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IoT-Based Automatic Transfer Switch System Design on Solar Home System

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Abstract

The challenge hybrid system power sources face is switching from one source to another. This transfer is required to anticipate the depletion of energy sources in the battery owing to unfavorable weather, such that the solar panels do not receive sufficient sunlight. An automatic switching process with minimal time lag is required to maintain the continuity of the electrical energy flow. In addition, there is a growing need to analyze the energy consumption in certain areas and periods. This project designed and built an Internet of Things (IoT) based Automatic Transfer Switch (ATS) system. The ATS prototype uses the Arduino MEGA 2560 microcontroller to switch the power source and the ESP32 DevKit V1 microcontroller to send the data logger to the IoThingsHub cloud platform for monitoring systems that are useful for sustainable ecosystems. The sensor exhibited accuracies of 99.8% for voltage and 96.5% for current readings. The ATS prototype could switch between power sources with an average time lag of 47 ms. The results of the field trials show that the ATS prototype design utilized solar photovoltaic for approximately 26% of the usage, with a 100 Ah 12V battery system and three 100 Wp solar panels in sunny/partly cloudy conditions for 50 W lamp loads.

1. Introduction

Solar Home Systems (SHS) components include solar generators (PV modules), inverters, battery banks, charge controllers, and linked appliances. Solar PV modules charge batteries during the day to provide nighttime power, while the charge controller handles the battery bank's input and output energy [1]. Regarding the economic value, the battery was the component with the most significant investment value per use. The battery life of an SHS is usually approximately two to five years for a lead-acid battery, and the battery price is still relatively high. Battery cost and reduced lifetime are often limiting factors for such applications. In particular, battery lifetime is limited by the operating conditions of battery energy storage [2]. Therefore, SHSs are often backed by other power plants (hybrids) or connected to a national electricity source (on-grid). The challenge faced by the hybrid system power source is switching from one source to another. This transfer is required to anticipate the depletion of energy sources in the battery owing to unfavorable weather such that the solar panels do not receive sufficient sunlight. When photovoltaic (PV) power generation and battery storage are insufficient, the system switches to grid mode via an Automatic Transfer Switch (ATS). The grid supplied the load entirely, and the battery was recharged using a solar PV system. The system returns to PV mode when the battery is charged to a certain energy level [3]. An automatic switching process with minimal time lag is crucial to maintain the continuity of electrical energy flow.

These systems can operate and promptly restore interrupted services to consumers, thereby enhancing the system's reliability and operational efficiency [4].

Currently, several inverters are equipped with a transfer switch feature; however, the price is relatively high, up to twice (100%) that of a standard inverter. Therefore, to increase the use of this hybrid system, it is necessary to develop other innovative switching systems that are easier and cheaper to implement. Furthermore, a dependable ATS system is essential to sustain support for government programs aimed at augmenting the installed capacity of New and Renewable Energy (NRE), with a focus on dominating solar energy resources over other NRE power plants by 2050 [5]. An ATS device automatically transfers electricity from one electrical power source to another [6]. ATS was developed to support solar power generation systems using magnetic contacts and timers [7], relay drivers, and relay contactors [8, 9]. Digitization of the system has also been developed using a microcontroller so that ATS can utilize radio frequency modules and Internet networks to transmit data. However, a lag time constraint of ± 22 s to switch the power source to a backup energy source inconveniences the continuity of electricity flow [10] and the utilization of public cloud platform applications with security and subscription limitations [11].

To build an ATS device, several essential components must be integrated, such as the controller, the voltage-sensing mechanism, and the switching mechanism. The system should be connected to the Internet for further development to measure its performance remotely and in real time. With the development of Internet of Things (IoT) technology, cloud computing, and automation, intelligent ATS can be developed to significantly impact the development of solar power generation and distribution technology. A combination of Programmable Logic Control (PLC) applications as ATS control systems for on-grid solar home systems and Supervisory Control and Data Acquisition (SCADA) as a user interface has also been developed [12]. The ESP8266 and ESP32 modules can also send ATS data to a database server. The test results show that the system design successfully displays data in the form of voltage, current, and estimated battery usage on the website page in real time [11,13]. However, the switching lag times must be enhanced, given their crucial role in maintaining the seamless continuity of electrical energy flow. It was reported that the switching time lag from the state electricity company Indonesian National Grid (PLN) to solar PV was 5 s and that from the PLN to the generator was 10 s in the developed ATS system [14]. ATS also enhances Smart Home Systems for seamless power source switching between the grid and backup batteries. This development ensured uninterrupted operation during power disruptions. Hardware testing demonstrated the reliability with a 2-4 s ATS response [15]. Other studies have utilized an open transition operating system or break-before-make in the switching process with a lag of 300 ms [16].

