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Design and Development of an Internet of Things (IoT) Based Automatic Transfer Switch (ATS) Monitoring System Using an Expert System Approach For Electrical Energy Backup

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ABSTRACT

Reliable electrical power availability is essential for various applications, especially in facilities that rely on continuous power supply. To address power interruptions, this study developed an Internet of Things (IoT)-enabled Automatic Transfer Switch (ATS) monitoring system based on an expert system approach for electrical energy backup. The proposed system integrates an ESP32 microcontroller with a ZMPT101B voltage sensor, PZEM-004T power meter, DC voltage sensor, relay module, SIM900A GSM module, inverter, LCD, and a 12 V 35 Ah battery. The system automatically changes the power source from the utility supply (PLN) to the backup battery when a power failure occurs and restores the utility source after normal supply conditions are detected. System conditions and electrical parameters are monitored remotely in real time using the Blynk platform, which also provides system notifications. For decision-making, expert system principles are implemented through a Mamdani Fuzzy Inference System (FIS) developed in MATLAB R2018b, evaluating utility voltage, battery voltage, and load condition to determine the appropriate ATS power-source status. Experimental evaluation at the Instrumentation and Control Laboratory, Universitas Negeri Jakarta, confirmed the system functionality, with average measurement errors of 0.45% for the ZMPT101B sensor and 0.24% for the DC voltage sensor, while the PZEM-004T produced errors of 0.45% for voltage, 3.7% for current, and 0.91% for power measurements. The ATS completed the source transfer within 3 seconds, with the inverter maintaining an output voltage between 217 and 232 VAC. Under a 50 W load, the 12 V 35 Ah battery provided backup power for 3 hours and 30 minutes, and the MATLAB simulation generated a crisp output of 1.86, corresponding to the battery-supplied load condition. Beyond these technical validations, the scientific contribution of this research lies in the successful integration of a Mamdani FIS with IoT-based monitoring to enable adaptive, rule-based decision-making that overcomes the rigidity of conventional fixed-threshold ATS systems. Practically, this intelligent backup solution offers an affordable and reliable alternative for critical infrastructures, such as small-scale healthcare facilities and data centers, particularly in regions with unstable grid conditions. The modular system architecture also provides a scalable foundation for future integration with renewable energy sources and expansion to higher-capacity industrial applications.

Keywords: Automatic Transfer Switch (ATS), Expert System, Fuzzy Logic, Internet of Things (IoT), Real-Time Monitoring

INTRODUCTION

Electrical energy has become an indispensable fundamental resource supporting various sectors of modern life, including residential households, industrial manufacturing, healthcare services, telecommunications infrastructure, and critical data centers. The increasing reliance on continuous electricity supply is reflected in Indonesia's per capita electricity consumption, which rose from 1,411 kWh in 2024 to 1,548 kWh in 2025, representing a growth of nearly 10% within a single year [1]. As the state-owned electricity provider, PT Perusahaan Listrik Negara (PLN) faces significant challenges in maintaining supply reliability while simultaneously meeting the escalating energy demand driven by economic growth and urbanization [2].

Despite ongoing infrastructure development, power supply disturbances remain an inherent challenge in electricity distribution systems. These disruptions, caused by generation capacity constraints, transmission line failures, substation malfunctions, and unpredictable weather-related outages, can result in substantial economic losses and pose serious threats to critical-load facilities [3]. Hospitals, data centers, telecommunications towers, and financial institutions require uninterrupted power to maintain operational continuity and prevent potentially life-threatening situations or massive data losses [4]. Furthermore, power instability increases operational costs and business risks for micro, small, and medium-sized enterprises (MSMEs), which often lack the financial capacity to invest in comprehensive backup power solutions. Therefore, an effective backup system capable of automatically assuming the electrical supply during utility interruptions is essential for ensuring power continuity and protecting sensitive equipment from damage caused by abrupt power transitions.

