

IoT-Based Electrical Power Monitoring and Control using NodeMCU and PZEM-004T for Energy Management in Small-Scale MSMEs

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Abstract—Efficient monitoring and management of electrical energy are important for small-scale micro, small, and medium enterprises (MSMEs). Conventional prepaid electricity monitoring requires users to inspect the meter directly, which is less practical for continuous monitoring. This study presents the design and implementation of an Internet of Things (IoT)-based electrical power monitoring and control prototype using a NodeMCU/ESP32 controller and PZEM-004T sensor. The system measures voltage, current, power, energy, frequency, and power factor, displays data locally through an I2C LCD, accepts prepaid-energy top-up input through a 4×4 keypad, and controls the electrical load using a relay. Blynk is used for real-time remote monitoring. Top-up values in Indonesian rupiah are converted into kWh using a fixed electricity tariff, while the energy balance is reduced according to measured consumption. Tests were performed by comparing the prototype with a digital watt meter and by evaluating top-up, balance reduction, relay control, and Blynk monitoring functions. The prototype successfully displayed electrical parameters in real time. At 60 min, the prototype measured 234.4 V, 0.2 A, 22 W, and 0.022 kWh, while the reference watt meter measured 232.4 V, 0.175 A, 21 W, and 0.021 kWh. The reported maximum errors were 1.52% for voltage, 14.29% for current, 6.28% for power, 10.00% for energy, 15.69% for power factor, and 0% for frequency. Top-up and relay-control tests were successful, and the five principal functional tests achieved a reported 100% success rate.

Keywords—energy monitoring, IoT, NodeMCU, PZEM-004T, prepaid electricity

I. INTRODUCTION

Electrical energy is an important operational resource for micro, small, and medium enterprises (MSMEs). Inefficient electricity use can increase operating costs, while many small businesses still rely on direct meter observation or estimation of daily consumption. IoT-based monitoring provides an opportunity to collect electrical data continuously and make it available remotely through a network connection [1]–[3].

Microcontroller platforms such as ESP8266/ESP32 are widely used in IoT prototypes because they integrate wireless communication and can process sensor data locally [8]–[12]. The PZEM-004T is designed to measure AC electrical parameters including voltage, current, active power, energy, frequency, and power factor, and can be integrated with a microcontroller through

serial communication [13]–[15]. Blynk provides a practical interface for remote visualization and control of IoT devices [16]–[19].

Previous work discussed in the thesis has demonstrated IoT-based electrical monitoring using NodeMCU and PZEM-004T, including remote monitoring through mobile applications and load control using relays. However, the thesis identifies a need for a prototype that combines real-time electrical monitoring with prepaid-energy balance management, keypad-based top-up, and automatic load disconnection for a small-scale MSME context.

Therefore, this study aims to design and build an IoT-based electrical power monitoring and control system using NodeMCU and PZEM-004T, and to evaluate its performance for electrical-parameter monitoring, prepaid-energy top-up, balance reduction, automatic relay control, and Blynk-based remote monitoring. The research contribution is the integration of these functions in a single prototype.

II. METHODS

A. System Design

The research followed sequential stages consisting of literature study, problem identification, data collection, system design, prototype construction, functional testing, and data collection. The prototype was designed for a single-phase 220 V AC installation. The implementation described in the thesis uses ESP32 as the central controller, while NodeMCU/ESP8266 terminology is also used in the stated scope and system description. The article therefore retains the NodeMCU terminology from the research title while reporting the implemented controller as ESP32/NodeMCU.

B. Hardware and Software

The principal components were an ESP32/NodeMCU controller, PZEM-004T electrical sensor, I2C 16×2 LCD, 4×4 keypad, relay module, AC load/controlled socket, power supply, Wi-Fi network, Arduino IDE, and Blynk IoT. The PZEM-004T supplies electrical measurements to the controller. The controller processes the measurements, updates the energy balance, drives the LCD, sends data to Blynk, and controls the relay.

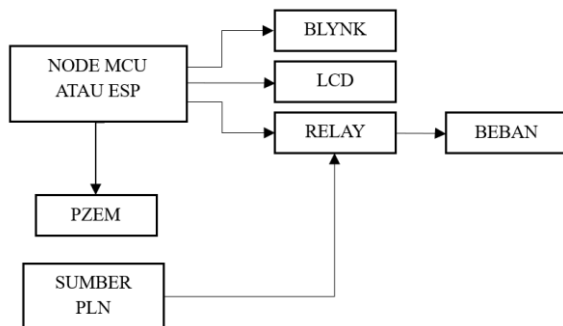


Fig. 1. Block diagram of the monitoring and control system.

