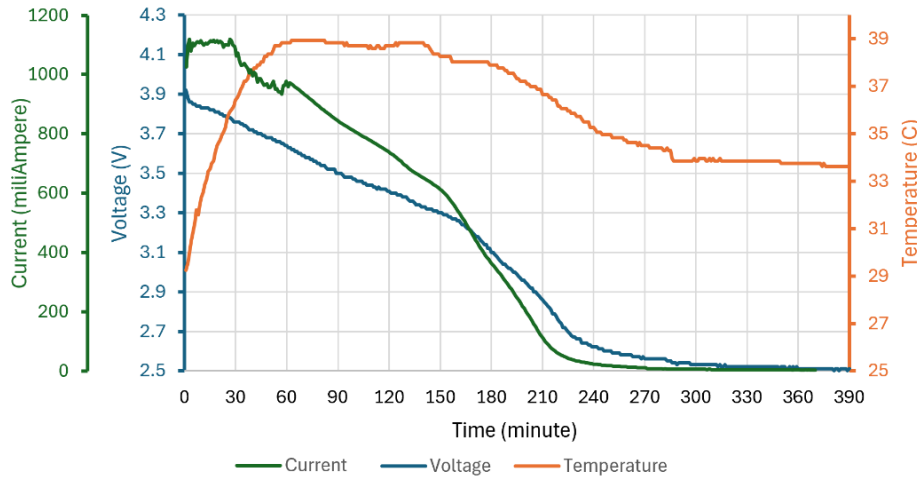


Figure 9. Battery Discharge Condition Graph

Real-time battery discharge condition monitoring data is captured every 30 minutes. Battery data shows the battery voltage from a fully charged state of 3.92 volts to a lower limit of 2.52 volts. Battery temperature increases during the first 1-2 hours of testing, peaking at 38.83°C, then gradually decreases. The results of the battery voltage and temperature measurements are processed into fuzzy logic that determines notifications on the battery condition during the test.

Table 5. Real-Time Battery Discharge Condition Monitoring Data

No.	Time (Minute)	Voltage (Volt)	Temperature (Celsius)	Fuzzy Logic Output	Notification
1	1	3.92	29.25	5	LED YELLOW ON
2	30	3.76	36.41	6.51	LED YELLOW ON
3	60	3.64	38.83	5.5	LED YELLOW ON
4	90	3.5	38.83	5	LED YELLOW ON
5	120	3.41	38.72	5	LED YELLOW ON
6	150	3.3	38.25	8.66	LED RED ON
7	180	3.1	37.9	8.91	LED RED ON
8	210	2.86	36.64	8.81	LED RED ON
9	240	2.62	35.28	8.92	LED RED ON
10	270	2.56	34.51	8.86	LED RED ON
11	300	2.53	33.85	8.78	LED RED ON
12	330	2.52	33.85	8.78	LED RED ON

Next, the battery is tested in charging condition using the tp4056 module which has a power output of 5 volts 1 ampere. In figure IV. 6 the initial voltage is at 2.5 volts which corresponds to the lower limit of the battery voltage when in discharge condition with load. On the graph the voltage increases from the beginning of charging until 330 minutes or about 5 hours 30 minutes. Charging voltage is at 4 volts, the voltage is stable until full charging is at 4.24 volts which is indicated by a blue indicator on the tp4056 module. Then the battery temperature is in charging condition, on the graph the peak battery temperature is at 39.9° Celsius 3 hours after the temperature decreases, this happens because the battery adjusts from the voltage and current entering from the tp4056 module power, then slowly the temperature continues to decrease until the battery is fully charged.