An Automatic Transfer Switch (ATS) is a critical component in backup power systems that automatically transfers an electrical load from a primary power source to a secondary source when a disturbance is detected, thereby maintaining supply continuity without manual intervention [5]. However, conventional ATS systems exhibit several significant limitations. First, they lack real-time monitoring capabilities, making it difficult for operators to assess system conditions remotely. Second, they operate based on fixed voltage thresholds without considering the dynamic interplay between utility voltage, battery state-of-charge, and load characteristics. Third, battery health and backup duration cannot be predicted accurately, leading to unexpected power failures when the backup source is depleted. These shortcomings underscore the need for a more intelligent and connected ATS solution.

The convergence of Internet of Things (IoT) technology with power management systems offers promising opportunities to address these limitations [6]. IoT-enabled ATS systems allow electrical parameters to be monitored remotely via smartphones, tablets, or web-based dashboards, enabling faster disturbance detection and more responsive maintenance interventions [7]. Additionally, IoT connectivity facilitates automated notifications, data logging, and predictive analytics that can anticipate potential failures before they occur, thereby improving overall system reliability and reducing downtime [8].

Several previous studies have explored IoT-based ATS implementations. Akbar [9] designed an ATS and battery monitoring system based on AVR and ESP32 microcontrollers, achieving an average delay of 10.4 seconds for Android application updates and 2.234 seconds for LCD display updates. Putra et al. [10] developed an ATS based on Arduino Nano and ESP8266, reporting approximately 1.0% voltage and current measurement errors and providing Telegram notifications for overload and undervoltage conditions. Alfariski et al. [11] developed an Arduino Uno-based ATS with a power-source transfer time of approximately 2 seconds and enabled web-based monitoring. More recently, Rakhmawati et al. [12] proposed a safety design using ATS with fuzzy logic-based voltage interference identification to improve decision-making in power transfer scenarios.

Despite these contributions, previous research has not adequately addressed the need for a comprehensive expert system that classifies ATS operational conditions by simultaneously considering the combined parameters of utility voltage, battery voltage, and load condition within a unified intelligent framework. Most existing systems rely on simple threshold-based logic, which fails to capture the nuanced relationships among these interdependent variables. Moreover, no prior study has integrated a Mamdani Fuzzy Inference System (FIS) with IoT-based real-time monitoring for ATS applications, creating a research gap that this study seeks to fill.

In addition to real-time monitoring and automated control, dynamic electrical conditions require a system capable of interpreting sensor data to determine the appropriate power source under varying operational scenarios. An expert system is a computer-based system that emulates the decision-making ability of a human expert by encoding domain knowledge into a structured rule base [13], [14]. In this study, knowledge concerning utility voltage behavior, battery voltage degradation, and load power demand is represented through a fuzzy rule base using the Mamdani Fuzzy Inference System (FIS), originally introduced by Ebrahim Mamdani in 1975 [15]. The Mamdani FIS was selected because of its intuitive rule representation using linguistic variables, which aligns well with human reasoning processes, and its ability to handle uncertainty and imprecision in electrical measurements [16]. Unlike fixed-threshold logic, the fuzzy approach enables gradual transitions between states, reducing unnecessary switching events and improving system stability. The FIS is implemented using the Fuzzy Logic Toolbox in MATLAB R2018b, which provides a robust development environment for designing, simulating, and validating fuzzy inference systems.

This study addresses the identified research gap by integrating ESP32-based IoT monitoring through the Blynk platform, utilizing a SIM900A GSM module for network connectivity, PZEM-004T for comprehensive power measurement, ZMPT101B for AC voltage sensing, and a DC voltage sensor for battery state monitoring—all combined 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 designed specifically for small-scale critical loads, offering an affordable and intelligent alternative to conventional ATS systems.

The primary contributions of this research are threefold. First, it presents a novel integration of IoT-based real-time monitoring with expert system decision-making for ATS applications. Second, it provides a systematic methodology for designing and implementing a Mamdani FIS that considers three critical input parameters for ATS status classification. Third, it offers experimental validation demonstrating the system's performance in terms of sensor accuracy, transfer time, backup duration, and fuzzy logic classification reliability.

Based on this background and identified research gap, this study aims to design, develop, and evaluate an IoT-based ATS monitoring system using an expert system approach to provide real-time information on ATS operational status and battery conditions as an intelligent electrical energy backup solution for critical loads.

