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Energy Monitoring and Control of Automatic Transfer Switch between Grid and Solar Panel for Home System

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ABSTRACT

In this digital age, most aspects of life require an electric supply. The availability of electrical power is very critical to maintaining the continuity of the system in various applications. To maintain system continuity, the Energy Monitoring and Control of an Automatic Transfer Switch (ATS) between the Grid and Solar Panel is proposed. The system consists of an Automatic Transfer Switch, Home Solar Power Plant, and Automatic Charging. The function of the monitoring system is to monitor the voltage, current, and power across the device, the operation mode of the ATS, and the State of Charge (SoC) of the battery. The control system is to control the operation mode of ATS according to the energy source selected by the user on the Internet of Things (IoT) interface. The results show that the system can successfully monitor solar panel conditions, AC output, and battery's State of Charge through Blynk IoT. The ATS works automatically with a switching delay of 20ms to 26ms, while on the user's command, the average switching delay is 303.33ms to activate the relay and 185ms to deactivate the relay.

1. Introduction

As technology develops, the need for electrical energy also increases, but the demand for electric power is not proportional to the increase in the availability of electric power [1]. In this digital era, most aspects of life require a supply of electrical energy to run correctly, and some people in Indonesia depend on electrical power from the National Electric Company (PLN), so it can be said that electricity is one of the primary needs [2][3]. The fossil fuels used in electricity production also increase to meet the increasing availability of electricity. In addition, there is the possibility of disruption in the distribution of PLN's electricity from power plants to consumers, which is distributed through an open transmission network, causing power outages on the consumer side [4].

The use of new and renewable energy continues to be developed to reduce the use of fossil fuels to meet electricity needs. One of the renewable energies that are being intensively developed is solar energy. Solar energy can be used on a small scale, such as the household scale, so it is a form of renewable energy power generation that is easily accessible. However, solar power plants have limited irradiation time and have an average effective irradiation of only eight hours a day, so if it is not

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combined with a grid electricity source to meet household electricity needs, it can disrupt the continuity of the system [5].

To maintain system continuity, an Automatic Transfer Switch (ATS) was designed, which allows the system to work using two power sources, the primary power source and a secondary power source, so that when the PLN as the primary power source goes out, the system will automatically change the other power source [6]. Batteries and inverters can be used as a secondary source of electricity to maintain system continuity, but batteries must always be charged as electrical energy storage. This problem can be overcome by implementing an automatic charging system, where a battery that has been used and its charge has been reduced to a certain point can be charged automatically. To save on electricity usage from PLN and lessen the need for fossil energy sources, charging can also be done by utilizing new and renewable solar energy. Due to the limitations of irradiation in solar energy utilization, automatic charging is also provided with a PLN backup power source to maintain system continuity.

Technological developments also have an impact on continuing to develop creativity in various fields of service [7]-[10]. The emerging technology currently used in various fields is the Internet of Things (IoT) [11]. The IoT means some devices are connected to the internet and can be monitored and controlled online [12]-[14]. By implementing the Internet of Things on numerous types of electronic equipment, this equipment can be monitored and controlled flexibly [15]. It is also widely applied in some sectors such as homes, cities, industries, agriculture, hospital, health, and food [16]-[19]. There are many IoT platforms, such as Blynk, Ubidots, IBM Bluemix, and Devicepilots [20]-[22]. that can be used. Blynk provides a monitoring and control interface using the web or smartphone so that the Blynk platform has easy access [23]. Therefore, the Blynk platform is chosen.

Hasanah, *et al.* designed an Automatic Transfer Switch that runs automatically and manually, which is assembled using a relay and Arduino microcontroller to control the relay; this research uses energy reserves from Emergency Power Generator and PZEM sensors to detect the presence of voltage on the power source [24]. Kurniawan *et al.* designed an Automatic Change Over Switch (ACOS) using the OMRON PLC as a control device and a generator as a backup energy source. This design turns on the generator after the primary power source goes out, so there is a delay [25]. Audia *et al.*, in their research entitled Automatic Transfer Switch (ATS) Tool as a Solar Cell Hybrid Electrical System in Households, designed ATS without using a controller. ATS uses a contactor with a battery backup that is charged with an inverter. The inverter turns on after the PLN power goes out so that the power supply is cut off for a few seconds [26]. Taiwo and Ezugwu, in their research, designed an Internet of Things-based Smart Home monitoring system [27]. The IoT platform used is Blynk, whereas the variables monitored are indoor air quality, fire detection, and door conditions using a magnetic switch. This system can also be monitored via Twitter using the auto-tweet feature [28].