On the other hand, to meet the demand for electricity in a particular area, traditional electricity grids generally provide power plants with capacity adjusted to the peak power consumption of that area. An analysis of the use of electrical energy in the household sector shows that, in most periods, energy consumption does not reach peak values [17]. Smart grids have been designed as a sustainable solution to the challenge of increasing power demand, ensuring increased energy efficiency without compromising on usage [18]. By adding computers and sensors at various points in the electricity network, data on the energy usage needs in each area at a specific time can be identified. These data were further processed and analyzed to produce information on energy consumption in specific regions and periods. By utilizing this information, the power grid can be designed to route the electricity generated by power plants that do not consume peak power. The development of a safe electricity system requires the consideration of two primary factors: resilience and connection. In addition, the concept of the Internet of Things (IoT), which is crucial for the creation and design of intelligent power systems, has a significant bearing on the safety of these systems. IoT implies high-security requirements, necessitating the creation of policies, rules, and standards related to the security advancement of these systems [19].

In this study, an ATS system was designed to monitor real-time data based on a web server connected to the Internet of Things (IoT) of the university-based cloud platform IoThingsHub developed by Universitas Multimedia Nusantara (UMN) for security reasons. The target of the switching lag time should be less than 300 ms to protect the sensitive loads against power quality problems. Such a remote monitoring tool could be utilized in areas with potential renewable energy sources so that these areas can take advantage of hybrid electricity systems, such as those originating from micro-hydro, wind, and solar energy.

2. Methodology

The design of the ATS system aims to minimize the number of batteries used while optimally utilizing energy sources from solar power. The PLN functions as an energy reserve or power backup. This research focuses on designing an ATS to send data to a cloud platform to access data remotely. The utilization of the ATS system in installing solar PV and national grid networks in the Solar Home System (SHS) is presented in Figure 1.

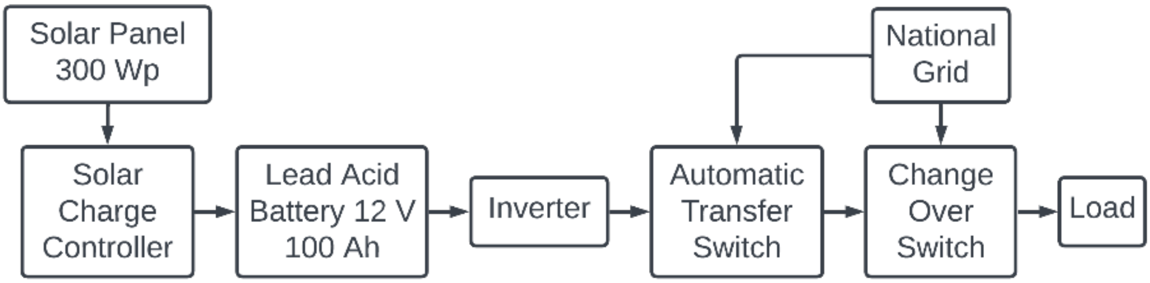

Fig. 1 *Block diagram of ATS system installation on a solar home system*

The ATS prototype was designed for SHS and consists of monitoring and switching systems. An Arduino MEGA 2560 microcontroller was used on the ATS prototype to read real-time date and time from the Real Time Clock (RTC)-DS3231 sensor, and current and voltage data from ACS712 and INA219 sensors. In addition, the Arduino microcontroller plays a role in recording data, which is then sent to the IoThingsHub website cloud platform belonging to the UMN with the help of a microcontroller with WiFi connectivity, namely the ESP32 DevKit V1. The data logger stored on the IoThingsHub cloud platform of Universitas Multimedia Nusantara contained data on the time of data collection, ATS status, AC load current, battery voltage, and current.

The Arduino program coding section consists of six parts: the library initiation stage, variable setup stage, battery voltage limit for switching on the inverter, sensor reading stage, switching stage, sending data logger to ESP32, and data appearance on serial monitoring. In addition, in the ESP32 program, the coding section consists of five sections: library initiation stage, variable setup stage (WiFi SSID, URL, IoThingsHub root certificate authority, JSON format), WiFi connectivity stage, registration stage to the IoThingsHub cloud platform, receiving sensor data from Arduino, and sending data to the IoTingsHub cloud platform.