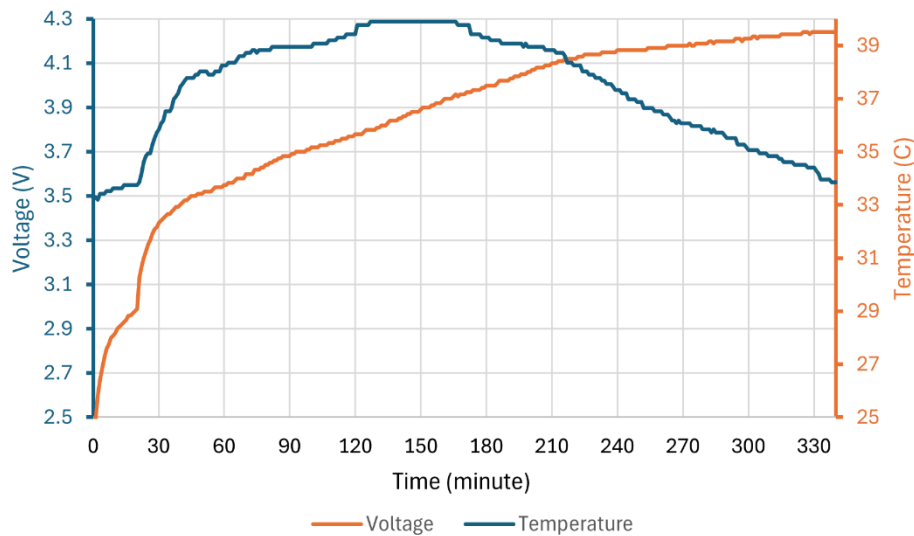


Figure 10. Battery Charge Condition Graph

Real-time battery charge condition monitoring data is captured every 30 minutes. Battery data shows the battery voltage from an empty battery condition of 2.49 volts to a fully charged battery at 4.24 volts. Battery temperature increases at the beginning of the 1-2 hours of testing, peaking at 39.9°C, then the temperature slowly decreases. The results of the battery voltage and temperature measurements are processed into fuzzy logic that determines notifications on the battery condition during the test.

Table 6. Real-Time Battery Charging Condition Monitoring Data

No .	Time (minute)	Voltage (Volt)	Temperature (Celsius)	Fuzzy Logic Output	Notification
1	1	2.49	33.3	8.7	LED RED ON
2	30	3.38	35.85	5.62	LED YELLOW ON
3	60	3.55	38.25	5	LED YELLOW ON
4	90	3.68	38.95	5.87	LED YELLOW ON
5	120	3.78	39.42	6.71	LED YELLOW ON
6	150	3.89	39.9	8.6	LED RED ON

No .	Time (minute)	Voltage (Volt)	Temperature (Celsius)	Fuzzy Logic Output	Notification
7	180	4	39.3	8.91	LED RED ON
8	210	4.1	38.83	8.92	LED RED ON
9	240	4.16	37.32	8.92	LED RED ON
10	270	4.18	36.07	8.92	LED RED ON
11	300	4.21	35.06	8.92	LED RED ON
12	330	4.24	34.40	8.85	LED RED ON

3.3.3. Battery Monitoring System Testing with Fuzzy Logic Implementation

This battery monitoring test was conducted by applying fuzzy logic with the voltage and temperature of the battery as input variables, and the output is a notification in the form of a green LED light for safety, a yellow for caution, and a red for danger. The purpose of applying fuzzy logic to this battery monitoring system is to determine the health condition of the battery when the battery is charging and discharging with or without a load, such as when the battery voltage is above or below the normal limit, and the battery temperature changes when the battery is charging.

Table 7. Application of fuzzy logic in monitoring battery charge conditions

No.	Voltage (V)	Temperature (Celsius)	Notification	Test Output	MATLAB Output	Error (%)
1	2.60	28.86	Alert (yellow LED on)	5	5	0
2	2.76	29.32	Alert (yellow LED on)	5	5	0
3	3.32	33.52	Danger (red LED on)	7	7.72	9.32
4	2.87	29.21	Alert (yellow LED on)	4	4.01	0.24
5	2.94	29.09	Safe (green LED is on)	3	2.97	1.01
6	3.32	33.52	Danger (red LED on)	7	7.72	9.32
7	3.45	27.55	Safe (green LED is on)	1	1.26	20.63
8	3.33	28.52	Safe (green LED is on)	1	1.36	26.47
9	3.77	36.38	Alert (yellow LED on)	6	5	20
10	3.82	27.44	Safe (green LED is on)	3	2.29	31.01
11	4.14	31.28	Alert (yellow LED on)	4	5	20
12	4.10	33.32	Danger (red LED on)	8	8.73	8.36
Average error						12.19

