

Design of an Automatic Transfer Switch for Grid-Solar Systems to Determine Transfer Accuracy and 7-Day Stability

Muchammad Fardin Alifi¹, Nur Vida Laksmi², Widi Aribowo³, As'ad Shidqy Aziz⁴ and Ayusta Lukita Wardani⁵

^{1,2,3,4,5*} Universitas Negeri Surabaya, Surabaya, Indonesia



ABSTRACT

Keywords:

Automatic Transfer Switch
Outseal PLC
ESP8266
Modbus RTU
Node-RED
Grid-Solar Power System
IoT Monitoring

The increasing dependence on electrical energy in residential buildings requires a reliable Automatic Transfer Switch (ATS) to maintain uninterrupted power supply during grid disturbances. This study presents the design and development of an ATS for a Grid-Solar Power System (PLN-PLTS) using an Outseal PLC as the primary controller and an ESP8266 (Wemos D1 Mini) as the Internet of Things (IoT) communication module. The proposed system integrates Modbus RTU communication for data exchange between the PLC and ESP8266 and utilizes MQTT with a Node-RED dashboard for real-time monitoring and data logging. Experimental evaluations were conducted using resistive (10 W incandescent lamp), capacitive (10 W LED lamp), and inductive (40 W electric fan) loads under various PLC time-base settings of 200 ms, 100 ms, 50 ms, 40 ms, and 30 ms. The results indicate that reducing the PLC time base significantly improves the switching performance, with the optimum configuration achieved at a 30 ms time base, producing an actual transfer time of 30 ms and a standard deviation of 0 ms in both PLN-to-PLTS and PLTS-to-PLN transitions. Furthermore, a continuous 24-hour operation over seven consecutive days demonstrated stable system performance, maintaining supply voltages between 218.4 V and 226.9 V and operating temperatures below 39 °C while providing uninterrupted monitoring and reliable power transfer. These findings confirm that the proposed ATS is fast, accurate, stable, and suitable for continuous residential power management applications.

INTRODUCTION

Electrical energy has become a vital, necessity in human life to support various daily activities within the household environment (Eswaran & Khan, 2025). Almost all domestic activities, ranging from lighting and water pumps to electronic appliances and security systems, rely heavily on the power supply from the State Electricity Company. Along with the growing human population and massive technological advancements, electrical energy consumption continues to increase significantly (Aripurnomo et al., 2023). This high dependency demands a stable and continuous power supply to ensure the smooth running of daily activities and to maintain the functionality of household electronic devices (Tian et al., 2026)(Terrén-Serrano et al., 2026).

However, this increasing consumption is often accompanied by disturbances in the main distribution grid from PLN, such as undervoltage phenomena and total power outages (*blackouts*). Such power stability disturbances have negative impacts on connected electronic equipment, potentially triggering instant damage or system malfunctions. According to the General Electrical Installation Regulations (PUIL, 2000). a Special Backup Power Supply

(*Special Backup Power Supply / SBPS*) must automatically take over the load if the main grid voltage drops by more than 10%. Therefore, a reliable mitigation system is required to maintain the continuity of the electricity supply by automatically transferring the main flow to a backup source during a disturbance, and reverting it once the primary line stabilizes. As a solution to this problem, an Automatic Transfer Switch (ATS) system is implemented, which is an automated device designed to switch connections from one power source to another. While backup sources generally utilize generator sets (gensets), the current trend is shifting toward renewable energy, such as Solar Power Plants (*Pembangkit Listrik Tenaga Surya / PLTS*). In its development, the ATS can also function like an Uninterruptible Power Supply (UPS) to prioritize PLN electricity as the primary source and utilize the PLTS as a backup supply (Apriani et al., 2023). The implementation of this ATS control system requires a Programmable Logic Controller (PLC) as the main controller for ON/OFF logic based on Ladder Diagrams, combined with relay components as the power connectors to the load (Simanjuntak & Risfendra, 2021).

