Design and Implementation of an Unbalanced Load Monitoring System Using Lora-Based Wireless Sensor at State Polytechnic of Malang

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Abstract— **Load imbalance in three-phase electrical systems remains a common issue, particularly in educational environments such as laboratories. This is caused by uneven load distribution across phases, which can result in power losses, excessive heat, and equipment damage. Currently, there is no monitoring system capable of automatically and real-time detecting load imbalance within a local scope. This research aims to design a load imbalance monitoring system for three-phase electrical systems using LoRa-based wireless sensor technology. The system is designed to read voltage, current, and power in real time using the PZEM-016 sensor and transmit data wirelessly using the LoRa RFM95W module. Testing showed that the system successfully transmitted data from the transmitter to the receiver with a 100% success rate, and the average reading error of the PZEM-016 sensor was 0.842% compared to a standard measuring instrument. The received data was successfully stored in Firebase and displayed as tables and graphs on a website dashboard. This system has been implemented in the Telecommunications Engineering Laboratory of Politeknik Negeri Malang, and the monitoring results indicate load imbalance across phases exceeding the PLN (Indonesian national utility) standard threshold of 10%, thus enabling the system to automatically provide warning notifications.**

***Keywords*— Firebase, LoRa RFM95W, PZEM-016, Unbalanced Load.**

I. INTRODUCTION

Three-phase electrical systems are widely used in large-scale power distribution due to their ability to deliver greater power with the same conductor size and current compared to single-phase systems, making them more efficient and economical. In principle, a balanced three-phase system ensures equal load distribution among the R, S, and T phases. However, in practice, perfect balance is rarely achieved due to unequal load distribution, especially in environments with diverse and varying electrical equipment [1].

In the Telecommunications Engineering Laboratory of Malang State Polytechnic, unbalanced loads often occur due to uneven usage of electrical devices across phases. Such imbalance results in unequal phase currents, causing a non-zero neutral current, which can lead to excessive heat, power losses, or even equipment damage. Currently, there is no automated real-time monitoring system to detect load imbalances locally, which increases the risk of prolonged operation under unsafe conditions.

To address this, a wireless three-phase load monitoring system is proposed, integrating the PZEM-016 sensor for measuring voltage, current, and power with LoRa RFM95W for data transmission [2]. LoRa (Long Range) is a low-power, long-range wireless communication technology operating in sub-GHz ISM bands (e.g., 433 MHz, 868 MHz, and 915 MHz). It employs Chirp Spread Spectrum (CSS) modulation, which enables robust communication over distances of several kilometers while maintaining low energy consumption [3]. These characteristics make LoRa particularly suitable for Internet of Things (IoT) and Wireless Sensor Network (WSN) applications where long-distance data transmission and minimal maintenance are required.

According to PLN standards (SK ED PLN No.0017.E/DIR/2014), a three-phase system is considered within safe operating conditions if the imbalance is less than 10% [2]. This research aims to design and implement a LoRa-based wireless monitoring system capable of detecting load imbalances exceeding this threshold and providing early warning notifications via a web-based dashboard [4]. In a three-phase electrical system, there are two main connection configuration types, namely the star (Y) and delta (Δ) circuits [5].

To determine the magnitude of the load imbalance on each phase, the following equation can be used [3]:

$$I_{rata-rata} = \frac{I_R + I_S + I_T}{3} \quad (1)$$

$$I_R = a \, . \, I_{rata-rata}, \quad a = \frac{I_R}{I_{rata-rata}} \quad (2)$$

$$I_S = b \, . \, I_{rata-rata}, \quad b = \frac{I_S}{I_{rata-rata}} \quad (3)$$

$$I_T = c \, . \, I_{rata-rata}, \quad c = \frac{I_T}{I_{rata-rata}} \quad (4)$$

After obtaining the values of coefficients a, b, and c, the percentage of imbalance can be determined using the following equation:

$$\frac{|a-1|+|b-1|+|c-1|}{3} \times 100\% \quad (5)$$

PZEM-016 AC Energy Meter to measure voltage, current, active power, energy, frequency, and power factor [6]. The PZEM-016 module does not have a display function, therefore, data is sent via RS-485 UART (Universal Asynchronous Receiver-Transmitter) Serial Converter [7]. The PZEM sensor can provide accurate information about the electrical condition of a load. The PZEM sensor operates by utilizing technology that can read values of voltage, current, frequency, and power in a specific environment [8].

