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IoT-Based Monitoring of an Automatic Transfer Switch Using an Expert System for Power Backup Applications

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***Abstract*—Electrical energy is a fundamental requirement that must be continuously available, particularly in critical facilities. This study proposes and develops an Internet of Things (IoT)-based Automatic Transfer Switch (ATS) monitoring system incorporating expert system principles for backup power management. The system consists of an ESP32 microcontroller, ZMPT101B voltage sensor, PZEM-004T power meter, DC voltage sensor, relay module, SIM900A GSM module, inverter, LCD, and a 12 V 35 Ah battery. When the utility power (PLN) fails, the power source is automatically transferred to the battery and switches back to the utility supply once normal conditions are restored. The ATS operating status can be monitored in real time through the Blynk platform with notification support. The developed system adopts expert system principles implemented using the Mamdani fuzzy inference method in the MATLAB R2018b Fuzzy Inference System (FIS), with input parameters consisting of utility voltage, battery capacity, and load condition. The inference results are used to determine the ATS power source status. Experimental testing conducted at the Instrumentation and Control Laboratory, Universitas Negeri Jakarta, demonstrated that the proposed system operates effectively. The measurement errors were 0.45% for the ZMPT101B voltage sensor, 0.24% for the DC voltage sensor, and 0.45%, 3.7%, and 0.91% for the PZEM-004T in voltage, current, and power measurements, respectively. The ATS successfully transferred the power source within 3 seconds while maintaining an inverter output voltage of 217–232 VAC. The 12 V 35 Ah battery was able to supply a 50 W load for 3 hours and 30 minutes. MATLAB simulation produced a crisp output value of 1.86, indicating that the load was supplied by the battery.**

***Index Terms*—Automatic Transfer Switch (ATS), Expert System, Fuzzy Logic, Internet of Things (IoT), Real-Time Monitoring**

I. INTRODUCTION

Electrical energy is a fundamental requirement supporting various sectors, including residential, industrial, healthcare, and telecommunications applications. Electricity consumption per capita in Indonesia increased from 1,411 kWh in 2024 to 1,548 kWh in 2025, indicating increasing dependence on reliable electricity supply (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2025). As the national electricity provider, PT Perusahaan Listrik Negara (PLN) faces challenges in maintaining supply reliability as energy demand continues to increase (Anggoro, 2019).

Power supply disturbances caused by generation constraints, transmission failures, and outages can result in economic losses and threaten critical-load facilities, such as hospitals and data centers (Nugroho & Fitriani, 2022). Power instability can also increase operating costs and the risk of losses, particularly for micro, small, and medium-sized enterprises (MSMEs) (Arief, 2026). Therefore, a backup system capable of automatically taking over the electrical supply is required.

An Automatic Transfer Switch (ATS) is a system that automatically transfers an electrical load between power sources without interrupting supply continuity (Abdillah et al., 2022). However, conventional ATS systems still have limitations in real-time monitoring of operating conditions and battery status. Integrating ATS with the Internet of Things (IoT) enables electrical parameters to be monitored remotely via smartphones, allowing disturbances to be detected more rapidly (Keran & Nugraha, 2023).

In addition to monitoring, dynamic electrical conditions require a system capable of interpreting sensor data to determine the appropriate power source. An expert system is a computer-based system that adopts expert knowledge to solve specific problems (Kusrini, 2006). In this study, knowledge concerning utility voltage, battery voltage, and load condition is represented through a fuzzy rule base using the Mamdani Fuzzy Inference System (FIS), introduced by Ebrahim Mamdani in 1975 (Rindengan & Yohanes, 2019), and implemented using the Fuzzy Logic Toolbox in MATLAB R2018b. The fuzzy approach was selected because it can handle uncertainty in electrical parameters, allowing power-source transfer decisions to be more adaptive than those based on fixed thresholds.

Several previous studies have developed IoT-based ATS systems. Akbar (2022) designed an ATS and battery monitoring system based on AVR and ESP32, with an average delay of 10.4 seconds in the Android application and 2.234 seconds on the LCD. Putra et al. (2019) developed an ATS based on Arduino Nano and ESP8266, achieving approximately 1.0% voltage and current measurement error and providing Telegram notifications for overload or undervoltage conditions. Alfariski et al. (2022) developed an Arduino Uno-based ATS with a power-source transfer time of approximately 2 seconds and web-based monitoring.