In this study, the ATS circuit was made using a Miniature Circuit Breaker (MCB) circuit, contractors, DC relays, and 220V AC relays. This aims to minimize the time required to perform switching when the primary power source is out by using only analog devices. Adding a DC relay in the circuit allows the ATS to be controlled remotely using a microcontroller and IoT. As a backup power source, VRLA batteries are used. When the VRLA battery charge drops to a specific setpoint and the system is running with the primary power source, charging is done in one of two charging modes, namely using a solar panel or with a VRLA battery charger. A VRLA battery charger is intended as a backup when it is needed to charge the battery, but the solar panel does not get enough input. The microcontroller measures the variables in the system and uploads them to the IoT server, where monitoring and control can be carried out.

The contribution of the proposed system is, compared to previous research, the update starts from the ATS circuit, which uses two contactors and a relay with a short switching time. In addition, in the solar panel system, there is an INA260 sensor to observe panel conditions in real-time, and a relay is added for protection against solar panel temperatures. As well as the State of Charge (SoC), the battery is classified into several types based on the working state of the battery.

2. Material and Method

Fig. 1 shows the research flow of this study. Starting from the literature review to know the research update in this field. Next, system design is done, which consists of hardware and software design. Next, the hardware is assembled. After both hardware and software are ready, then the system is tested. There are five tests, including sensors, solar panels, ATS, automatic charging, and IoT Systems.

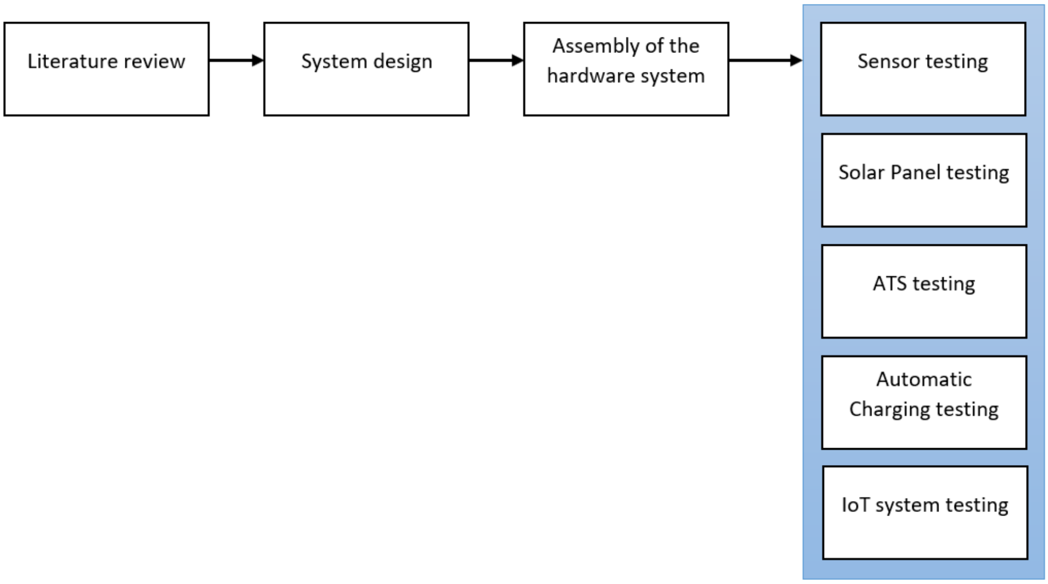

Fig. 1. Research flow

2.1. Proposed System

The system's design consists of ATS, a solar panel system, and automatic charging. This system uses the Arduino Mega 2560 and ESP32 microcontrollers to get measurement readings from the sensors used and to control the relays installed, which function for automatic charging control, connecting loads, and changing ATS operating modes via the Internet of Things. ESP32 is connected to Blynk's Internet of Things via a Wi-Fi network.

The diagram in Fig. 2 explains how the system works with the Arduino Mega 2560 as the system control assisted by the ESP32. Arduino Mega 2560 gets input from the INA260 sensor to measure voltage, current, and power from solar panels, while from the PZEM-004T sensor to measure voltage, current, power, frequency, and power factor from AC output, and a voltage divider circuit to measure the battery voltage. It also controls the relay on the solar panel and on the VRLA battery charger to disconnect and connect power for charging the battery. ESP32 completes the system to connect with the Blynk server to upload information from the system; besides that, ESP32 also gets solar panel temperature measurements from the DS18B20 temperature sensor. This sensor is connected to ESP32, not Arduino Mega, because DS18B20 requires a minimum delay of 750ms while the Arduino program runs the minimum delay smoothly while the ESP32 programming is given a delay of 1000ms as an interval for uploading data to the IoT server. Through Blynk Apps and Blynk Console, monitoring of the system can be carried out and can change the operation of the ATS and control the load by disconnecting or connecting the contact box using a relay.