The Long Range (LoRa) communication model is used to send data via radio frequency, using a transmitter as the sender of the data and a receiver as the recipient of the data [9]. LoRa is also a long-range, low-power, and low-bitrate wireless system. LoRa is one of the Low Power Wide-Area Network (LPWAN) protocols[10]. The RSSI value is influenced by several parameters, one of which is distance; the further the distance between the sender and the receiver, the weaker the received signal will be [11]. In addition, the environment between the sender and receiver also affects the received signal [12] [13].

The objectives of this research are :

1. To design a LoRa-based wireless monitoring system for detecting unbalanced loads in three-phase electrical networks.

2. To develop a real-time measurement platform for voltage, current, and power using the PZEM-016 sensor.

3. To implement an online monitoring interface that issues alerts when load imbalance exceeds the safety limit defined by PLN.

By combining long-range, low-power communication capabilities with accurate electrical parameter sensing, this system offers an efficient, low-complexity solution for improving electrical reliability in educational and industrial environments, while also serving as a practical learning tool for students in the field of wireless sensor applications [14] [15].

II. METHOD

The proposed system is designed to detect and monitor unbalanced loads in a three-phase electrical network using wireless communication. It consists of a transmitter node that measures electrical parameters from each phase and a receiver node that collects and displays the data through a monitoring dashboard.

A. Block Diagram System

The unbalanced three-phase load monitoring system is designed using a wireless communication link based on the LoRa RFM95W module. The overall system is divided into two main parts: the Transmitter Node (TX) and the Receiver Node (RX).

The transmitter node is responsible for measuring three-phase electrical parameters and transmitting the processed data to the receiver node. The receiver node receives, processes, and displays the data to the user via an online monitoring dashboard.

The complete system block diagram is shown in Figure 1, which illustrates the data flow from the measurement stage to the user interface.

Block Diagrams can be seen in Figure 1.

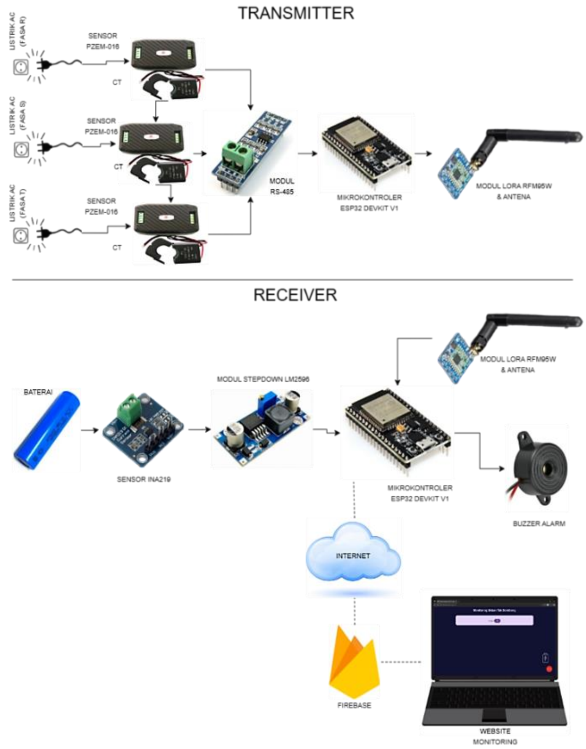


Figure 1. Block Diagram

B. System Description

1) Transmitter :

The Transmitter Node acts as the main data acquisition unit. Three PZEM-016 sensors are used to measure the electrical parameters of each phase: R, S, and T. Each sensor can measure voltage, current, active power, energy consumption, and power factor in real time.

Since the PZEM-016 communicates using the RS-485 protocol, an RS-485 to TTL converter is required to interface the sensor with the ESP32 microcontroller. The ESP32 processes the measurement data from the three sensors simultaneously and sends the processed data to the LoRa RFM95W module via the SPI interface for wireless transmission.