Among the various types of controllers available, the Outseal PLC stands out as an interesting choice because it is a locally manufactured, open-source product that utilizes Arduino-based microcontroller technology, such as Arduino Nano or Mega, programmed via Outseal Studio software. The use of the Outseal PLC in ATS systems has been explored by several previous researchers, including the design of a 1-Phase ATS based on the Outseal PLC Mega V.3 for household installations (Kurniawan & Haryudo, 2024). That study utilized the PZEM-004T sensor to detect undervoltage and overvoltage disturbances in the PLN supply (Yusuf et al., 2025). Additionally, prior research has developed a three-phase ATS system based on the Outseal PLC Mega V.3 Slim integrated with an Android application as a Human Machine Interface (HMI) to monitor voltage conditions in real-time. Based on the literature and previous studies, this research presents a project titled “Design of an Automatic Transfer Switch for Grid-Solar Systems to Determine Transfer Accuracy and 7-Day Stability”. This system utilizes an Outseal PLC and a Wemos D1 Mini (featuring an ESP8266 12F core) as the main control units integrated via Modbus RTU communication (Donjaroennon et al., 2026). A PZEM-004T sensor is used to monitor PLN blackouts and voltage drops, while a Voltage Divider sensor is tasked with monitoring the PLTS battery level, set to disconnect at 11 Volts DC and reconnect when fully charged at 13.4 Volts DC (Apriani et al., 2023). All parameter data will be transmitted via the MQTT protocol to be remotely monitored through a Node-RED dashboard, by testing the power switching speed using three loads simultaneously is, a 10 W incandescent light bulb (resistive load), a 10 W LED light bulb (capacitive load), and a 40 W electric fan (inductive load) and testing their durability over a period of 7 day.

RESEARCH METHOD

A. Research Design / Experimental Setup

The experimental research method is used in the design and evaluation of an Internet of Things (IoT)-based Automatic Transfer Switch (ATS) power integration system. This method is used to directly test the system's performance in a residential single-phase electricity network connected to a simulated Solar Power Plant (PLTS) setup in Ambeng-Ambeng Village, Waru District, Sidoarjo Regency.

The assembly of hardware, the creation of software, and the overall system testing are the stages of the experiment. To directly monitor changes in electrical and grid factors, such as AC voltage stability and battery levels, and the device's response to these changes, the device prototype was connected to a domestic single-phase PLN grid alongside a simulated PLTS battery-inverter unit. To ensure that the device operates efficiently, adaptively, and reliably, field testing was conducted to evaluate the optimal baud rate for Modbus serial transmission; the system's response speed to power grid anomalies (blackouts and undervoltage) and low-battery thresholds; the accuracy of the PZEM-004T and Voltage Divider sensor measurements; and the load power transfer time stability across resistive, capacitive, and inductive loads.

B. System Architecture

The proposed system consists of an Outseal PLC Nano, Wemos D1 Mini (ESP8266) microcontroller, PZEM-004T electrical monitoring module, Voltage Divider sensor, relay interlocking driver (5V relays and Omron MY2N 24VDC relays), protection devices (MCB and fuses), a buffer power supply, an electronic buzzer, and a Node-RED dashboard cloud platform.

The PZEM-004T module measures grid electrical parameters including AC voltage stability, current, and active power from the PLN source, while the Voltage Divider sensor monitors the DC voltage conditions of the PLTS backup battery. The Wemos D1 Mini processes all sensor information and transmits the operational states via Modbus RTU serial communication to the Outseal PLC Nano, which serves as the central controller to determine the automatic or manual operating mode of the switching relays. A supplementary buffer power supply utilizing 18650 lithium batteries acts as a backup mechanism to sustain the control board's power during transition intervals. Data are continuously transmitted via MQTT protocol to the Node-RED platform, allowing users to remotely monitor system parameters and execute control overrides simultaneously through a web-based dashboard interface. To see the complete wiring diagram for the ATS that has been created, refer to Figure 1.

