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IoT-Based Electrical Parameter Monitoring System for Railway Level Crossing Gate Panels

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To speed up the handling of disruptions and improve safety at level crossings, an alternative system is needed to help officers deal with disruptions at level crossings. The implementation of an Internet of Things (IoT) system can be a solution for monitoring the actual condition of level crossings in real time. This system was developed using an ESP 32 microcontroller, an INA226 sensor, and an ACS712 sensor to measure battery voltage, motor voltage, and charger current. Monitoring is conducted through a website equipped with a Threshold Detection method to send early notifications via Telegram. Functionality testing using the black box method showed that the system operates as designed. Sensor accuracy testing revealed that the INA226 sensor has a voltage accuracy of 99.25%. However, the ACS712 20A sensor showed lower accuracy (65.26%) due to incorrect sensor type selection and noise during calibration.
Keywords: Monitoring, Railway Crossing Gate, IoT, Website, INA226, ACS712, Threshold Detection.

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1. Introduction

Level crossings are a key component of railway infrastructure that play a crucial role in ensuring the safety of both trains and road users. Nationwide, PT Kereta Api Indonesia (KAI) recorded 337 traffic accidents at level crossings throughout 2024, prompting KAI to proactively close 309 level crossings that did not meet safety requirements as stipulated in Ministry of Transportation Regulation No. 94 of 2018 [1]. PT Kereta Api Indonesia (KAI) Regional Division II West Sumatra, through its Signal and Telecommunications (Sintel) Resort, is responsible for the maintenance and repair of 34 level crossings (JPL). Based on data from January–April 2025, there were 35 malfunctions at railroad crossings, with 26% (9 cases) related to damage to batteries and chargers.

This situation is exacerbated by operational challenges, namely the large number of railroad crossings that must be monitored by a single signal and telecommunications resort, as well as the significant distance between the crossings and the resort office, which slows down the identification and resolution of malfunctions [2]. Moreover, delays in addressing technical malfunctions at railroad crossings create unsafe conditions that could potentially lead to accidents due to procedural failures [2]. This situation underscores the urgency of addressing these issues, given that railroad crossings are directly linked to human safety. Various previous studies have developed IoT-based railroad crossing control and monitoring systems to overcome the limitations of conventional monitoring, such as a railroad crossing control and monitoring system using an ESP32 and a database-connected Android application, because facilities for controlling and monitoring railroad crossing safety in Indonesia are still minimal, making it difficult for station personnel [3]. Another study developed a prototype of an IoT-based automatic railroad crossing gate using an ESP32, infrared sensors, a servo motor, and the Telegram app, driven by the fact that many crossing gates still operate manually, thereby increasing the risk of accidents due to operator negligence [4]. However, these

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studies generally focus on detecting passing trains and vehicles, rather than on the electrical conditions of the gate drive panel itself such as battery/charger voltage and current which, based on field data, are actually the dominant sources of malfunctions.

This study focuses on developing an IoT- and web-based voltage and current monitoring system for railroad crossing gate panels, using an ESP32 microcontroller integrated with current and voltage sensors. This type of IoT-based battery electrical monitoring approach has been applied to other backup power systems, such as monitoring the voltage, current, temperature, and state of charge (SoC) of batteries in recloser control panels [5]. The proposed system employs the Threshold Detection method to detect fault indications, drawing on an approach that has been proven capable of detecting faults with high accuracy and low sensor error in similar IoT-based early detection studies [6], and delivers early warnings to personnel via Telegram notifications and indicator color changes on the web interface. The scope of this research is limited to monitoring electrical parameters (voltage and current) on the railroad crossing gate panel as indicators of the condition of the battery and charger, without covering mechanical aspects or other components of the overall railroad crossing gate system.

Based on the above description, this study aims to design and implement an IoT- and web-based voltage and current monitoring system for railroad crossing gate panels, as well as to evaluate the system’s ability to detect early indications of malfunctions in batteries and chargers using the Threshold Detection method, thereby accelerating the process of identifying and addressing malfunctions by staff at the PT. KAI Divre II West Sumatra signal station.