The TX node is powered from an AC source which is converted to the required DC levels using a step-down converter. This configuration ensures continuous real-time monitoring, where any change in load condition is immediately sent to the RX node.

2) Receiver :

The Receiver Node receives data sent from the TX node through the LoRa RFM95W module connected to the ESP32. Once the data is received, the ESP32 processes it for display on the web-based monitoring dashboard.

In addition to processing measurement data, the RX node includes an INA219 sensor to monitor the voltage and current of the system's battery supply. If the battery voltage drops below a predefined threshold, the buzzer alarm is triggered as an alert to the user. The processed data is stored in the Firebase Realtime Database, from which it is displayed to the user in real time through the online dashboard.

C. Components Description

1) Sensor PZEM-016: A power measurement module capable of measuring voltage, current, active power, energy, and power factor. Communication is carried out via the RS-485 protocol, enabling reliable long-distance data transmission.

2) ESP32: A microcontroller with built-in Wi-Fi and Bluetooth connectivity. In the transmitter node, it collects data from the PZEM-016 sensors and sends it via LoRa. In the receiver node, it receives LoRa data and uploads it to Firebase.

3) LoRa RFM95W: A low-power long-range wireless communication module operating at 915 MHz, used for transmitting data between the transmitter and receiver nodes.

4) RS-485 To TTL Converter: A signal converter that adapts RS-485 differential signals from the PZEM-016 to TTL levels compatible with the ESP32.

5) Sensor INA219: A current and voltage sensor used in the RX node to monitor the battery supply status.

6) Buzzer Alarm: An audio actuator used to alert users when battery voltage is low or when an excessive unbalanced load is detected.

7) LM2596 Step-Down Converter: A voltage regulator that steps down battery or AC-converted voltage to the appropriate operating levels for the ESP32 and other electronics.

8) Firebase Realtime Database: A cloud-based data storage platform used to log measurement data and serve it to the monitoring dashboard in real time.

D. Schematic Diagram

Transmitter Schematic Diagram can be seen in Figure 2.

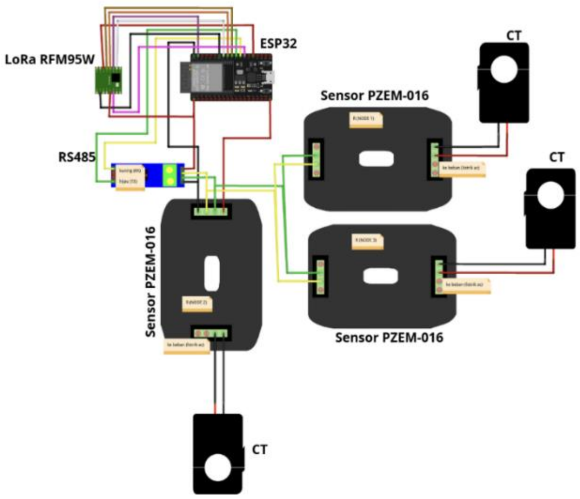


Figure 2. Transmitter Schematic Diagram

Receiver Schematic Diagram can be seen in Figure 3.

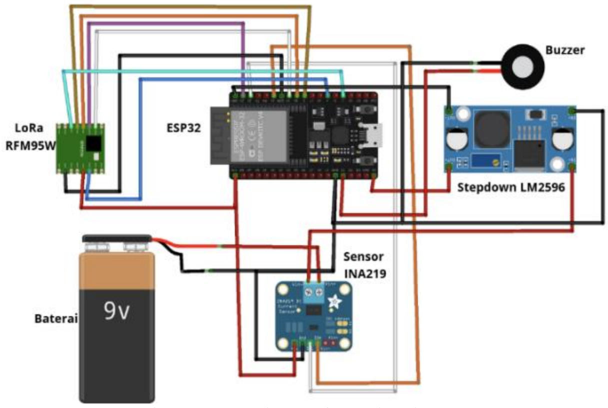


Figure 3. Receiver Schematic Diagram

III. RESULTS AND DISCUSSION

The results and discussion chapter is a chapter that contains the results and discussion of the implementation of the design planning that has been done in the research methods chapter.

A. Implementation of Hardware

Transmitter's Box can be seen in Figure 4.