2.2. Working Principle

Arduino Mega 2560 aims to obtain data measured by sensors and determine the appropriate action from the sensor readings. The data that has been received and processed is then sent to ESP32 via serial communication. Fig. 3 is an Arduino programming logic flowchart where it is found the process of collecting voltage, current, and power data from solar panels and AC output using the INA260 and

PZEM-004T energy sensors, as well as battery voltage using a voltage divider circuit. If the grid is ON, then the battery supply is cut-off, and the battery voltage is checked if the SoC is lower than 55%, it will be charged. The priority of the energy supply for battery charging is a solar panel. If its voltage is below the threshold, then the charging will be done by the grid. In another way, if the grid is OFF, the system will be supplied by the battery until the lower limit of battery voltage is reached.

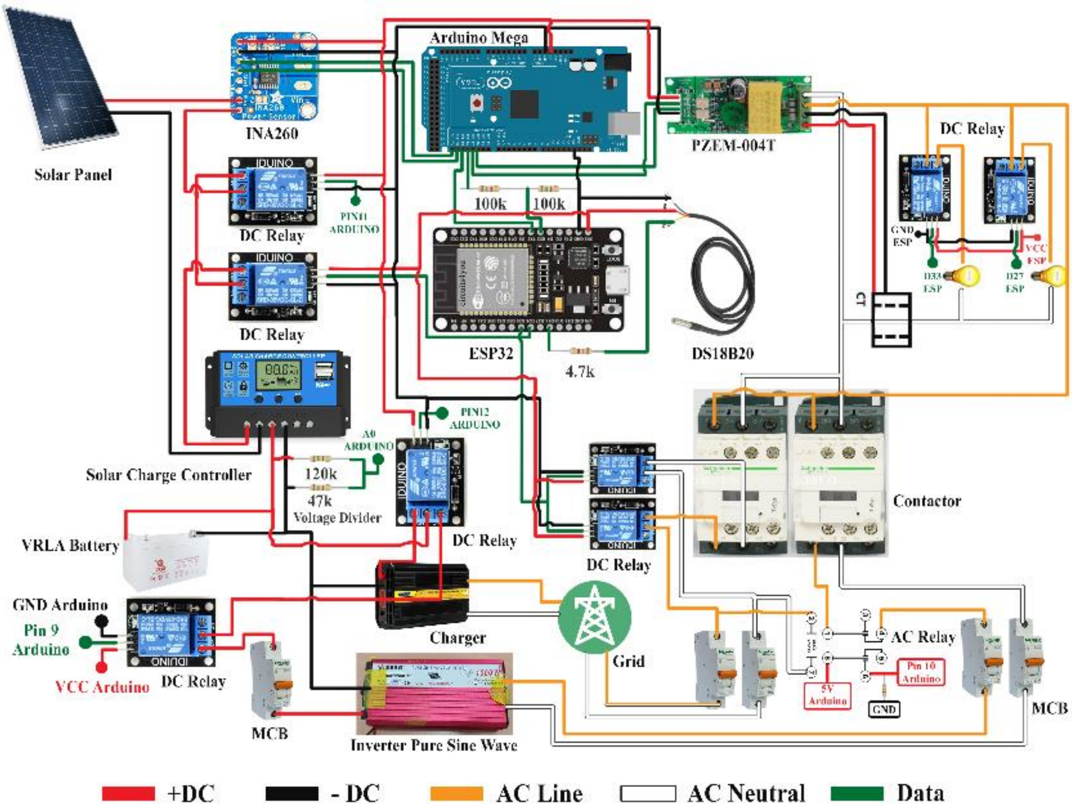

Fig. 2. Wiring diagram of the proposed system

Fig. 4 explains the logic flow of ESP32, where ESP receives data from Arduino Mega and measures the temperature of the solar panel using the DS18B20 sensor to activate and deactivate DC relays for control and protection. ESP32 is connected to the Blynk server via Wi-Fi to carry out monitoring and control functions.

2.3. Internet of Things

The interface display of the developed Blynk GUI is in Fig. 5. It is separated for each section by title and color. At the top, there are two indicators, "Charge" and "Op" these indicators provide information about whether the battery is being charged and the ATS operating mode. Between the two arrows, there is a dual-state button that functions as a control button for the ATS operating mode, while below the indicator are two buttons to activate the relay that connects the ATS output to the load. The following section is the output, which displays information about the output voltage, current, power, frequency, and power factor measured using the PZEM sensor. In the Input section, information on voltage, current, power, and temperature is displayed from the solar panel. This information is obtained from the INA260 DC energy sensor and the DS18B20 temperature sensor. The bottom shows battery information in gauge and graph form.