METHOD

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 [17]. The development process followed the ADDIE model, consisting of five stages: Analysis, Design, Development, Implementation, and Evaluation [18]. 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.

TABLE 1. 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

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 [19].

Hardware and Software Configuration

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

RESULT AND DISCUSSION

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 [20].

TABLE 2. 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

Sensor Accuracy Testing

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

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

TABLE 3. 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

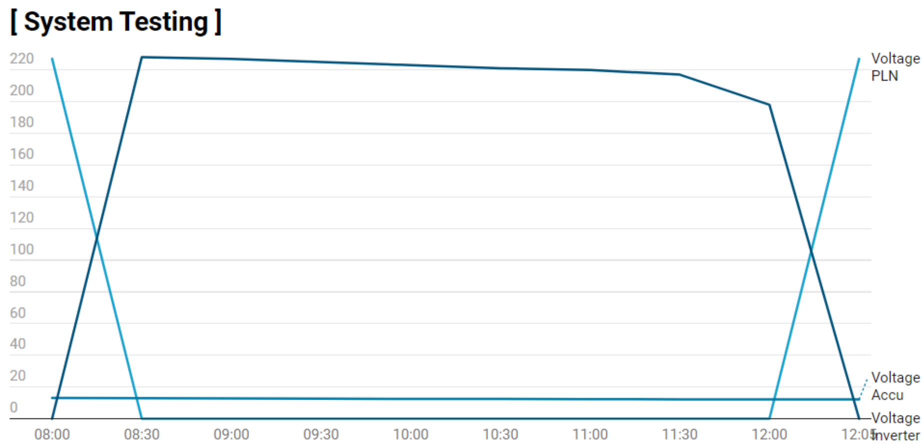

FIGURE 1. System testing of ATS

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. FIGURE 1 presents the overall system testing results of the proposed IoT-based Automatic Transfer Switch (ATS) monitoring system with fuzzy under a 50W resistive load.

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 µ53 (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.

The influence of each pair of input variables on the ATS output status is further illustrated through the fuzzy surface plot shown in FIGURE 2 The system turns off the load only when a low battery condition and an abnormal utility voltage occur simultaneously. For other combinations, the load is supplied either by the battery, when the battery voltage is normal and the utility voltage is abnormal, or by the utility supply, when the utility voltage is within the normal range. For small to medium loads, the source-selection boundary tends to favor maintaining the power supply, whereas a large load combined with an out-of-range utility voltage or a low battery condition is more likely to trigger the OFF state.

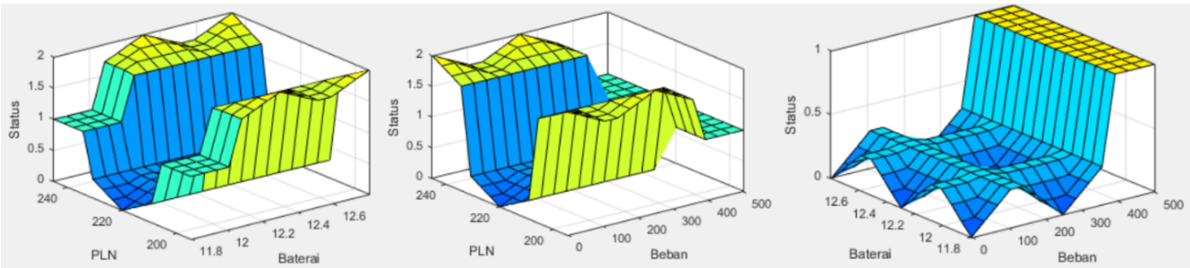

FIGURE 2. Surface fuzzy logic of ATS

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 3 shows the ATS product.