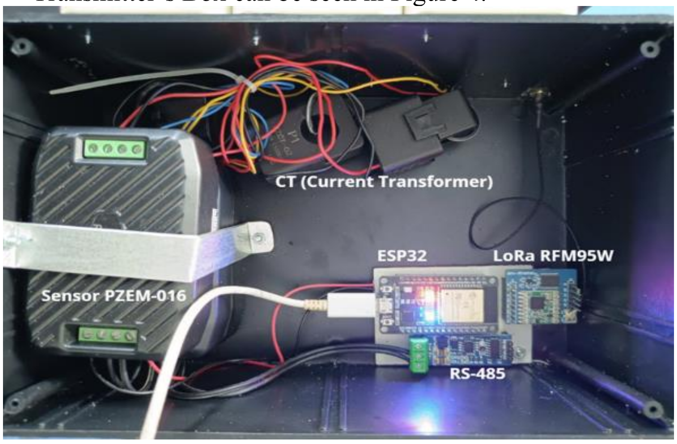


Figure 4. Transmitter's Box

Receiver's Box can be seen in Figure 5.

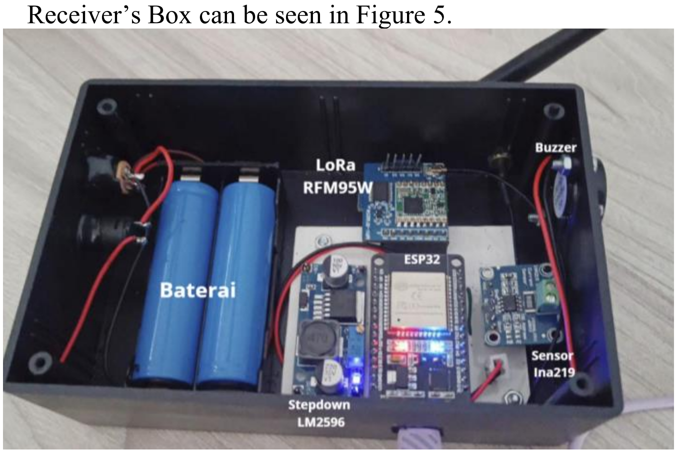


Figure 5. Receiver's Box

Sensor PZEM 016 Testing Without Load can be seen in Figure 6.

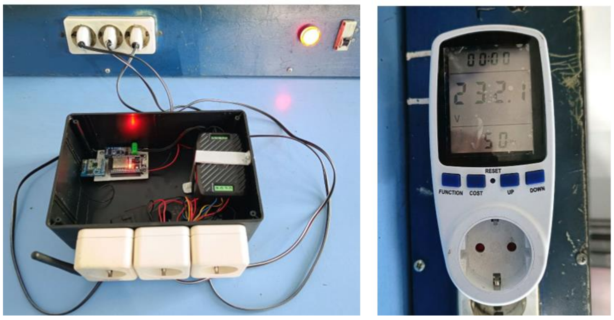


Figure 6. Sensor PZEM 016 Testing Without Load

Sensor PZEM 016 Testing With Load can be seen in Figure 7.

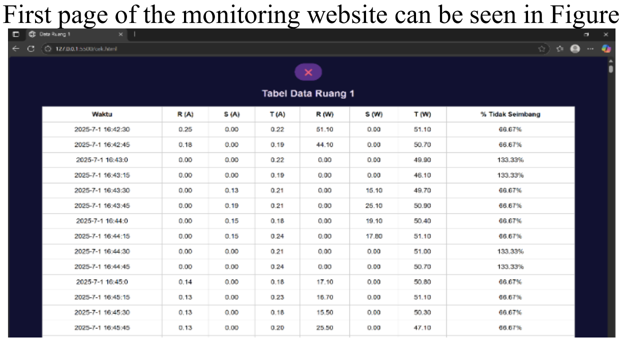
Figure 7. Sensor PZEM 016 Testing With Load

B. Implementation of Software

First page of the monitoring website can be seen in Figure 8.

Figure 8. First page of the monitoring website

First page of the monitoring website can be seen in Figure 9.