The explanation of the table above can be explained as follows:

1. When the battery is charged, the voltage shows 2.60 volts and the temperature is 26.11 degrees Celsius, and the notification results show a red LED as a danger sign.
2. When the battery is charged, the voltage shows 2.50 volts and the temperature is 29.08 degrees Celsius, and the notification results show a yellow LED as a warning sign.
3. When the battery is charged, the voltage shows 2.70 volts and the temperature is 30.86 degrees Celsius, and the notification results show a yellow LED as a warning sign.
4. When the battery is charged, the voltage shows 30.86 volts and the temperature is 26.00 degrees Celsius, and the notification results show a red LED as a danger sign.
5. When the battery is charged, the voltage shows 2.94 volts and the temperature is 29.09 degrees Celsius, and the notification results show a green LED as a safe sign.
6. When the battery is charged, the voltage shows 3.32 volts and the temperature is 34.52 degrees Celsius, and the notification results show a red LED as a danger sign.
7. When the battery is charged, the voltage shows 3.40 volts and the temperature is 32.52 degrees Celsius, and the notification results show a green LED as a safe sign.
8. When the battery is charged, the voltage shows 3.43 volts and the temperature is 27.55 degrees Celsius, and the notification results show a green LED as a safe sign.
9. When the battery is charged, the voltage shows 3.45 volts and the temperature is 33.55 degrees Celsius, and the notification results show a yellow LED as a warning sign.
10. When the battery is charged, the voltage shows 3.82 volts and the temperature is 29.57 degrees Celsius, and the notification results show a green LED as a safe sign.
11. When the battery is charged, the voltage shows 4.11 volts and the temperature is 32.64 degrees Celsius, and the notification results show a yellow LED as a warning sign.
12. When the battery is charged, the voltage shows 4.14 volts and the temperature is 35.90 degrees Celsius, and the notification results show a red LED as a danger sign.

Table 8. Application of Fuzzy Logic in Monitoring Battery Discharge Conditions

No.	Voltage	Temperature	Notification	Test Output	Fuzzy Logic Output	Error
1	4.24	34.18	Danger (red LED on)	8	8.85	9.60
2	3.88	29.89	Alert (yellow LED on)	4	4.65	13.97
3	3.78	28.58	Safe (green LED is on)	3	3.4	11.76
4	3.74	32.52	Alert (yellow LED on)	4	5.08	21.2
5	3.53	27.67	Safe (green LED is on)	1	1.32	24.24
6	3.41	28.12	Safe (green LED is on)	1	1.3	23.07
7	3.32	32.98	Danger (red LED on)	7	7.59	8.42
8	3.20	28.24	Safe (green LED is on)	1	1.28	21.87
9	2.87	28.87	Alert (yellow LED on)	4	3.99	0.25
10	2.95	34.98	Danger (red LED on)	7	8.76	19.07
11	2.80	29.04	Alert (yellow LED on)	5	5	0

No.	Voltage	Temperature	Notification	Test Output	Fuzzy Logic Output	Error
12	2.50	27.67	Alert (yellow LED on)	6	5	20
Average error						14.45

The description in the table above can be explained as follows:

1. In the condition of battery discharge, the voltage shows 4.24 volts, and the temperature is 34.18 degrees Celsius, the result is a notification showing a red LED as a danger sign.
2. In the condition of battery discharge, the voltage shows 3.88 volts, and the temperature is 29.89 degrees Celsius; the result is a notification that shows a yellow LED as a warning sign.
3. In the condition of battery discharge, the voltage shows 3.78 volts, and the temperature is 29.08 degrees Celsius; the notification results show a green LED as a safe sign.
4. In the condition of battery discharge, the voltage shows 3.74 volts, and the temperature is 32.52 degrees Celsius; the result is a notification that shows a yellow LED as a warning sign.
5. In the condition of battery discharge, the voltage shows 3.53 volts, and the temperature is 27.67 degrees Celsius; the notification results show a green LED as a safe sign.
6. In the condition of battery discharge, the voltage shows 3.41 volts, and the temperature is 28.12 degrees Celsius; the notification results show a green LED as a safe sign.
7. In the condition of battery discharge, the voltage shows 3.35 volts, and the temperature is 32.98 degrees Celsius; the result is a notification showing a red LED as a danger sign.
8. In the condition of battery discharge, the voltage shows 3.20 volts, and the temperature is 28.24 degrees Celsius; the notification results show a green LED as a safe sign.
9. In the condition of battery discharge, the voltage shows 3.23 volts, and the temperature is 25.14 degrees Celsius, the result is a notification that shows a yellow LED as a warning sign.
10. In the condition of battery discharge, the voltage shows 2.83 volts, and the temperature is 32.07 degrees Celsius, the result is a notification that shows a yellow LED as a warning sign.
11. In the condition of battery discharge, the voltage shows 2.80 volts, and the temperature is 29.04 degrees Celsius; the result is a notification that shows a yellow LED as a warning sign.
12. In the condition of battery discharge, the voltage shows 2.49 volts, and the temperature is 27.56 degrees Celsius, the result is a notification that shows a red LED as a danger sign.

4. Discussion

From the results of calibration tests with a digital multimeter, the INA219 sensor in measuring voltage in discharge conditions shows an average error of 0.35%, while in charge conditions, the average error is 0.97%. Then the results of the NTC thermistor sensor calibration in measuring battery temperature show an average error of 0.85% when compared with a digital thermometer measuring instrument. From the results of the calibration test, the INA219 sensor has good accuracy in measuring battery voltage in charge and discharge conditions, and the NTC thermistor is able to make accurate temperature measurements.

The system implementation involves several processes. First, the battery is determined to be charging or discharging. Then, the two sensors read the voltage and temperature data for the battery being measured. The obtained data are then entered into the fuzzy logic stage, with voltage and temperature as input variables. Then, in the inference stage, fuzzy rules are created to determine which rules should be applied. The final defuzzification stage is the final decision to determine the output, which will be a red, yellow, or green LED notification.

The battery monitoring system can read the battery voltage and temperature in discharge and charge conditions. In the discharge battery condition with a load of 2 LEDs, the battery voltage is at 3.92 volts with a current load of 1025.9 milliamperes and a temperature of 29.25 degrees Celsius. On the voltage and current graph, it decreases linearly until 150 minutes, the voltage is at 3.3 volts and the current load is at 643.2 milliamperes. The battery temperature in minutes 60-150 is at its highest

temperature peak at 38.95 degrees Celsius. Then the voltage drops again until in minute 240 the battery voltage is at 2.62 volts and the current is at 38 milliamperes. After 2 hours of testing, the graph forms a straight line which means the battery voltage has reached the lower limit and the current load is getting smaller. This shows that the battery is working optimally, the battery is able to supply power to the load within 2 hours and the temperature increases in the first 150 minutes which means the battery is working hard when supplying power to the LED lights. Afterward, the battery voltage was low enough to supply the load, and the LED light was dim.

The next test involved charging the battery. The battery was tested after the discharge test, with the battery voltage at 2.5 volts. The battery was charged using a TP4056 module with a 5 volt, 1 ampere specification. The graph shows a spike in battery voltage at 3.13 volts after 25 minutes, then a linear increase in battery voltage during charging. This occurs because the battery is low on power, so when it is charged, the current from the charger is immediately drawn into the battery. As the battery charges, the battery temperature also increases over 25 minutes, peaking at 39.90°C at 127-166 minutes. The temperature then decreases until charging is complete, when the battery voltage increases linearly during charging.