2. Literature Review And Problem Statement

Previous research on IoT-based systems for railroad crossings has generally focused on mechanical automation and traffic detection, rather than on the electrical condition of the control panel itself. Nugraha et al. developed a control and monitoring system for railroad crossings using an ESP32 connected to a database and an Android app, with the aim of helping crossing guards monitor the status of the barriers and traffic congestion in the crossing area [3]. A similar approach was developed by Lestari et al., who designed a prototype of an automatic railroad crossing gate based on an ESP32, infrared sensors, a servo motor, and Telegram notifications, with a focus on object detection to trigger the automatic opening and closing of the gates [4]. Both studies demonstrate that the integration of the ESP32 and notification platforms such as Telegram has proven effective for remote monitoring of railroad crossing infrastructure; however, neither addresses aspects of electrical panel health such as voltage and current conditions in batteries and chargers which are actually the dominant causes of disruptions based on field data from the KAI Divre II Sumbar Sintel Resort (accounting for 26% of total disruptions). On the other hand, the application of the Threshold Detection method for early fault detection based on electrical parameters has proven effective in other domains: Dewantara applied the Threshold and Fuzzy Logic methods to detect operational faults in a Micro-Hydro Power Plant (PLTMH) with a detection accuracy of 100% and low voltage and current sensor errors [6], while Jatmiko designed an IoT-based system for monitoring voltage, current, temperature, and the state of charge (SoC) of batteries on recloser panel boxes to monitor battery condition as a backup power source [5].

A research gap identified from the above literature review is the lack of research integrating a Threshold Detection-based electrical monitoring approach which has proven effective in the domains of micro-hydro power plants and other backup power panels [5], [6] with the specific context of railroad crossings, which have distinct operational characteristics: a large number of locations, widely dispersed from the resort office, and limited staff resources for on-site inspections. Existing IoT studies on railroad crossings [3], [4] remain limited to mechanical and traffic detection aspects, while threshold-based electrical monitoring research

[5], [6] has not yet been applied to railroad crossings while considering the operational needs of the Sintel district, such as the integration of a website dashboard as a Human Machine Interface and early notifications via Telegram that staff can access remotely without having to conduct manual inspections at each crossing point.

Based on these gaps, the research problems are formulated as follows: (1) how to design an IoT- and website-based voltage and current monitoring system for railroad crossing panels capable of displaying electrical data in real time to Sintel Resort personnel; (2) To what extent can the Threshold Detection method be applied to accurately detect early indications of malfunctions in level crossing batteries and chargers; and (3) How effective are early warning mechanisms via Telegram and website indicators in accelerating the process of identifying and addressing malfunctions compared to the manual inspection methods currently in use.

3. Method

Research Methodology

This study employs the Research and Development (R&D) method by building upon the existing system[7]. In this study, the 4D model (Define, Design, Develop, Disseminate) was used to develop the system. The research stages were systematically designed as follows:

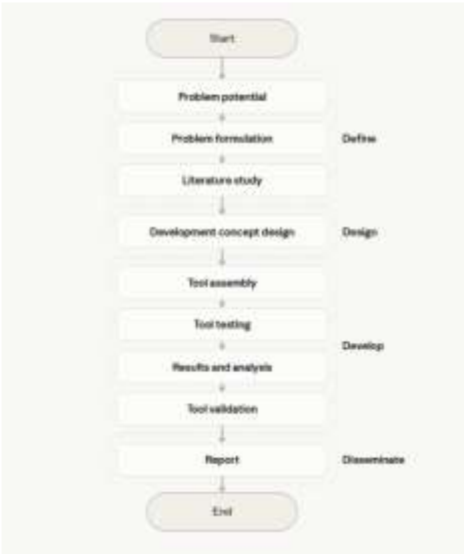

Figure 1. Diagram of the 4D R&D Research Model

1. Define: This stage involves identifying problems in the field, formulating the problem, and conducting a literature review to gather a theoretical foundation and compare it with previous studies.
2. Design: This stage focuses on system design, including component selection, the creation of wiring diagrams, the physical design of the device enclosure, and the design of the website interface.
3. Develop: This phase involves hardware assembly and software development (programming the ESP32 using the Arduino IDE and website development). System functionality and accuracy are also tested during this phase.
4. Disseminate: The final stage, in which the research results are documented in a final project report.