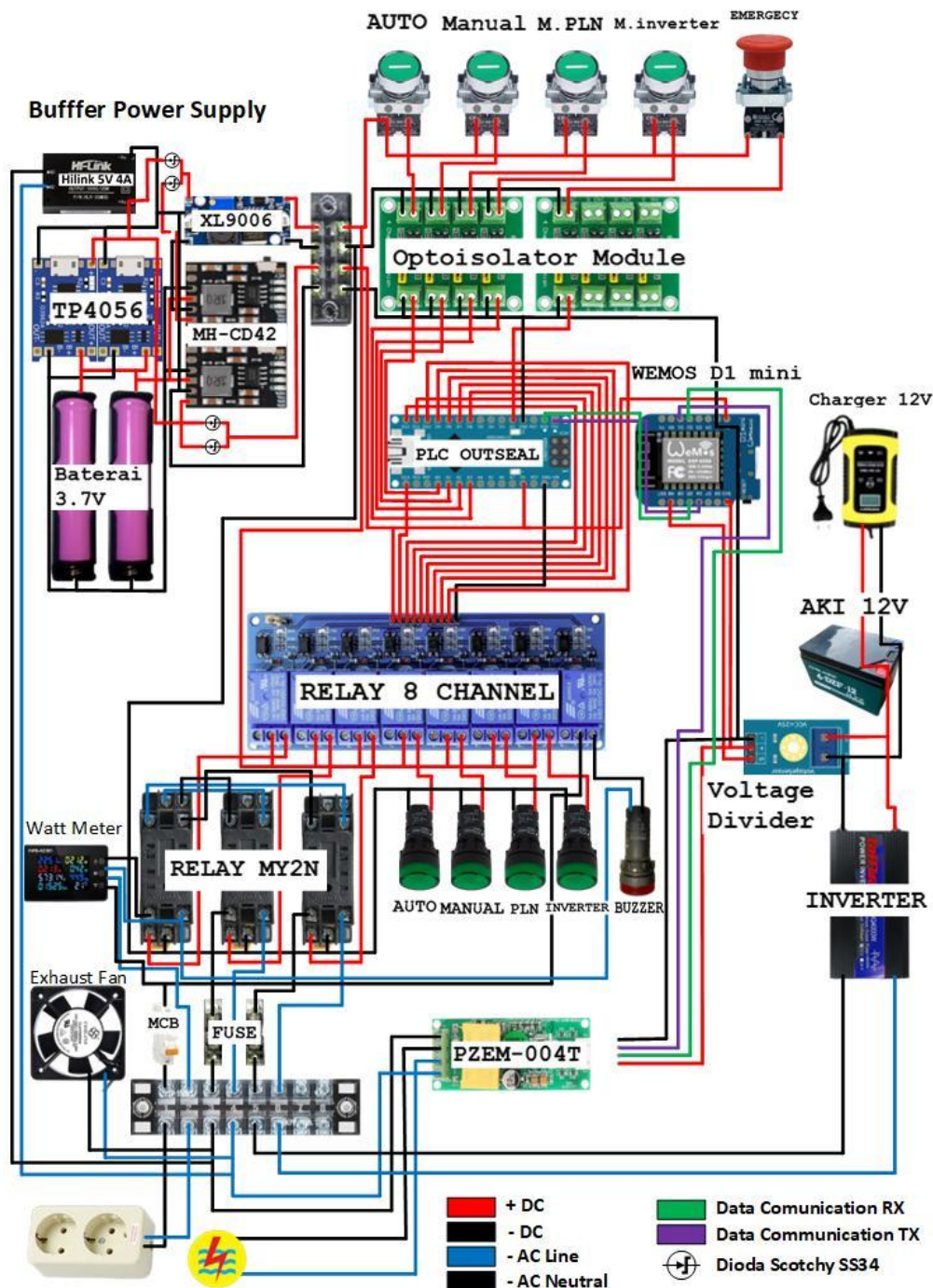


Figure 1. System Diagram

C. Component and Power Supply Buffer Capacity Calculations

The power requirements for the internal control system are supplied by a buffer power supply (Hilink 5V 2A, TP4056 module, MH-CD42 charge/discharge module, and XL6009 boost converter) designed to maintain a continuous control power supply of 8.83 W during the main power supply transition. The selection of the household backup battery capacity is based on a total test load of 102 W (10 W