The programming logic in Arduino program coding consists of the monitoring and switching processes, which are presented as block diagrams in Figure 2. Arduino obtained voltage and current data from INA219, ACS712, and RTCDS3231 sensors, which were then displayed on a serial monitor and sent approximately every 1 minute to the ESP32 microcontroller. Regarding Arduino programming, ATS switches to solar power when the battery voltage is charged to 80% (13.62 V) and utilizes the on-grid PLN when the battery voltage is 11.67 V or 30% of the battery capacity. The process of sending sensor data from Arduino to ESP32 utilizes the JSON format, according to the requirements of sending data to the IoThingsHub cloud platform. The programming flow of the monitoring process is in detail in Figure 3, and the switching process is presented in Figure 4. In ATS system programming, coding is performed using the Arduino programming language with the Arduino IDE software.

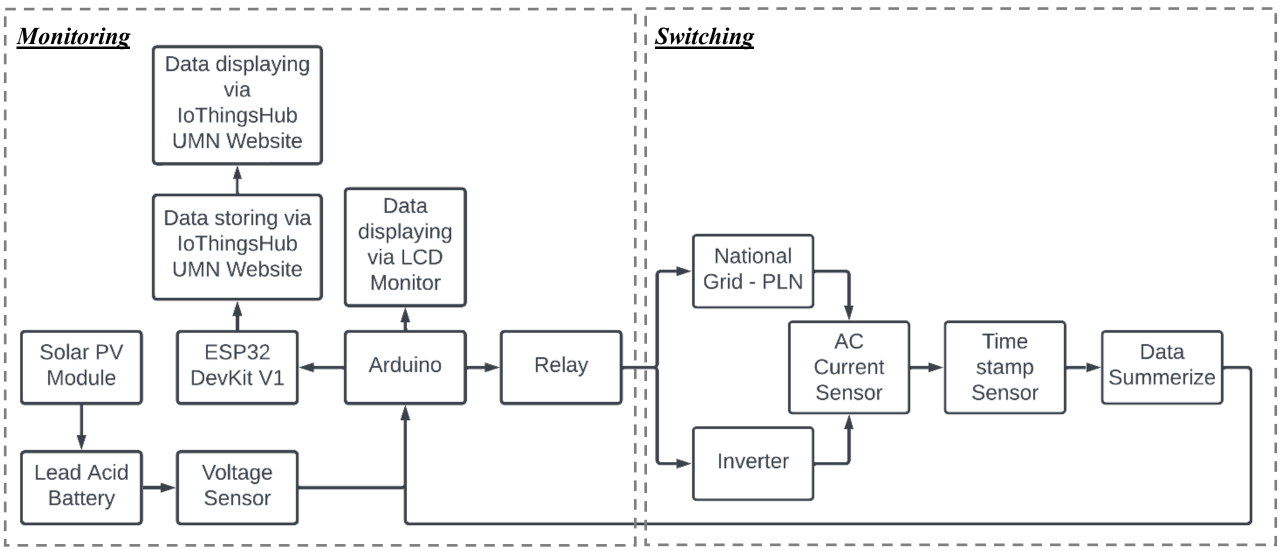

Fig. 2 *System block diagram on ATS prototype*

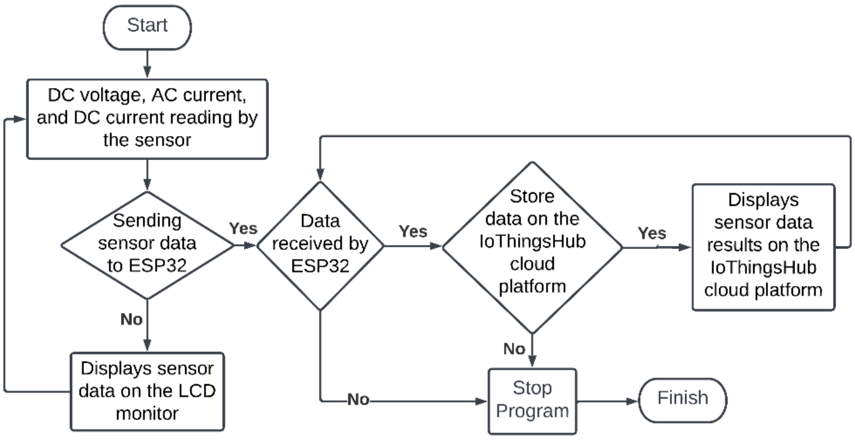

Fig. 3 *Monitoring process programming flowchart*

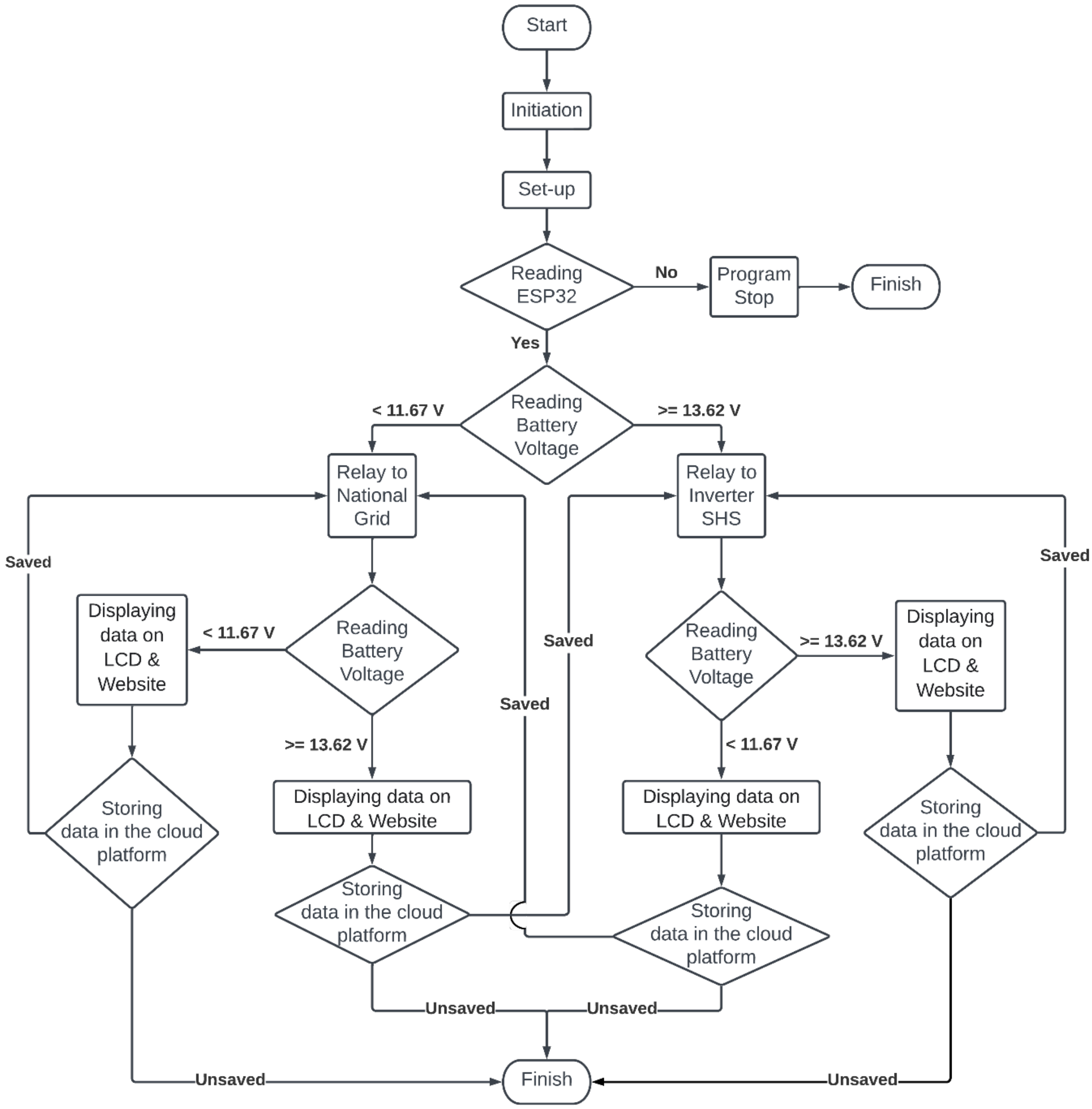

Fig. 4 *Switching process programming flowchart*

The ATS prototype hardware was assembled on a breadboard. The main electronic components for creating ATS prototypes include the Arduino MEGA 2560, ESP32 DevKit V1, INA219, ACS712, RTC DS3231, relay modules, change-over switch, LED, resistor, and jumper cables. There are supporting components from the solar home system when conducting field trials, including 300 Wp solar panel modules, solar charge controllers, inverters, 12 V – 100 Ah lead-acid batteries, and 50 W lamp loads. The breadboard-based ATS prototype electronic circuit is illustrated in Figure 5.