Hardware Design

Hardware design is the process of designing and developing devices. The design process consists of several stages, including:

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1. Device Requirements, assembling the device requires several hardware components, including:
   a. ESP32 microcontroller
   b. INA 226 Sensor
   c. ACS 712 Sensor
   d. HCSR 12V Relay
   e. TP 4056 module
   f. SX 1308 Module
   g. On/Off Push Button
   h. 3.7-volt lithium battery
   i. Jumper Cable
2. Wiring Diagram
   Based on the selection of components above, a wiring diagram was created to provide a visual representation that serves as a guide for assembling the hardware circuit. This diagram makes it easier to understand the connection paths between components and their physical layout.

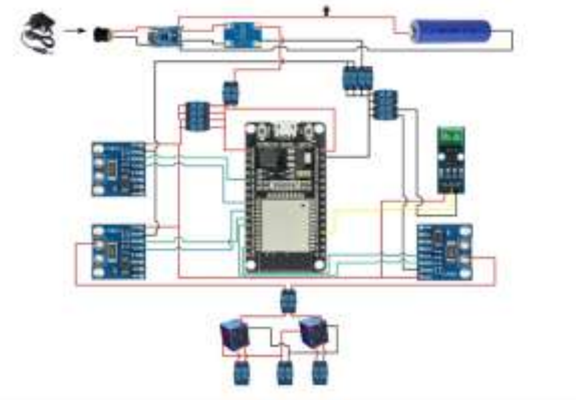

Fig 2. Wiring Diagram of the Device

3. Assembly Results
   The results of the hardware design were implemented in the device assembly. The device assembly was based on the design as outlined in the wiring diagram. The results of the device assembly are as follows:

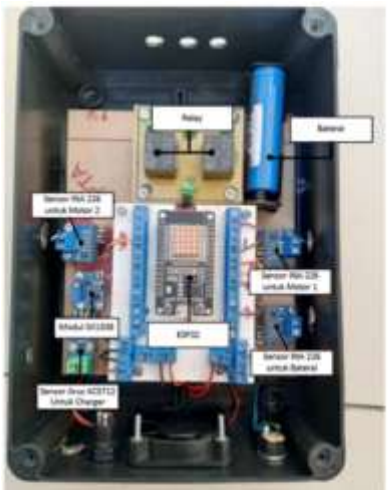

Fig 3. Device Assembly Results

Software Design

1. Website
   The website serves as an interface for monitoring the voltage and current values on the railroad crossing gate panel. For the voltage and current values, there are three indicator colors (green,

yellow, red) that change based on using a threshold method. The website also includes several other features, such as monitoring graphs and summaries of monitoring data in Excel and PDF formats.

Fig 4. Monitoring Website Display

Fig 5. Monitoring Data Graph Display

2. Telegram
   The Telegram platform is used as a medium to send notifications when there are indications of a disruption. A threshold method is used to trigger notifications if the values of monitored variables fall outside the threshold limits. Warning messages can be sent to all personnel by adding "id_telegram" to the device's program.

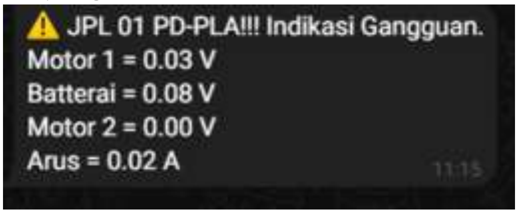

Figure 6. Telegram Message Display

Device Testing

Testing is used to determine and measure the success rate of the tool's development. Testing is conducted using several methods, including:

1. Black Box Testing
   This testing focuses on verifying functionality from an external perspective, without considering the program code or its internal structure. The goal is to ensure that the functionality of the assembled device conforms to the design specifications.
2. Sensor Testing
   Sensor testing is performed by comparing the sensor readings with those of a measuring instrument. A multimeter is used to measure voltage, while an amp clamp is used to measure current.

The measurement results are analyzed by calculating the measured values using the following formula [8]:

1. Deviation, deviation is the difference between the sensor reading and the measuring instrument reading.
2. Error Percentage
   The error percentage is the percentage of the difference between the measuring instrument's value and the sensor's value.