incandescent lamp, 10 W LED lamp, 40 W fan, 22 W exhaust fan, and 20 W PSU). Based on an inverter efficiency of $\eta = 95\%$ and a Depth of Discharge (DOD) of 80%, the required battery capacity is calculated using the following equation.

$$E_{\text{battery}} = \frac{E_{\text{total}} + (E_{\text{total}} \times (100\% - \text{efficiency Inverter}))}{\text{DOD}\%} \dots\dots\dots (1)$$

$$E_{\text{battery}} = \frac{80 + (80 \times (100\% - 95\%))}{80\%}$$

$$E_{\text{battery}} = \frac{80 + 4,0880\%}{80\%} = 105,1\text{W}$$

The nominal battery capacity in ampere-hours (Ah) in a 12V DC bus system is determined using the following formula:

$$\text{Battery Capacity} = \frac{E_{\text{battery}}}{V_{\text{DC}}} \dots\dots\dots (2)$$

$$\text{Battery Capacity} = \frac{105,1\text{W}}{12\text{V}}$$

$$\text{Battery Capacity} = 8,75\text{Ah}$$

Therefore, the use of a 12V 12Ah VRLA battery has met and even exceeded the minimum system design criteria.

D. Automatic Control Strategy (Auto Mode)

The ATS system operates based on a digital interlock in the Outseal PLC's binary memory. The safe voltage limit for the PLN grid is set at 198 VAC (a 10% drop from the nominal 220 V, in accordance with the PUIL 2000 standard). If the PZEM-004T sensor reads a PLN voltage ≤ 198 VAC or a complete loss of power (0 V), the Wemos D1 Mini sends a Modbus RTU function 05 instruction to binary coil address 130 with a binary status of 0 (OFF). The Outseal PLC automatically disconnects the PLN relay and activates the Inverter relay within the minimum release time of the electromechanical contact:

$$\begin{aligned} T_{\text{off}} &= T_{\text{release Relay 5V}} + T_{\text{release relay_MY2N}} \\ 10 \text{ ms} + 20 \text{ ms} &= 30 \text{ ms} \end{aligned}$$