Nevertheless, these studies have not integrated an expert system capable of classifying ATS conditions based on the combined parameters of utility voltage, battery voltage, and load. This study addresses this gap by integrating ESP32-based

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IoT monitoring through Blynk using a SIM900A GSM module, PZEM-004T, ZMPT101B, and DC voltage sensors with a Mamdani FIS for ATS condition classification and automated decision support. The system is implemented in an integrated panel incorporating a pure sine wave inverter as an electrical energy backup solution for small-scale critical loads.

Based on this background, this study aims to design, develop, and test an IoT-based ATS monitoring system using an expert system approach to provide real-time information on ATS and battery conditions as an electrical energy backup system.

II. METHODS

A. Product Development Method

This study employed a Research and Development (R&D) approach, which is a research method used to develop new products or improve existing products and to evaluate their feasibility and effectiveness for optimal utilization (Sugiyono, 2017). The development process followed the ADDIE model, consisting of five stages: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). The study was conducted at the Instrumentation and Control Laboratory, Department of Electronic Engineering Education, Faculty of Engineering, Universitas Negeri Jakarta, from February 2025 to June 2026.

B. System Architecture

The ZMPT101B sensor detects the AC utility voltage and triggers the utility and battery relays; the PZEM-004T measures the voltage, current, and power delivered to the load; the DC voltage sensor monitors the battery voltage displayed on the LCD and Blynk; and the SIM900A module provides Internet access for the ESP32. On the output side, the utility and battery relays perform source switching, pilot lamps indicate the active power source, the LCD displays real-time measurements, and Blynk provides remote monitoring and fault notifications.

C. Hardware and Software Configuration

Table 1 presents the ESP32 input/output pin configuration used to connect the sensors, display, relays, and GSM module.

TABLE I. ESP32 INPUT/OUTPUT PIN CONFIGURATION

No.	Subystem	ESP32 Pin	Function
1	Sensor ZMPT101B	GPIO 35	*Input* analog
2	PZEM-004T (kanal 1)	GPIO 16 (TX) / 17 (RX)	Serial UART
3	PZEM-004T (kanal 2)	GPIO 26 (TX) / 25 (RX)	Serial UART
4	PZEM-004T (kanal 3)	GPIO 33 (TX) / 32 (RX)	Serial UART
5	Sensor tegangan DC	GPIO 13	*Input* analog
6	LCD 20x4 (I2C)	GPIO 22 (SCL) / 21 (SDA)	Bus I2C
7	Relay dua kanal	GPIO 2 (IN1) / 15 (IN2)	*Output* digital
8	Modul GSM SIM900A	GPIO 5 (TX) / 18 (RX)	Serial UART

The firmware was developed using Arduino IDE and uploaded to the ESP32, while Blynk served as the IoT dashboard for displaying sensor data and sending push notifications for low-battery conditions and utility status. The Mamdani FIS was implemented in MATLAB R2018b with three input variables—utility voltage, battery voltage, and load power—and one output variable representing the ATS load status on a normalized 0–2 scale. The output was divided into three operational categories: load supplied by the utility (0–0.5), load OFF/overload (0.5–1.5), and load supplied by the battery (1.5–2).

III. RESULTS AND DISCUSSION

A. Power Source and Inverter Testing

Multimeter measurements confirmed that all voltage paths met the design specifications: the utility supply measured 227 VAC, the battery measured 12.31 VDC, the ESP32 supply measured 4.99 VDC, and the LM2596 regulator output measured 5.00 VDC. The inverter received an input voltage of 12.31 VDC and produced an output voltage of 228 VAC, consistent with the specifications of the pure sine wave inverter used.

B. Sensor Accuracy Testing

Table 2 summarizes the accuracy of the three sensing subsystems compared with reference instruments (multimeter and clamp meter) across multiple trials.

TABLE II. SENSOR ACCURACY TEST RESULTS

Sensor	Parameter	Reference Instrument	Mean Error (%)
ZMPT101B	AC Utility Voltage	Multimeter	0,45
Sensor tegangan DC	Battery Voltage	Multimeter	0,24
PZEM-004T	AC Voltage	Multimeter	0,45
PZEM-004T	AC Current	*Clamp meter*	3,7
PZEM-004T	AC Power	Reference Load	0,91

All measured error values were below 4%, which is considered acceptable for real-time power-quality monitoring. The relatively higher current measurement error (3.7%) was caused by the small current drawn by the light test load (0.12–0.28 A), for which absolute measurement noise had a proportionally greater effect on the percentage error.