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$$\%\text{error} = \left[\frac{\text{Measured value} - \text{Sensor value}}{\text{Measured value}}\right] \text{x } 100\ \%$$

From the total %error values, an average can be calculated to represent the value of the entire dataset.

$$\text{Average }\%\text{error} = \frac{\sum \%\text{error}}{\text{n}}$$

3. Percentage Accuracy

   The accuracy percentage is calculated by subtracting the error percentage from 100%. This value indicates the accuracy of the sensor's measurements relative to the measuring instrument.

$$\%\text{accuracy} = 100\% - \%\text{error}$$

From the overall accuracy percentages, an average accuracy value can be calculated to represent the entire dataset.

$$\text{Average }\%\text{accuracy} = \frac{\sum \%\text{accuracy}}{\text{n}}$$

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4. Results And Discussion

Functionality Test Results

This testing verifies that all hardware components function as intended by the design. Functionality testing was conducted using the *black-box* testing method by providing a questionnaire to the testers. The testers were tasked with validating the consistency between the expected results and the actual results of the hardware testing. Based on the testing that was conducted, the results show that:

Table 1. Hardware Functionality Testing

No	Test Scenario	Expected Results	Test Results			
			Tester 1		Tester 2	
			A	D	A	D
1	Connecting the power supply to the INA 226 voltage sensor	The sensor displays the voltage value on the serial monitor	✓		✓	
2	Connecting the power supply to the ACS 712 current sensor	The sensor displays the current value on the serial monitor	✓		✓	
3	Connecting the 5V adapter to the socket	The TP4058 *charger* module turns on	✓		✓	
4	Press the *on/off button* on	Turning the monitoring device on and off	✓		✓	
5	Measuring the voltage on the voltage booster module	Boosting the voltage from 3.7 volts from the charger module to 5 V	✓		✓	
6	Connecting the fan to the 5 V power supply on the ESP32	The fan will turn on when supplied with a 5 V input	✓		✓	
7	Upload the program to the ESP32	Programs created in the Arduino IDE can be uploaded to the ESP32 via the USB port	✓		✓	

Table 1. contains the functionality test data for the hardware design. The test results show that the hardware as a whole function in accordance with the device design.

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Table 2. Website Functionality Testing

No	Test Scenario	Expected Results	Test Results: Tester 1 A	Tester 1 D	Tester 2 A	Tester 2 D
1	Test the JPL selection in the JPL list *dropdown* menu	The system redirects to the monitoring page for the selected JPL	✓		✓	
2	Test for selecting a monitoring period from the period *dropdown* menu	The data period displayed on the graph changes according to the selection (1 day, 1 week, 1 month)	✓		✓	
3	Test the color changes of the indicators for the 4 monitoring variables	The colors change according to the intervals specified in the legend	✓		✓	
4	Changes to the indicators on the summary page	The indicator color changes from red to yellow to green	✓		✓	
5	Time and date display	The time and date are correct and accurate	✓		✓	
6	Test the monitoring variable *dropdown* menu	Monitoring variables can be changed (all, current, battery, motor 1, motor 2)	✓		✓	
7	Test *zooming out* and *in* on the graph	The graph can be *zoomed out* or *zoomed in*	✓		✓	
8	Test the *zoom reset* button	The chart view will return to its *default* settings	✓		✓	
9	Test the "*Export to PDF*" button	The system will download the monitoring data in PDF format	✓		✓	
10	Test the "*Export to Excel*" button	The system will download the monitoring data in Excel format	✓		✓	

Table 2 presents the results of the black-box testing on the website's monitoring page. The test results show that all features on the website's monitoring page function as intended. In general, this page is able to display monitoring variable values and visualize them in graph form.