The ATS prototype was tested in both the laboratory and field trials. The lab trials consisted of comparing the voltage and current data on the sensors and direct measurements to determine the effectiveness of the ATS prototype, as well as voltage and current accuracy readings and switching 20 times to determine the lag time from the ATS prototype. Prototype testing was also performed to determine the effect of LCD on the ATS system. The lag time between systems using an LCD and without an LCD was measured, and the differences were analyzed. Field trials were conducted by integrating the Solar Home System with ATS to measure its overall performance.

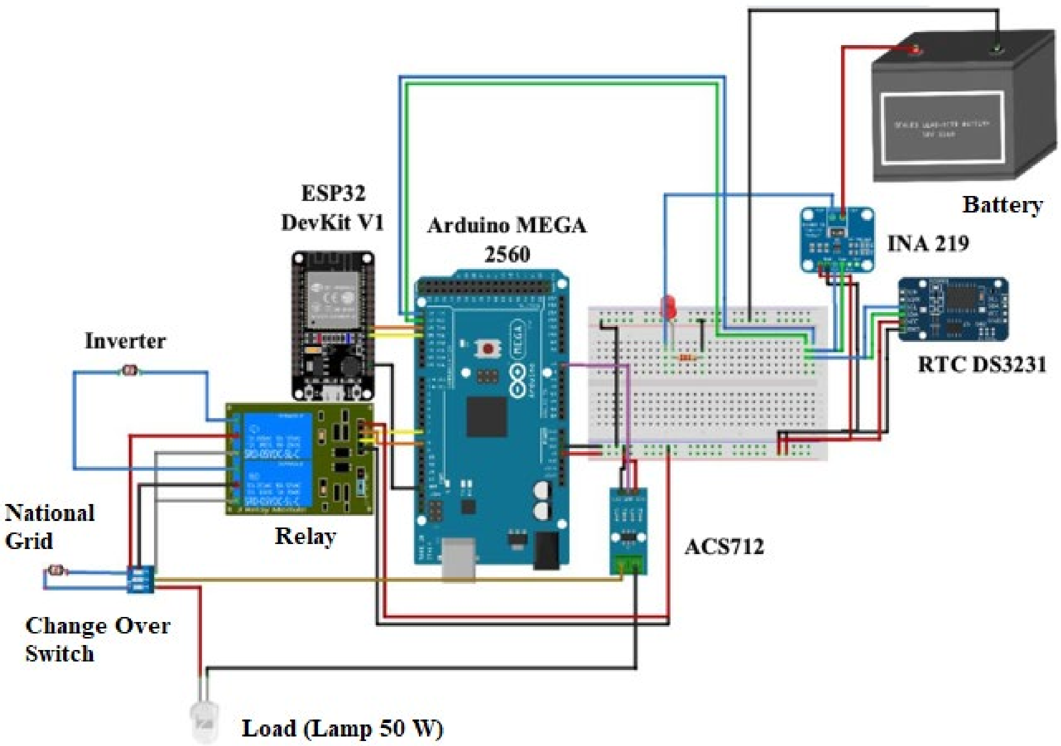

Fig. 5 *ATS system electronic circuit*

3. Results and Discussion

3.1 ATS Prototype Lab Performance

The accuracies of the voltage and current sensors used in the ATS prototype are reviewed. The accuracy of the INA219 sensor was tested using a DC power supply as a substitute for a battery. The DC power supply is regulated at 13.35 VDC with a current of approximately 52 mA. Based on the data processing results, the average of 20 digital multimeter measurement results showed a voltage of 13.35 VDC and a current of 51.78 mA. In comparison, the average of 20 data read by the INA219 sensor shows a voltage of 13.34 VDC and a current of 52.78 mA. The calculation results showed that the standard deviation values of the INA219 sensor measurements were 0.005 and 0.267 for voltage and current, respectively. The standard deviation was smaller than the average value, indicating that the INA219 sensor readings represented the overall measurement results. Furthermore, the INA219 sensor exhibited accuracies of 99.8% for voltage and 96.5% for current readings. Based on these observations, INA219 exhibited an excellent accuracy. The ACS712 sensor was not examined because the current could not be read even though it was measured using two devices: a digital multimeter and a clamp meter. The current could not be read because the current flowing at the 50 W lamp load was relatively small.