E. Automatic Control Strategy (Auto Mode)

A. Auto Mode Flowchart

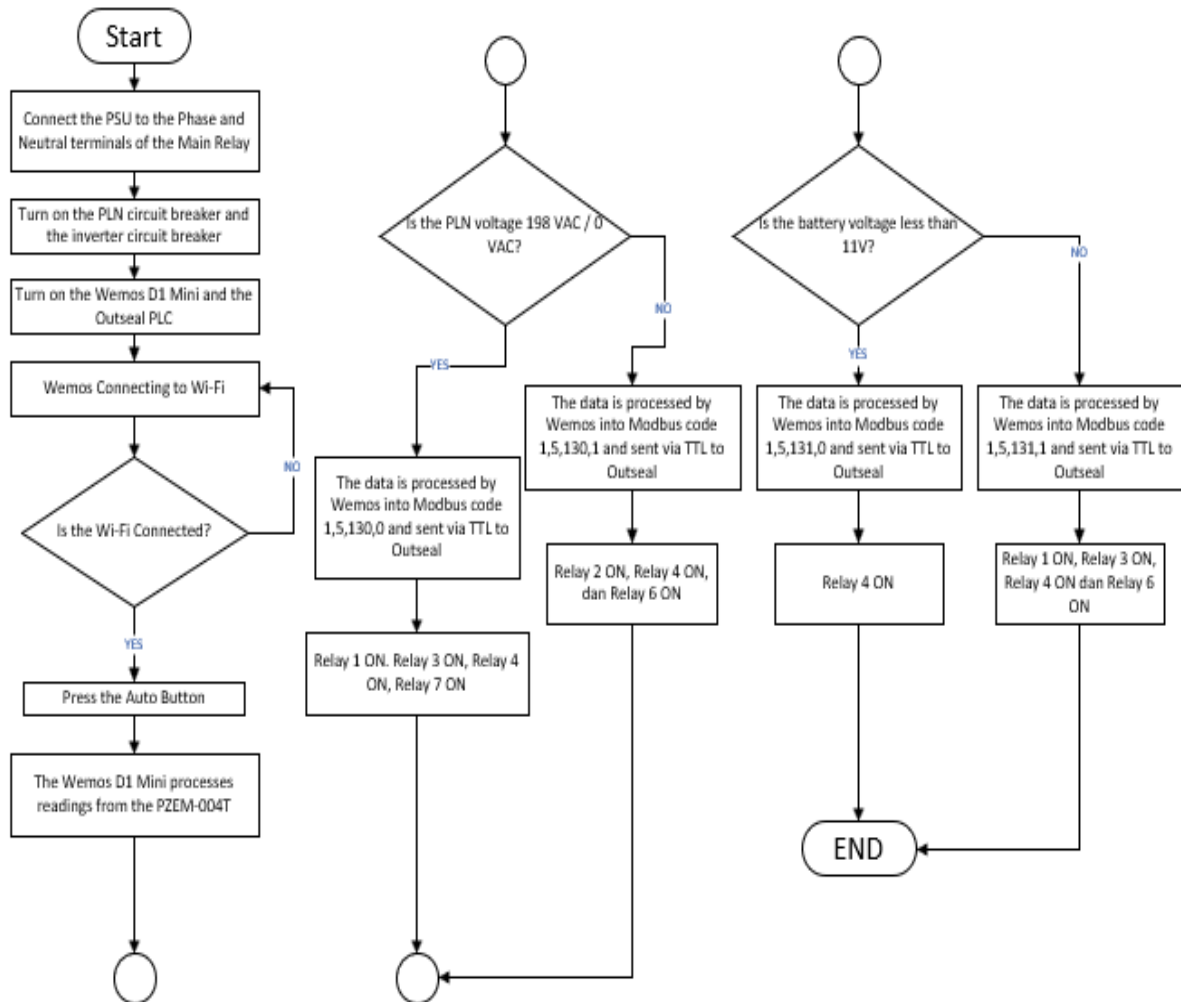


Figure 1. Hardware System Auto Mode

B. Manual Mode Flowchart

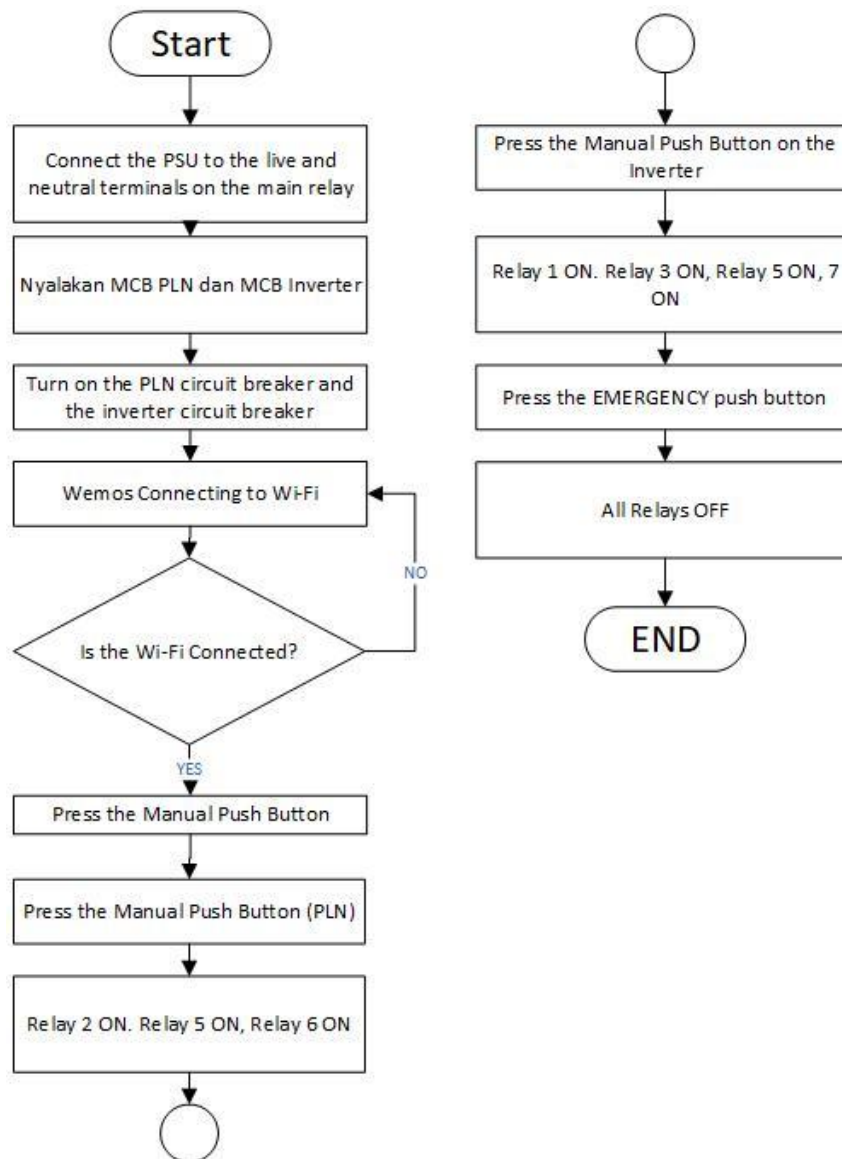


Figure 3. Manual Mode Flowchart

RESULTS AND DISCUSSION

A. Analysis of Power Transfer Time to Different Load Types

Power transition testing was conducted in both directions (from the utility grid to the solar power system and vice versa). In this test, five different time intervals were used: 200 ms, 100 ms, 50 ms, 40 ms, and 30 mm with the same load, namely a 10W incandescent bulb as a resistive load, a 10W LED bulb as a capacitive load, and finally a 40W fan as an inductive load; all three loads were tested simultaneously. The data

from these tests were then averaged, and the data distribution was calculated using standard deviation, resulting in the data distribution shown in Table 1.

Table 1. Power Switching Data

Power Transfer Testing	Time base on PLC	Average Results	Standard Deviation Results
PLN-PLTS	200 ms	223,1ms	15,9
PLTS-PLN		223,1 ms	15,9
PLN-PLTS	100 ms	119,8 ms	17,04
PLTS-PLN		123,1 ms	15,94
PLN-PLTS	50ms	49,5 ms	17,39
PLTS-PLN		46,2 ms	17,04
PLN-PLTS	40 ms	66ms	0
PLTS-PLN		66 ms	0
PLN-PLTS	30ms	30 ms	0
PLTS-PLN		30 ms	0

Based on the experimental results evaluating the various PLC time base settings in Table 1, a consistent positive correlation is observed between the reduction of the programmed time base and the actual power transfer time of the ATS system. At the highest time base configuration of 200 ms, the power transition yields an average real-world transfer time of 223.1 ms with a standard deviation of 15.9 ms. Progressively lowering the time base successfully minimizes the transfer time significantly, reaching an optimal threshold at the 30 ms setting, which generates the fastest real-world transfer time of exactly 30 ms. Furthermore, the system demonstrates highly symmetrical switching characteristics between both power sources (PLN-to-PLTS and PLTS-to-PLN), as the average duration for the bidirectional power transfer registers identical values across each tested time base tier.