Sensor Test Results

Sensor testing was conducted to determine the accuracy of sensor readings by comparing them with measurements from a measuring instrument. The sensor testing was divided into:

Battery Voltage Sensor Testing

Table 3. Battery Voltage Analysis Results 1

Experiment	Voltage Reading (VDC)		Deviation	*Error %*	Accuracy %
	INA 226	Multimeter			
1	13.36	13.08	0.28	2.14	97.86
2	13.21	13.06	0.15	1.15	98.85
3	13.17	13.15	0.02	0.15	99.85
4	13.39	13.17	0.22	1.67	98.33
5	13.39	13.18	0.21	1.59	98.41
6	13.38	13.18	0.20	1.52	98.48
7	13.39	13.18	0.21	1.59	98.41
8	13.38	13.18	0.20	1.52	98.48

Experiment	Voltage Reading (VDC)		Deviation	*Error %*	Accuracy %
	INA 226	Multimeter			
9	13.39	13.19	0.20	1.52	98.48
10	13.39	13.19	0.20	1.52	98.48
11	13.39	13.2	0.19	1.44	98.56
12	13.39	13.2	0.19	1.44	98.56
13	13.4	13.2	0.20	1.52	98.48
14	13.39	13.2	0.19	1.44	98.56
15	13.38	13.2	0.18	1.36	98.64
16	13.39	13.2	0.19	1.44	98.56
17	13.4	13.2	0.20	1.52	98.48
18	13.39	13.2	0.19	1.44	98.56
19	13.4	13.2	0.20	1.52	98.48
20	13.39	13.2	0.19	1.44	98.56
Average	**13.37**	**13.18**	**0.19**	**1.45**	**98.55**

Testing of the battery voltage sensor was conducted using 20 random samples. Based on the data in Table 3, the average difference (deviation) between the sensor's readings and those of the measuring instrument was found to be 0.19 volts. The sensor's reading accuracy relative to the measuring instrument reached 98.55%, indicating a high level of accuracy in measuring voltage values

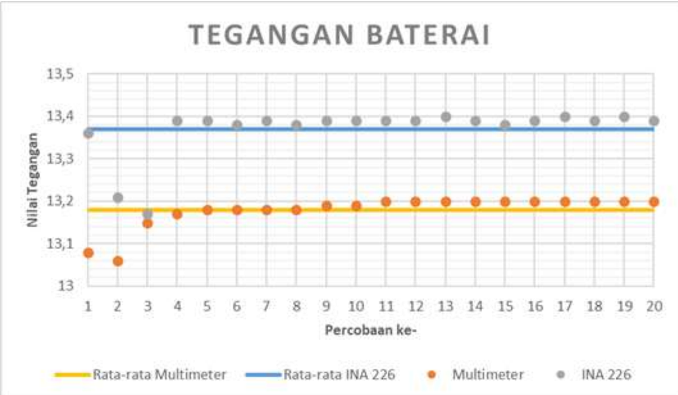

Fig 7. Battery Voltage Graph

Figure 7. show a scatter plot. This graphical visualization helps to understand the distribution of the test results. It can be seen that the battery voltage test results are relatively constant, with the distribution of the measurement results clustered near the average reading line. Motor 1 Voltage Sensor Testing

Table 4. Motor Voltage Analysis 1

Experiment	Voltage Reading (VDC)		Deviation	*Error %*	Accuracy %
	INA 226	Multimeter			
1	13.4	13.36	0.04	0.30	99.70
2	13.39	13.36	0.03	0.22	99.78
3	13.4	13.4	0	0.00	100.00
4	13.4	13.36	0.04	0.30	99.70
5	13.4	13.37	0.03	0.22	99.78
6	13.4	13.37	0.03	0.22	99.78
7	13.4	13.36	0.04	0.30	99.70
8	13.4	13.36	0.04	0.30	99.70
9	13.4	13.37	0.03	0.22	99.78

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Experiment	Voltage Reading (VDC)		Deviation	*Error %*	Accuracy %
	INA 226	Multimeter			
10	13.4	13.37	0.03	0.22	99.78
11	13.4	13.36	0.04	0.30	99.70
12	13.4	13.37	0.03	0.22	99.78
13	13.38	13.37	0.01	0.07	99.93
14	13.4	13.36	0.04	0.30	99.70
15	13.4	13.36	0.04	0.30	99.70
16	13.39	13.36	0.03	0.22	99.78
17	13.4	13.36	0.04	0.30	99.70
18	13.4	13.37	0.03	0.22	99.78
19	13.4	13.37	0.03	0.22	99.78
20	13.4	13.36	0.04	0.30	99.70
Average	**13.40**	**13.37**	**0.033**	**0.24**	**99.76**

Testing of the voltage sensor for Motor 1 was conducted by taking 20 random samples. Based on the data in Table 4, the average difference (deviation) between the sensor readings and those of the measuring instrument was found to be 0.033 volts. The accuracy of the sensor readings relative to the measuring instrument reached 99.76%, indicating a high level of accuracy in reading voltage values.