Tabel Data Ruang 1

Waktu	R (A)	S (A)	T (A)	R (W)	S (W)	T (W)	% Tidak Seimbang
2025-7-1 16:42:30	0.25	0.00	0.22	51.10	0.00	51.10	66.67%
2025-7-1 16:42:45	0.18	0.00	0.19	44.10	0.00	50.70	66.67%
2025-7-1 16:43:0	0.00	0.00	0.22	0.00	0.00	49.90	133.33%
2025-7-1 16:43:15	0.00	0.00	0.19	0.00	0.00	46.10	133.33%
2025-7-1 16:43:30	0.00	0.13	0.21	0.00	15.10	49.70	66.67%
2025-7-1 16:43:45	0.00	0.19	0.21	0.00	25.10	50.90	66.67%
2025-7-1 16:44:0	0.00	0.15	0.18	0.00	19.10	50.40	66.67%
2025-7-1 16:44:15	0.00	0.15	0.24	0.00	17.80	51.10	66.67%
2025-7-1 16:44:30	0.00	0.00	0.21	0.00	0.00	51.00	133.33%
2025-7-1 16:44:45	0.00	0.00	0.24	0.00	0.00	50.70	133.33%
2025-7-1 16:45:0	0.14	0.00	0.18	17.10	0.00	50.80	66.67%
2025-7-1 16:45:15	0.13	0.00	0.23	16.70	0.00	51.10	66.67%
2025-7-1 16:45:30	0.13	0.00	0.18	15.50	0.00	50.30	66.67%
2025-7-1 16:45:45	0.13	0.00	0.20	25.50	0.00	47.10	66.67%

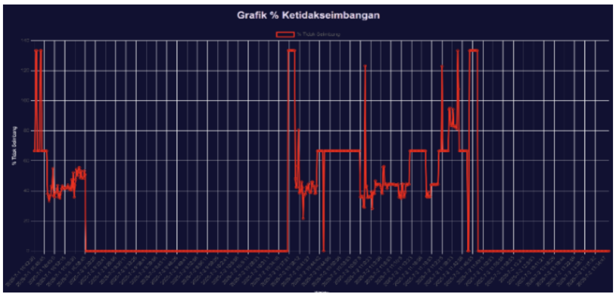


Figure 9. The page if you click the 'check' icon

C. LoRa Communication Testing

The purpose of this test is to evaluate the data transmission performance between nodes using the LoRa RFM95W module at various distances. The RSSI value is measured to determine the signal strength and the effective range of the system's wireless communication. Lora RFM95W Testing Results can be seen in Table 1.

TABLE I
LORA RFM95W TESTING RESULTS

Distance (m)	Status LoRa	Average value of RSSI (dBm)
2	Success	- 51
4	Success	-66
6	Success	-75
8	Success	-80
10	Success	-84
12	Success	-94
14	Success	-96
16	Success	-102
18	Success	-103
20	Success	-105

The test results in Table I show that the RSSI value for LoRa RFM95W has the best value of -51 dBm at a distance of 2 meters and the worst value of -105 dBm at a distance of 20 meters. Comparison Chart of Distance against RSSI values can be seen in Figure 10.

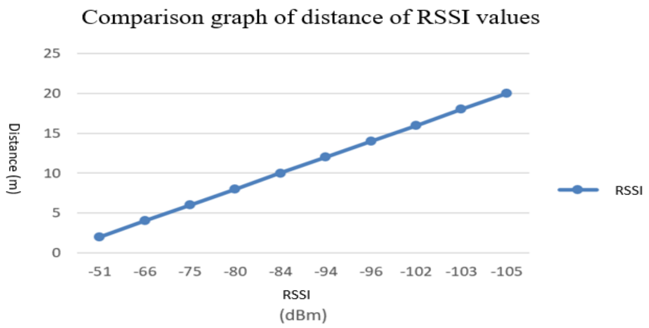


Figure 10. Comparison Chart of Distance against RSSI values

From Figure 10, it can be seen that the farther the distance between the transmitter and receiver, the lower the RSSI value becomes (more negative).

Overall Test Result can be seen in Table 2.