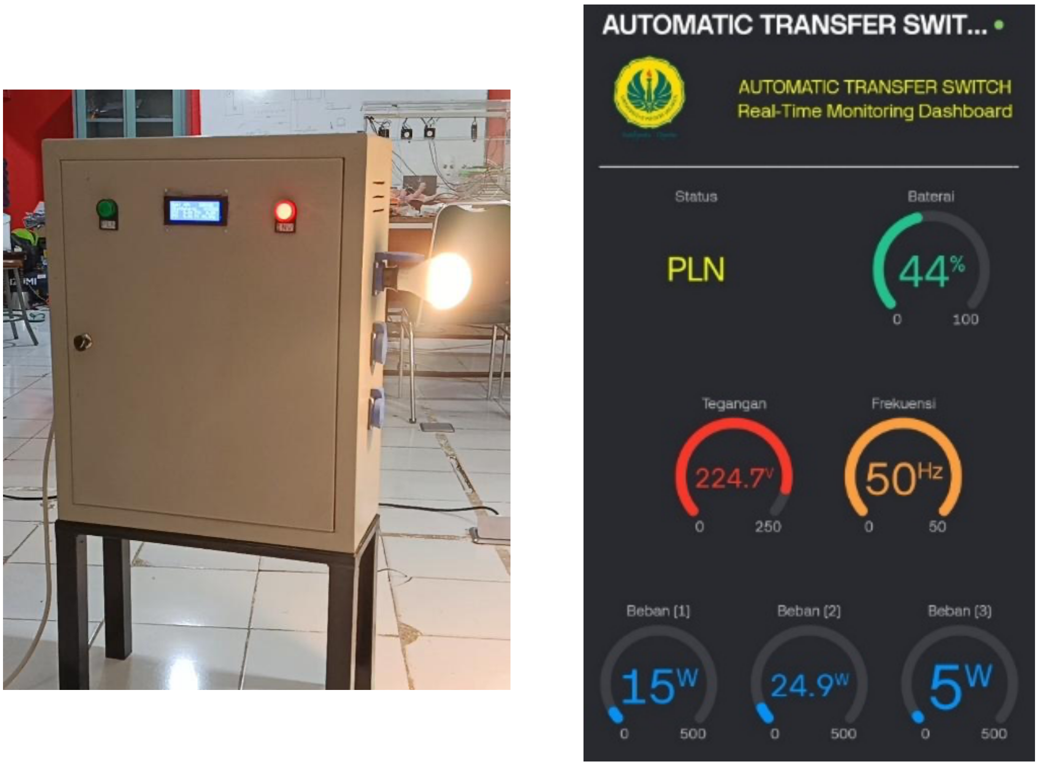

FIGURE 3. Product of ATS

CONCLUSION AND RECOMMENDATIONS

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.

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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REFERENCES

[1] Kementerian Energi dan Sumber Daya Mineral Republik Indonesia, "Paparkan Capaian Kinerja 2025, Menteri ESDM: Kapasitas Terpasang dan Konsumsi Listrik Meningkat," *Kementerian ESDM*, 2025. [Online]. Available: https://gatrik.esdm.go.id/berita/?slug=paparkan-capaian-capaian-kinerja-2025-menteri-esdm-kapasitas-terpasang-dan-konsumsi-listrik-meningkat&category=

[2] S. F. Anggoro, "Powerbank untuk Suplai Daya Beban pada Rumah Tinggal," Undergraduate thesis, Dept. Teknik Elektro, Univ. Negeri Yogyakarta, Yogyakarta, Indonesia, 2019.

[3] A. A. Nugroho and E. Fitriani, "Rancang Bangun Panel Automatic Transfer Switch (ATS) dengan Monitoring dan Kendali Via Android Berbasis Outseal PLC," in *Proc. Bina Darma Conf. Eng. Sci. (BDCES)*, 2022, pp. 43–52. [Online]. Available: http://conference.binadarma.ac.id/index.php/BDCES

[4] T. M. V. Arief, "Dunia Usaha Keluhkan Pemadaman Bergilir, Produksi hingga Investasi Terancam," *Kompas.com*, Jun. 22, 2026. [Online]. Available: https://money.kompas.com/read/2026/06/22/061800526/dunia-usaha-keluhkan-pemadaman-bergilir-produksi-hingga-investasi-terancam

[5] M. Abdillah, T. Mutia, T. A. Nugroho, and N. I. Pertiwi, "Design of Automatic Transfer Switch on A Renewable Energy Hybrid Grid System at PT Lentera Bumi Nusantara," *J. Adv. Technol. Multidiscipline*, vol. 1, no. 2, pp. 38–44, 2022, doi: 10.20473/jatm.v1i2.40293.