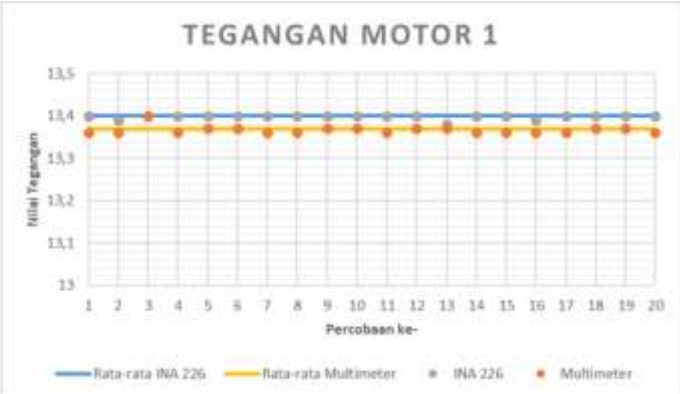

Fig 8. Voltage Graph for Motor 1

Figure 8. shows a scatter plot of the voltage measurements on Motor 1. From this graph, it can be seen that the lines representing the average sensor readings and multimeter readings are very close together, indicating a low level of measurement error in the sensor. The data in the graph also shows that the voltage readings from the sensor and multimeter are relatively stable.

Testing the Voltage Sensor on Motor 2

Table 5. Voltage Analysis of Motor 2

Experiment	Voltage Reading Results (VDC)		Deviation	*Error %*	Accuracy %
	INA 226	Multimeter			
1	13.44	13.36	0.08	0.60	99.40
2	13.44	13.36	0.08	0.60	99.40
3	13.44	13.37	0.07	0.52	99.48
4	13.44	13.38	0.06	0.45	99.55
5	13.45	13.38	0.07	0.52	99.48
6	13.44	13.37	0.07	0.52	99.48
7	13.44	13.37	0.07	0.52	99.48

Experiment	Voltage Reading Results (VDC)		Deviation	*Error %*	Accuracy %
	INA 226	Multimeter			
8	13.45	13.37	0.08	0.60	99.40
9	13.45	13.37	0.08	0.60	99.40
10	13.45	13.37	0.08	0.60	99.40
11	13.44	13.37	0.07	0.52	99.48
12	13.45	13.37	0.08	0.60	99.40
13	13.44	13.37	0.07	0.52	99.48
14	13.45	13.37	0.08	0.60	99.40
15	13.45	13.37	0.08	0.60	99.40
16	13.44	13.37	0.07	0.52	99.48
17	13.44	13.37	0.07	0.52	99.48
18	13.45	13.38	0.07	0.52	99.48
19	13.44	13.37	0.07	0.52	99.48
20	13.45	13.37	0.08	0.60	99.40
Average	**13.44**	**13.37**	**0.07**	**0.55**	**99.45**

Testing of the voltage sensor for Motor 2 was conducted by taking 20 random samples. Based on the data in Table 5. the average difference (deviation) between the sensor readings and those of the measuring instrument was found to be 0.07 volts. The accuracy of the sensor readings relative to the measuring instrument reached 99.45%, indicating a high level of accuracy in measuring voltage values.

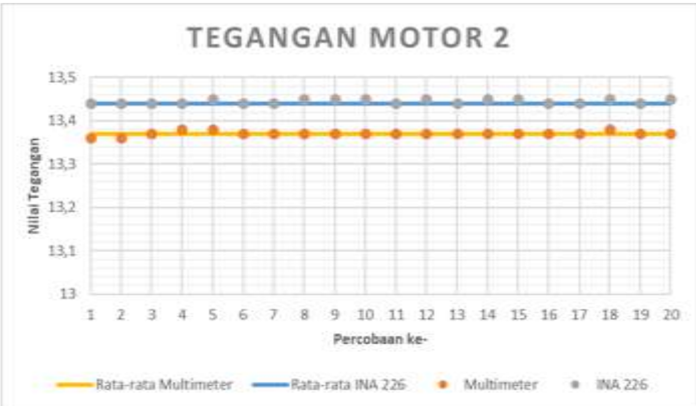

Figure 9. Voltage Graph for Motor 2

Figure 9. Voltage Measurement Results for Motor 2 From this graph, it can be seen that the sensor and multimeter readings lie very close to the mean line, indicating a low measurement error for the sensor. The data in the graph also show that the voltage readings from the sensor and multimeter are relatively stable.
Testing the ACS712 Current Sensor