A critical indicator of this ATS prototype's resilience lies in its exceptional stability and precision as the time base approaches its minimum threshold. While the higher time base settings (200 ms to 50 ms) exhibit minor data dispersion with standard deviations ranging from 15.9 ms to 17.39 ms due to PLC program scan time variations and transient relay mechanical latencies the standard deviation drops to an absolute value of 0 at the 40 ms and 30 ms configurations. This zero-deviation phenomenon represents perfect system repeatability, ensuring that the power switching is executed identically without any temporal fluctuation across consecutive iterations. Consequently, the 30 ms time base configuration is concluded to be the optimal operational setting, providing the rapidest power transition (30 ms) with flawless

precision to effectively prevent interruptions, resets, or damages in sensitive residential electronic appliances.

B. ATS Testing: 24 Hours to 7 Days

In order to demonstrate the system's resilience for continuous domestic deployment, the ATS device was subjected to a 24/5 stress test for seven consecutive days. The comprehensive operational outcomes, logging performance, and power transition statistics gathered during this non-stop monitoring phase are compiled in Table 2.

Table 2. Data Logging Results Over Seven Days

Time	Voltage (V)	Current (A)	Active Power (W)	Power Factor	Temp
11/7/2026, 22.01.04	221,4	0,021	4,3	0,92	34,4
12/7/2026, 10.15.02	223,7	0,174	38,6	0,99	37,6
12/7/2026, 22.05.00	218,4	0,022	4,3	0,89	37,6
13/7/2026, 10.15.02	226,9	0,171	38,6	0,99	37,9
13/7/2026, 22.05.00	220,6	0,022	4,3	0,89	37,8
14/7/2026, 10.04.58	224,6	0,177	39,4	0,99	38,1
14/7/2026, 22.04.56	223,3	0,022	4,3	0,88	37,4
15/7/2026, 10.09.59	221,2	0,171	37,5	0,99	38,3
15/7/2026, 22.09.10	214,3	0,022	4,4	0,93	37,6
16/7/2026, 10.09.08	219,6	0,177	38,3	0,99	38,4
16/7/2026, 22.09.41	218,2	0,022	4,3	0,9	38,4
17/7/2026, 10.09.39	221,9	0,171	37,6	0,99	38,3
17/7/2026, 22.15.51	219,9	0,022	4,4	0,91	37,6
18/7/2026, 10.15.49	222,4	0,167	36,8	0,99	38,3

The non-stop stress test demonstrates that the ATS device and its monitoring system are highly reliable and accurate in detecting and distributing power across different domestic loads. When supplying the 10 W LED lamp, the system measures an

efficient active power of 4.3 W with a power factor between 0.88 and 0.93. Once the load switches to the 40 W fan, the active power reading accurately rises close to its rated capacity at 38.6 W – 39.4 W, achieving optimal power quality as the power factor increases to 0.99. Throughout these load transitions, the supply voltage remains highly stable within normal limits (218.4 V – 226.9 V), and the device maintains excellent thermal management, with the operational temperature consistently staying safely below 39°C.

CONCLUSION

This research successfully designed and developed an Automatic Transfer Switch (ATS) system that seamlessly integrates the PLN grid and a Solar Power Plant (PLTS) using an Outseal PLC and an ESP8266 microcontroller. Experimental evaluations revealed that configuring the PLC to a 30 ms time base is the optimal setting, achieving a highly precise real-world power transfer time of exactly 30 ms with a zero standard deviation. This rapid and symmetrical switching capability ensured that resistive, capacitive, and inductive domestic loads experienced no interruptions or malfunctions during power transitions. Furthermore, a continuous seven-day (24/7) stress test proved the system's exceptional reliability for residential deployment; the ATS maintained stable supply voltages between 218.4 V and 226.9 V, effectively managed varying loads, and sustained safe operational temperatures consistently below 39°C. Supported by Modbus RTU communication and real-time data logging via a Node-RED dashboard, the developed ATS system is proven to be a highly effective, stable, and resilient solution for continuous non-stop residential power automation.

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