C. Interface, GSM, and Overall System Testing

Testing of the SIM900A GSM module showed that Internet and Blynk server connectivity required 48 seconds at the Instrumentation and Control Laboratory, UNJ, whereas connectivity at the area in front of the Electrical Engineering Building, Faculty of Engineering, UNJ, required 1 minute and 38 seconds. This difference in connectivity time occurred because, in areas with stronger signals, such as elevated locations, the module could register with the network more rapidly.

Table 3 presents the overall system test results, showing that the ATS successfully transferred the load from the utility supply to the battery and returned to the utility supply after power restoration within 3 seconds. This transfer time is substantially below the disturbance tolerance threshold perceptible to most electronic equipment. The inverter maintained an output voltage of 217–232 VAC while supplying the 50 W critical load.

The 12 V 35 Ah battery supported the load for 3 hours and 30 minutes, with the terminal voltage gradually decreasing from 13 VDC until the inverter reached its low-voltage cutoff limit of 11.8 VDC.

TABLE III. OVERALL SYSTEM TEST RESULTS

Time (hour: minute)	Utility Voltage (VAC)	Battery Voltage (VDC)	Inverter (VAC)	Status	Trip Time (s)
08:00	227	12,8	0	Load supplied by utility	-
08:30	0	12,7	232	Load supplied by battery	3
09:00	0	12,6	229	Load supplied by battery	-
09:30	0	12,5	225	Load supplied by battery	-
10:00	0	12,4	223	Load supplied by battery	-
10:30	0	12,3	221	Load supplied by battery	-
11:00	0	12,2	220	Load supplied by battery	-
11:30	0	12	217	Load supplied by battery	-
12:00	0	11,8	198	Load OFF	-
12:05	227	11,8	0	Load supplied by utility	3

D. Mamdani Fuzzy Logic Testing

The Mamdani FIS was verified using a representative scenario with a utility voltage of 200 VAC (categorized as low voltage), a battery voltage of 12.4 VDC (categorized as normal), and a 20 W load (categorized as small). The fuzzification process produced membership degrees of 0.7748, 0.8007, and 0.9600 for the three inputs, respectively. Applying the MIN operator to the rule conjunction produced a firing strength of 0.7748, which was used to construct the output fuzzy set in the category $\mu 53$ (load supplied by the battery). Defuzzification using the Mean of Maximum (MOM) method produced a crisp output of 1.86, which falls within the 1.5–2 range representing battery-supplied load. This value exactly matched the MATLAB Rule Viewer simulation result, confirming that the implemented rule base operated according to the design. MATLAB Rule Viewer.

E. Discussion

Referring to the ADDIE stages, the Analysis stage identified the absence of real-time monitoring, manual source transfer, and lack of IoT integration as the main limitations of conventional ATS installations. The Design and Development stages translated these requirements into a concrete architecture integrating an ESP32-based sensing and control unit, a Blynk-based IoT dashboard accessible through GSM, and a Mamdani fuzzy expert-system layer for automatic status classification. The Implementation and Evaluation stages confirmed that the assembled prototype met the design targets: sensor errors below 4%, stable inverter output at 217–232 VAC, an automatic transfer time of 3 seconds, and fuzzy-logic classification consistent with manual calculations. Figure 1 shows the ATS product.

Fig. 1. Product of ATS

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusion

This study successfully designed, developed, and tested an Internet of Things (IoT)-based Automatic Transfer Switch (ATS) monitoring system that applies expert system principles through a rule base implemented using the Mamdani Fuzzy Inference System (FIS) in MATLAB R2018b as an electrical energy backup solution. The ESP32-based system integrated with ZMPT101B, PZEM-004T, and DC voltage sensors was capable of automatically transferring the power source between the PLN utility grid and the backup battery with an average transfer time of 3 seconds. The test results showed that the measurement error of all sensors was below 4%, the inverter produced a stable output voltage in the range of 217–232 VAC, and the Mamdani fuzzy system successfully classified the ATS condition with a crisp value of 1.86, consistent with the manual calculation. In addition, system status information and notifications were displayed in real time through the Blynk platform and a 20×4 LCD. These results indicate that integrating IoT monitoring with expert-system-based decision-making provides an effective backup power solution with potential applicability to critical electrical loads.

B. Recommendations

Future studies are recommended to use batteries and inverters with larger capacities to extend backup duration and support higher loads. In addition, the use of a GSM module or SIM card with better network quality is recommended to improve connection stability and monitoring-system reliability under field conditions.

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