Table 6. Charger Current Analysis

Experiment	Current Reading Results (Amperes)		Deviation	*Error %*	Accuracy %
	ACS 712 20A	Ampere Clamp			
1	0.86	1.04	0.18	17.31	82.69
2	0.75	1.31	0.56	42.75	57.25
3	1.08	1.34	0.26	19.40	80.60
4	0.75	1.38	0.63	45.65	54.35
5	0.80	1.4	0.6	42.86	57.14
6	0.78	1.39	0.61	43.88	56.12

Experiment	Current Reading Results (Amperes)		Deviation	*Error %*	Accuracy %
	ACS 712 20A	Ampere Clamp			
7	0.82	1.32	0.5	37.88	62.12
8	0.83	1.3	0.47	36.15	63.85
9	0.95	1.23	0.28	22.76	77.24
10	0.87	1.35	0.48	35.56	64.44
11	0.95	1.44	0.49	34.03	65.97
12	0.82	1.32	0.5	37.88	62.12
13	0.97	1.36	0.39	28.68	71.32
14	0.79	1.4	0.61	43.57	56.43
15	0.83	1.44	0.61	42.36	57.64
16	0.77	1.43	0.66	46.15	53.85
17	1.18	1.36	0.18	13.24	86.76
18	1.00	1.38	0.38	27.54	72.46
19	0.96	1.41	0.45	31.91	68.09
20	0.79	1.44	0.65	45.14	54.86
Average	**0.88**	**1.35**	**0.47**	**34.74**	**65.26**

Table 6 shows the analysis results indicating that the average reading from the ACS712 sensor is 0.88 amperes, while the average reading from the clamp meter is 1.35 amperes. From this data, a fairly large average deviation of 0.47 amperes was found. From the data in Table 4.4, it is known that the sensor reading accuracy is 65.26%, with an error of 34.74%. These values indicate that the accuracy of the sensor readings is poor.

Fig 10. Charger Current Graph

The scatter plot in Figure 10 shows the distribution of the charger current test results. From the graph, it can be seen that all current values read by the ACS712 sensor are below those read by the clamp meter. The error margin of the ACS712 sensor is influenced by the offset voltage value. When measured with a multimeter, the offset voltage was 2.48 V, which deviates by 0.02 V from the standard value of 2.5 V specified in the program code. This discrepancy directly affects the sensor's calculation results. Therefore, using a sensor with a lower measurement range, such as the ACS712 5A (with a sensitivity of 0.185 V/A), will provide better accuracy. This is because the measured battery current ranges only from 1 to 4.5 A, and selecting the appropriate sensor can reduce sensor reading noise.

5. Conclusion

Based on the research findings, an IoT- and web-based voltage and current monitoring system for railroad crossing gates has been successfully developed to support early detection of malfunctions. This system integrates an ESP32 microcontroller with an INA226 voltage sensor and an ACS712 current sensor to measure data in real time, display it on a web interface, and send notifications via Telegram. Functional testing using the black-box method showed that the system operates as designed. As for the sensor accuracy test results, the INA226 sensor demonstrated a high voltage accuracy rate of 99.25%, while the ACS712 sensor showed lower accuracy (65.26%). The low accuracy of the ACS712 was attributed to an error in sensor type selection and the presence of noise during calibration.

Based on the research findings, there are several recommendations for future research. In future studies, greater care should be taken in selecting sensors; for example, replacing the ACS712 20A current sensor with a type that has a lower measurement range, such as the ACS712 5A, to improve measurement accuracy and reduce noise. In addition, the features on the website need to be optimized and developed to improve functionality and make it easier for staff to access informative data. Testing the device over a longer period is also recommended to analyze its stability and performance under various operational conditions.

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