In the laboratory trial, switching the ATS prototype with the LCD to display the data was performed by utilizing a DC power supply, which was used as a trigger for the input voltage, which was read by the INA219 sensor. The data retrieval results (20 switches) show that the average lag of the ATS prototype with an LCD was 1.14 s (Table 1).

Table 1 *Lag time ATS with LCD*

Switch Number	Time Stamp	Status	Lag Time [s]
1	11:17:39.984 11:17:41.088	National Grid Inverter	1.10
2	11:17:42.237 11:17:43.341	National Grid Inverter	1.10
3	11:17:44.497 11:17:45.647	National Grid Inverter	1.15
4	11:17:46.804 11:17:47.907	National Grid Inverter	1.10
5	11:17:49.057 11:17:50.214	National Grid Inverter	1.16
6	11:17:51.364 11:17:52.521	National Grid Inverter	1.16
7	11:17:53.624 11:17:54.774	National Grid Inverter	1.15
8	11:17:55.931 11:17:57.050	National Grid Inverter	1.12
9	11:17:58.238 11:17:59.341	National Grid Inverter	1.10
10	11:18:00.490 11:18:01.647	National Grid Inverter	1.16
11	11:18:02.797 11:18:03.900	National Grid Inverter	1.10
12	11:18:05.057 11:18:06.207	National Grid Inverter	1.15
13	11:18:07.364 11:18:08.514	National Grid Inverter	1.15
14	11:18:09.617 11:18:10.774	National Grid Inverter	1.16
15	11:18:11.924 11:18:13.080	National Grid Inverter	1.16
16	11:18:14.231 11:18:15.349	National Grid Inverter	1.12
17	11:18:16.491 11:18:17.641	National Grid Inverter	1.15
18	11:18:18.782 11:18:19.901	National Grid Inverter	1.12
19	11:18:21.038 11:18:22.189	National Grid Inverter	1.15
20	11:18:23.323 11:18:24.495	National Grid Inverter	1.17
	Average Lag Time		1.14 ± 0.24

The switching trials were also conducted without an LCD. From the data sent to IoThingsHub, an average lag time of 0.047 s or 47 ms was detected for the 15 switches. Furthermore, there are five switches in which the lag time cannot be read owing to overlapping data, which results in a lag time of 0 ms. Overlapping was likely to occur because the requests for data display were faster than 47 ms. Table 2 lists the switching data.

Table 2 *Lag time ATS without LCD*

Switch Number	Time Stamp	Status	Lag Time [s]
1	11:33:07.878 11:33:07.925	National Grid Inverter	0.047
2	11:33:08.707 11:33:08.754	Inverter National Grid	0.047

Switch Number	Time Stamp	Status	Lag Time [s]
3	11:33:09.690 11:33:09.737	National Grid Inverter	0.047
4	11:33:10.439 11:33:10.485	Inverter National Grid	0.046
5	11:33:11.454 11:33:11.454	National Grid Inverter	0*
6	11:33:12.297 11:33:12.344	Inverter National Grid	0.047
7	11:33:13.270 11:33:13.316	National Grid Inverter	0.046
8	11:33:14.016 11:33:14.062	Inverter National Grid	0.046
9	11:33:14.952 11:33:15.000	National Grid Inverter	0.048
10	11:33:15.894 11:33:15.894	Inverter National Grid	0*
11	11:33:16.876 11:33:16.876	National Grid Inverter	0*
12	11:33:17.672 11:33:17.719	Inverter National Grid	0.047
13	11:33:18.708 11:33:18.708	National Grid Inverter	0*
14	11:33:19.502 11:33:19.548	Inverter National Grid	0.046
15	11:33:20.482 11:33:20.482	National Grid Inverter	0*
16	11:33:21.372 11:33:21.418	Inverter National Grid	0.046
17	11:33:22.355 11:33:22.401	National Grid Inverter	0.046
18	11:33:23.148 11:33:23.195	Inverter National Grid	0.047
19	11:33:24.222 11:33:24.270	National Grid Inverter	0.048
20	11:33:25.020 11:33:25.066	Inverter National Grid	0.046
Average Lag Time (exclude 0 lag time)			0.047 ± 0.0007