TABLE II
OVERALL TEST RESULT

Step	Load	Phase	Tx (V)	Tx (I)	Tx (W)	Status LoRa	Rx (V)	Rx (I)	Rx (W)	Sensor Ina219	Notification *Website* Yes	Notification *Website* No
1	a	R	236.10	0.10	10.3	Success	236.10	0.10	10.3	7.69	×	
	b	S	234.90	0.21	51.10	Success	234.90	0.21	51.10	7.69	×	
	c	T	234.90	0.33	36.20	Success	234.90	0.33	36.20	7.69	×	
2	a	R	236.3	0.09	12.70	Success	236.3	0.09	12.70	7.69	×	
	b	S	235.30	0.22	51.10	Success	235.30	0.22	51.10	7.69	×	
	c	T	232.20	0.33	36.50	Success	232.20	0.33	36.50	7.69	×	
3	a	R	236.5	0.09	12.60	Success	236.5	0.09	12.60	7.68	×	
	b	S	235.20	0.21	51.10	Success	235.20	0.21	51.10	7.68	×	
	c	T	235.20	0.33	35.00	Success	235.20	0.33	35.00	7.68	×	
4	a	R	236.40	0.10	10.20	Success	236.40	0.10	10.20	7.68	×	
	b	S	235.20	0.21	51.10	Success	235.20	0.21	51.10	7.68	×	
	c	T	235.10	0.34	36.70	Success	235.10	0.34	36.70	7.68	×	
5	a	R	236.40	0.09	12.60	Success	236.40	0.09	12.60	7.68	×	
	b	S	235.10	0.21	51.10	Success	235.10	0.21	51.10	7.68	×	
	c	T	235.10	0.36	38.20	Success	235.10	0.36	38.20	7.68	×	
6	a	R	236.40	0.09	12.70	Success	236.40	0.09	12.70	7.68	×	
	b	S	235.20	0.22	51.10	Success	235.20	0.22	51.10	7.68	×	
	c	T	235.10	0.38	41.50	Success	235.10	0.38	41.50	7.68	×	
7	a	R	236.40	0.10	10.10	Success	236.40	0.10	10.10	7.68	×	
	b	S	235.10	0.22	51.10	Success	235.10	0.22	51.10	7.68	×	
	c	T	235.10	0.39	42.60	Success	235.10	0.39	42.60	7.68	×	
8	a	R	236.30	0.09	12.60	Success	236.30	0.09	12.60	7.68	×	
	b	S	235.10	0.22	50.70	Success	235.10	0.22	50.70	7.68	×	
	c	T	235.00	0.36	49.10	Success	235.00	0.36	49.10	7.68	×	
9	a	R	236.20	0.09	12.70	Success	236.20	0.09	12.70	7.68	×	
	b	S	235.00	0.22	50.70	Success	235.00	0.22	50.70	7.68	×	
	c	T	234.80	0.36	48.80	Success	234.80	0.36	48.80	7.68	×	
10	a	R	236.20	0.09	12.50	Success	236.20	0.09	12.50	7.68	×	
	b	S	234.90	0.22	50.90	Success	234.90	0.22	50.90	7.68	×	
	c	T	234.70	0.39	43.10	Success	234.70	0.39	43.10	7.68	×	

Based on the overall testing table of the device, the system successfully acquired voltage, current, and power data from the three phases (R, S, T) well, indicated by the LoRa status always being "Successful" and the Rx data matching the Tx data. The INA219 sensor was also able to detect the battery power in each phase with a constant value of 7.69 W, indicating the stability of the power supply. The system also successfully displays notifications on the website if there is an unbalanced load.

IV. CONCLUSION

The system successfully implemented wireless communication using the LoRa RFM95W module to send voltage, current, and power data from the transmitter (sensor node) to the receiver (master node) stably over a distance of 2–20 meters, with all tests showing a status of "Successful" and the received data matching what was sent. The PZEM-016 sensor is capable of reading voltage, current, and power on phases R, S, and T with an average error rate of 0.842%, and it provides consistent results under both no-load and load conditions. The data received by the ESP32 receiver is stored in the Firebase Realtime Database and displayed on the website dashboard in the form of tables and graphs, complete with calculations of the current imbalance percentage between phases based on the average current. The website is also capable of providing notifications when the imbalance value exceeds the system threshold of < 7%.

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