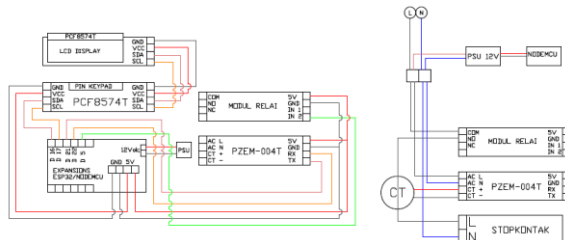


Fig. 2. Wiring diagram of the prototype.

C. Operating Procedure

After the AC source is connected, the PZEM-004T measures the electrical parameters of the load. The controller connects to Wi-Fi and the Blynk platform, reads the sensor periodically, and displays the results locally and remotely. A keypad entry is interpreted as a rupiah top-up value. Using the fixed tariff reported in the thesis, Rp1,444.70/kWh, the added energy is calculated as:

$$E_{\text{topup}} = N / T \quad (1)$$

where E_{topup} is added energy in kWh, N is the top-up amount in rupiah, and T is the fixed tariff in rupiah/kWh. For example, Rp10,000 produces approximately 6.922 kWh.

$$B_{\text{new}} = B_{\text{old}} + E_{\text{topup}} - E_{\text{used}} \quad (2)$$

where B_{new} and B_{old} are the new and previous energy balances and E_{used} is the measured energy consumption. The relay follows the control logic: when the balance is greater than zero, the relay remains ON; when the balance reaches or falls below zero, the relay is switched OFF.

D. Performance Test

Electrical measurements were compared with a digital watt meter under the same load condition. The thesis evaluates voltage, current, power, energy, frequency, and power factor. The percentage error was calculated as:

$$\text{Error (\%)} = |X_{\text{system}} - X_{\text{reference}}| / X_{\text{reference}} \times 100\% \quad (3)$$

Additional functional tests evaluated keypad top-up, automatic balance reduction, relay switching at the minimum balance, and data transmission to Blynk.

III. RESULTS AND DISCUSSION

A. Prototype Implementation

The resulting prototype integrates the controller, PZEM-004T, LCD, keypad, relay, and controlled socket inside a protective enclosure. The system is intended to be mounted on a wall for accessibility and protection. The PZEM-004T measures the AC input/load parameters, while the controller calculates the energy balance and controls the relay. The LCD provides local information and Blynk provides remote monitoring.

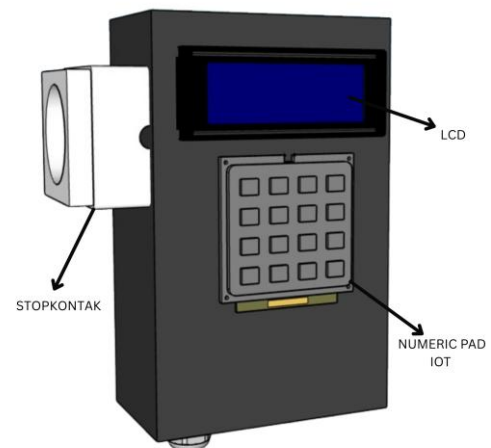


Fig. 3. Product design of the monitoring and control prototype.



Fig. 4. Example implementation environment.



Fig. 5. Prototype monitoring device.

B. Electrical Parameter Monitoring

Table I summarizes selected measurement points reported in the thesis. The prototype and watt meter were operated on the same load.

Time (min)	V Sys. / Ref. (V)	P Sys. / Ref. (W)
0	234.5 / 231.0	22 / 21.0
10	234.0 / 232.7	22 / 20.7
20	232.9 / 232.9	22 / 21.3
30	233.7 / 232.5	22 / 21.1
40	234.2 / 232.2	22 / 20.9
50	233.8 / 232.8	22 / 21.2
60	234.4 / 232.4	22 / 21.0

Table I. Selected comparison of prototype and watt-meter measurements.

The results show that the prototype followed the same general trend as the reference meter. At 60 min, the measured energy reached 0.022 kWh compared with 0.021 kWh on the watt meter. Frequency remained 50 Hz on both devices throughout the reported test. The differences were attributed in the thesis to sensor characteristics, instrument tolerance, non-simultaneous readings, and supply-voltage fluctuation.