* *overlapping time stamp data*

Both ATS systems (with or without LCD) were effective because they succeeded in switching between electrical energy sources. However, a system that accommodates the elimination of the LCD has succeeded in increasing the efficiency of the switching process by 24 times from 1.14 s lag time to 0.047 s. It is essential to understand that the switching speed of the relay is influenced by the number or length of codes in the Arduino program, the ability of the microcontroller to execute the code, and the read and write capabilities of the microcontroller. The greater the number of pins used, the longer the run time of the Arduino microcontroller. In addition, the efficiency of sending data to the IoThingsHub cloud platform relies on the upload speed of the Internet or the WiFi provider in use. The acquired data was directly forwarded to the cloud platform, bypassing the use of LCDs.

Upon further examination, it is observed that, during the switching tests of an ATS system without an LCD and under a lamp load of 50 W, the national grid electricity is expected to provide a current of approximately 0.23 A. However, some switches generate currents exceeding 0.23 A due to inrush currents. The inrush current is the maximum current drawn by the electric circuit when it is turned on, where the inrush current value is much higher than that when the current is in a steady state or the steady state of the circuit. High-surge currents can damage the device or trigger power cuts. However, because the generated current was relatively small, it was still relatively safe. A graph of the data collected from the first six switches is shown in Figure 6.

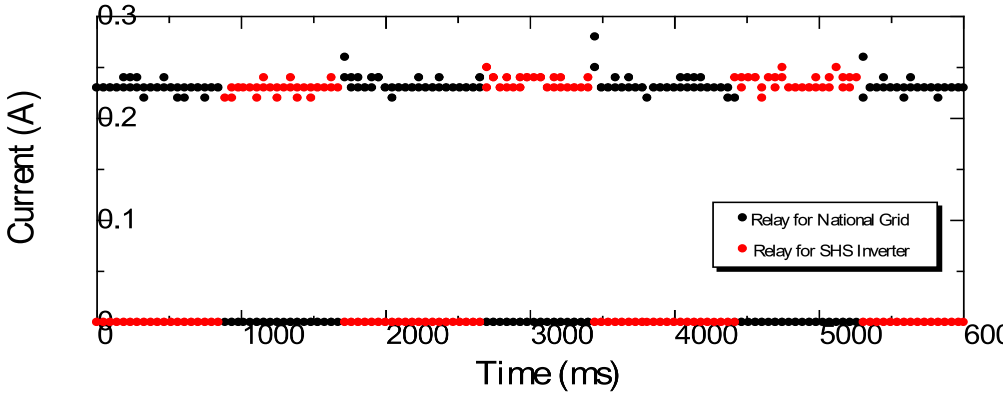

Fig. 6 *Results of laboratory tests of the effectiveness of switching*

3.2 ATS Prototype Field Trials

Field trials were conducted using an ATS system connected to Wi-Fi Internet. It was conducted under cloudy and sunny/partly cloudy conditions for approximately two days, for each condition. The electricity loads based on the data collected at IoThingsHub for both cloudy and sunny/partly cloudy conditions are shown in figure 7 and 8, respectively.