Table 9. Fuzzy Logic-based Battery Monitoring Testing

Voltage (Volt)	Temperature (Celsius)	Notification	Tool Output	MATLAB Output	Error (%)
3.76	36.41	Alert (Led Yellow On)	6.51	6.58	1.06

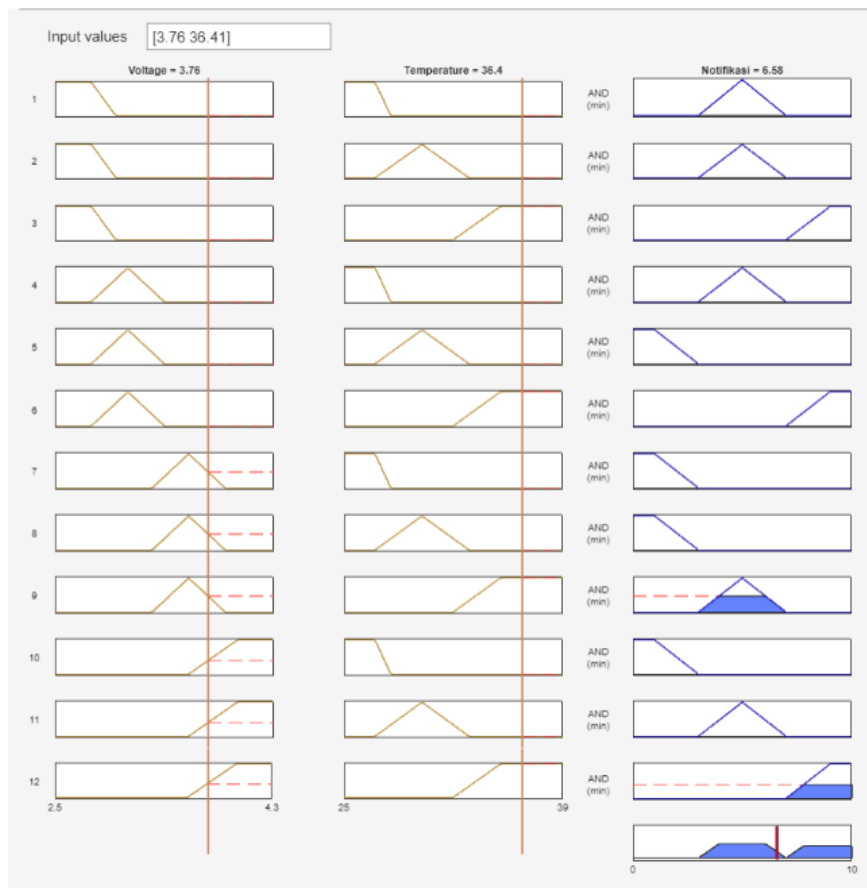


Figure 11. Fuzzy Logic Comparison

The fuzzy logic process, between the test tool and MATLAB, yielded quite satisfactory results with an average error value of 1.06% under discharge conditions. However, the results of this relatively small difference in the comparison of the tool and MATLAB tests did not affect the LED notification results as a warning on battery monitoring. In all tests in the fuzzy rules, the tool and MATLAB test results showed the same LED notification. So, even though there is a fairly large average error in the tool and MATLAB tests, the notification results remain the same and the overall system performance works well.

5. Conclusions

This research focuses on the development of a battery monitoring system using IoT-based fuzzy logic with INA219 sensors and NTC thermistors. The purpose of this research is to prevent excessive battery use and maintain battery health. This system is designed to show battery performance in real time by displaying voltage, temperature, and the use of fuzzy logic to get notification results as battery warnings when in discharge or charge conditions. The test results show that the system is able to work well in monitoring battery voltage and temperature accurately, and fuzzy logic successfully displays notifications. By using fuzzy logic, this system can make decisions to determine battery warning notifications in safe, alert, and dangerous conditions. In addition, the integration between the ESP8266 microcontroller, INA219 sensor, and NTC thermistor proves that the system can monitor the battery automatically. Several areas of this research method require further optimization to achieve more satisfactory results. Based on this research, a more complex protection system can be considered to maintain the output, prevent reverse current, and provide greater safety. Second, a sensor module with higher specifications than the INA219 sensor can be used to monitor batteries with higher voltages and currents.

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