[6] M. Yusro, A. Diamah, I. Sakti, B. Regowo, I. Zuhdi, and A. Izzudin, *Modul Pembelajaran Teori & Praktik Aplikasi IoT*. Jakarta, Indonesia: Univ. Negeri Jakarta, 2021.

[7] S. Keran and A. Nugraha, "Sistem Switching pada Automatic Transfer Switch (ATS) Menggunakan Arduino UNO," *J. Surya Energy*, vol. 7, no. 2, pp. 47–53, 2023, doi: 10.32502/jse.v7i2.5756.

[8] N. Patel, A. Dhikale, S. Utekar, and M. Dogra, "Improving Performance of IoT Applications Using Edge," *AIP Conf. Proc.*, vol. 3092, no. 1, p. 120004, 2024, doi: 10.1063/5.0186979.

[9] S. I. Akbar, "Monitoring Automatic Transfer Switch dan Baterai Berbasis IoT Menggunakan Mikrokontroler AVR dan ESP32," *Transient: J. Ilmiah Teknik Elektro*, vol. 11, no. 2, pp. 51–60, 2022, doi: 10.14710/transient.v11i2.51-60.

[10] R. P. W. Putra, M. Mukhsim, and F. Rofi'i, "Sistem Pemantauan dan Pengendalian Modul Automatic Transfer Switch (ATS) Melalui Android Berbasis Arduino," *TELKA: Telekomunikasi, Elektronika, Komputasi dan Kontrol*, vol. 5, no. 1, pp. 43–54, 2019, doi: 10.15575/telka.v5n1.43-54.

[11] M. R. Alfariski, M. Dhandi, and A. Kiswantono, "Automatic Transfer Switch (ATS) Using Arduino Uno, IoT-Based Relay and Monitoring," *JTECS: J. Sistem Telekomunikasi Elektronika Sistem Kontrol Power Sistem dan Komputer*, vol. 2, no. 1, p. 1, 2022, doi: 10.32503/jtecs.v2i1.2238.

[12] R. Rakhmawati, L. P. S. Rahaja, and M. M. Husnah, "Safety Design using ATS by Identifying Voltage Interference based on Fuzzy Logic," *ELKOMIKA: J. Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika*, vol. 11, no. 2, pp. 510–521, 2023, doi: 10.26760/elkomika.v11i2.510.

[13] Kusrini, *Sistem Pakar: Teori dan Aplikasi*. Yogyakarta, Indonesia: Andi, 2006.

[14] J. D. Susatyono, *Kecerdasan Buatan: Kajian Konsep dan Penerapan*. Semarang, Indonesia: Yayasan Prima Agus Teknik, 2021.

[15] A. J. Rindengan and Y. A. R. Langi, *Sistem Fuzzy*. Bandung, Indonesia: CV. Patra Media Grafindo, 2019.

[16] O. Purnawirawan and T. Afirianto, "Implementasi Algoritma Fuzzi Mamdani pada Sistem Pakar Menggunakan Software Aplikasi Matlab R2007B, Studi Kasus: Tanaman Hidroponik Selada Air," *J. Teknol. Informasi dan Ilmu Komputer*, vol. 11, no. 5, pp. 977–986, 2024, doi: 10.25126/jtiik.1077977.

[17] Sugiyono, *Metode Penelitian Kuantitatif, Kualitatif, dan R&D*. Bandung, Indonesia: Alfabeta, 2017.

[18] R. M. Branch, *Instructional Design: The ADDIE Approach*. New York, NY, USA: Springer, 2009, doi: 10.1007/978-0-387-09506-6.

[19] M. H. Rashid, *Power Electronics: Devices, Circuits & Applications*, 4th ed. Upper Saddle River, NJ, USA: Pearson, 2014.

[20] R. Elliott, "Inverter AC Power Supplies," *Elliott Sound Products*, 2014. [Online]. Available: https://sound-au.com/articles/inverters.htm