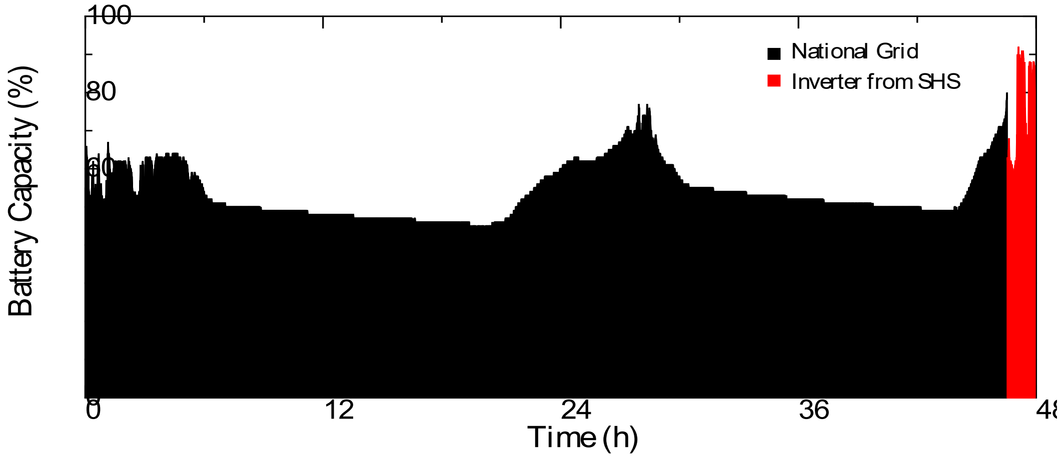

Fig. 7 *Field trial results under cloudy conditions*

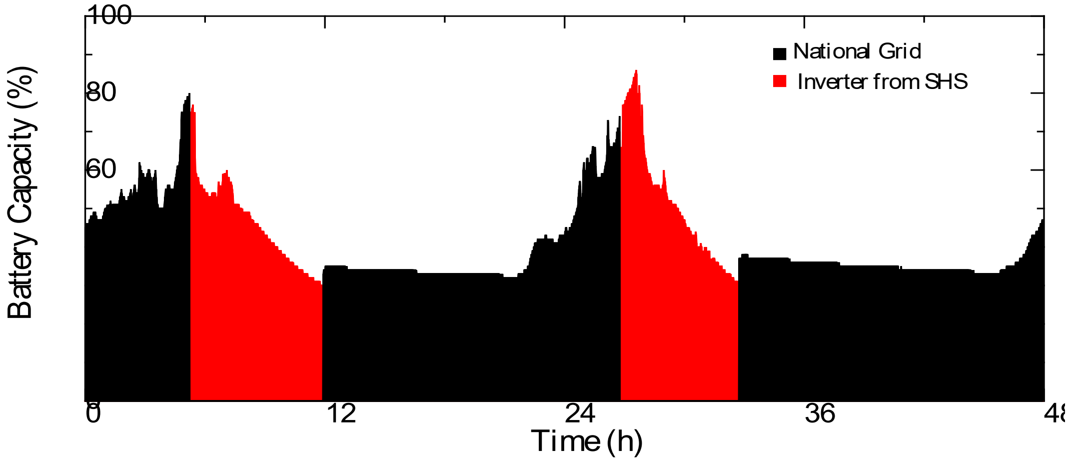

Fig. 8 *Field trial results under sunny/partly cloudy conditions*

Under cloudy conditions, the percentage of SHS use reaches 3% only because the battery cannot charge up to 80% during peak hours of sunlight, even though it uses a solar panel with a capacity of 300 Wp. In field trials under sunny/partly cloudy conditions, the percentage of SHS usage reached 26% or 12.6 hours for approximately two days of field trials. Lead-acid battery charging occurs from 06.00 to approximately 17.00. When the sun is bright, its peak occurs around 11.00 to 15.00. Even though the situation is slightly cloudy, the lead acid battery will be charged to 80% capacity while the sun shines at peak times. The ATS prototype designed in this study succeeded in switching between power sources and monitoring based on IoT and in measuring the performance of sending data to the University-based IoT platform, which has yet to be reported in previous studies [20-23].

4. Conclusions

The ATS prototype designed and manufactured has gone through the field trial stage in a state and has been proven to carry out transfers or switch in hybrid system (between national grid power sources and solar PV battery systems). Based on the results of the trials conducted, it can be concluded that the designed and manufactured ATS prototype can display data through a serial monitor and transmit data loggers in real time with a cloud platform. The sensor exhibited accuracies of 99.8% for voltage and 96.5% for current readings. Furthermore, this prototype successfully switched hybrid solar home electrical system, with an average switching lag time of 47 ms. Field trials for approximately two days resulted in the ATS prototype design using solar PV for approximately 26% of the usage, with a 100 Ah 12V battery system and three 100 Wp solar panels under sunny/partly cloudy conditions with a 50 W load. In a real-world scenario, the ATS can be applied to an SHS that switches the battery power source to a national on-grid source, or vice versa, when needed. ATS can optimize SHS by transferring the power source from the battery to the national grid when the battery runs out. Thus, the investment in batteries can be reduced.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Niki Prastomo, Angela Michelle Sutopo, Putu Gandhi Aditya Bayuntara;* ***data collection:*** *Angela Michelle Sutopo, Niki Prastomo, Putu Gandhi Aditya Bayuntara;* ***analysis and interpretation of results:*** *Niki Prastomo, Angela Michelle Sutopo, Putu Gandhi Aditya Bayuntara;* ***draft manuscript preparation:*** *Angela Michelle Sutopo, Niki Prastomo. All authors reviewed the results and approved the final version of the manuscript.*

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