Parameter	Max. error
Voltage	1.52%
Current	14.29%
Power	6.28%
Energy	10.00%
Frequency	0%
Power factor	15.69%

Table II. Reported measurement-error values.

The larger current and power-factor differences were associated in the thesis with low current levels, sensor characteristics, and differences in measurement methods. Despite these differences, the measured trends were considered adequate for prototype-scale energy monitoring.

C. Prepaid-Energy Top-Up

The keypad test confirmed that the system could accept rupiah values and convert them to kWh. The thesis reports Rp10,000 as producing 6.922 kWh, Rp20,000 producing 13.844 kWh, Rp50,000 producing 34.611 kWh, and Rp100,000 producing 69.219 kWh. Each test produced the LCD message “TOPUP OK” and updated the balance.

The conversion is linear with the fixed tariff used in the program. This function is a simulation of prepaid electricity management and is not the official PLN prepaid metering system. The thesis explicitly limits the research to a prototype simulation.

D. Balance Reduction and Relay Control

During the 60-minute balance-reduction test, the measured energy increased from 0.000 to 0.026 kWh, while the balance decreased from 0.692 to 0.666 kWh. The relay remained ON because the balance remained above the minimum threshold during this test.

A separate relay test showed ON status at balances of 6.922, 3.500, and 0.100 kWh. At 0.000 kWh the relay changed to OFF and the load became inactive. After a new top-up, the relay returned to ON. This behavior implements the intended prepaid-energy control logic.

Function	Result
Top-up	Successful
Balance reduction	Successful
Relay	OFF / load disconnected
Relay recovery	ON / load connected
Blynk	Successful

Table III. Functional-test summary.

E. Blynk Monitoring

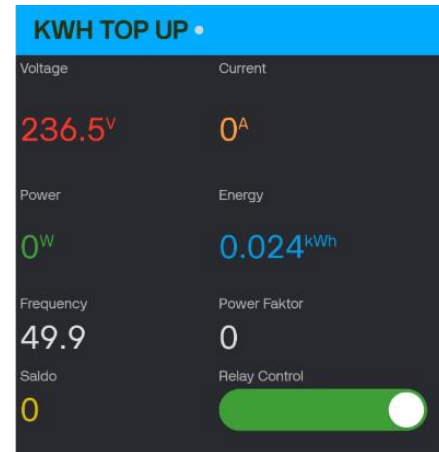


Fig. 6. Blynk monitoring interface reported in the thesis.

The Blynk test successfully displayed voltage, current, power, energy, frequency, power factor, energy balance, and relay status. The thesis reports that data updates could occur in approximately 1–2 s when the internet connection was stable. Therefore, Blynk provided remote access to the same operational information shown locally on the LCD.

F. Overall Performance

Five principal functions were evaluated: electrical-parameter monitoring, keypad top-up, balance reduction, relay control, and Blynk monitoring. All five were reported as successful, giving a reported functional success rate of 100%. The prototype therefore met the functional objectives defined in the thesis.

The system nevertheless has limitations. The balance is not stored in non-volatile memory, so a power interruption or controller reset can return the balance to its initial state. The tariff is fixed in the program and is not updated automatically. The system is also dependent on network availability for remote Blynk monitoring and was tested only on a single-phase 220 V AC installation. The thesis did not address advanced power-quality parameters such as harmonics, sag/swell, or waveform distortion.

IV. CONCLUSION

An IoT-based electrical power monitoring and control prototype using NodeMCU/ESP32 and PZEM-004T was successfully designed and implemented for small-scale MSME energy management. The prototype integrates electrical-parameter measurement, local LCD display, keypad-based prepaid-energy top-up, automatic balance reduction, relay control, and remote Blynk monitoring.

The reported measurements showed generally consistent trends with the digital watt meter. The prototype measured 234.4 V, 0.2 A, 22 W, and 0.022 kWh at 60 min, compared with 232.4 V, 0.175 A, 21 W, and 0.021 kWh from the reference meter. The maximum reported errors were 1.52% for voltage, 14.29% for current, 6.28% for power, 10.00% for energy, 15.69% for power factor, and 0% for frequency. Top-up conversion, balance reduction, relay switching, and Blynk monitoring operated according to the intended logic, and

the five principal functional tests were reported as 100% successful.

Future development should add non-volatile balance storage, calibrate the PZEM-004T against a standard instrument, provide low-balance warning indicators, improve the LCD interface and enclosure, test different loads, and extend the test duration.

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