The information displayed in the web application shown in Fig. 6 is the same as in the Android version. Information is displayed on two pages. The first page contains both “Charge” and “Op” indicators, dual-state buttons, panel temperature, and graphs of battery voltage and State of Charge. The second page contains information from the PZEM and INA260 sensors and controls for the load relay.

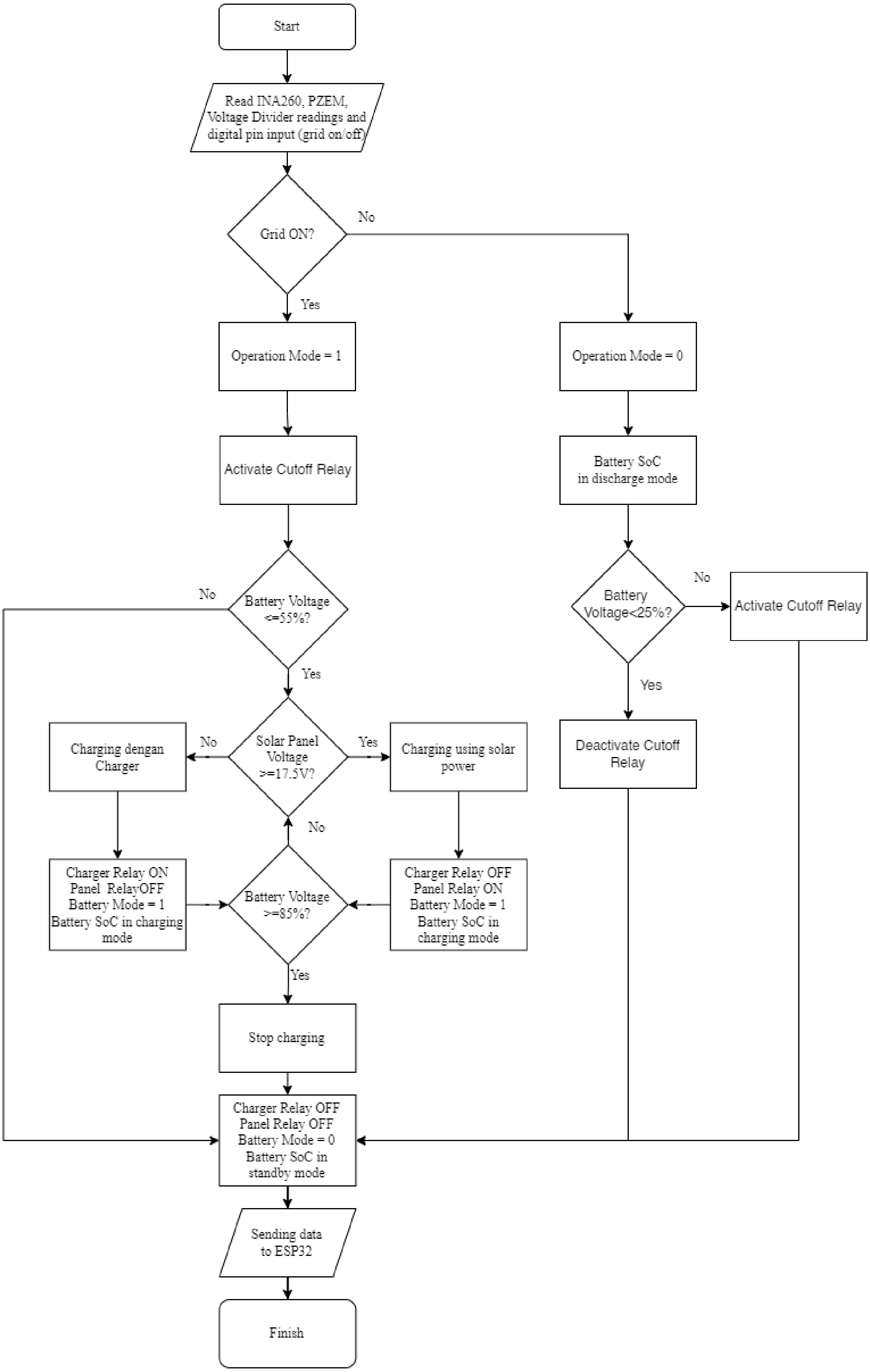

Fig. 3. Working principal flowchart

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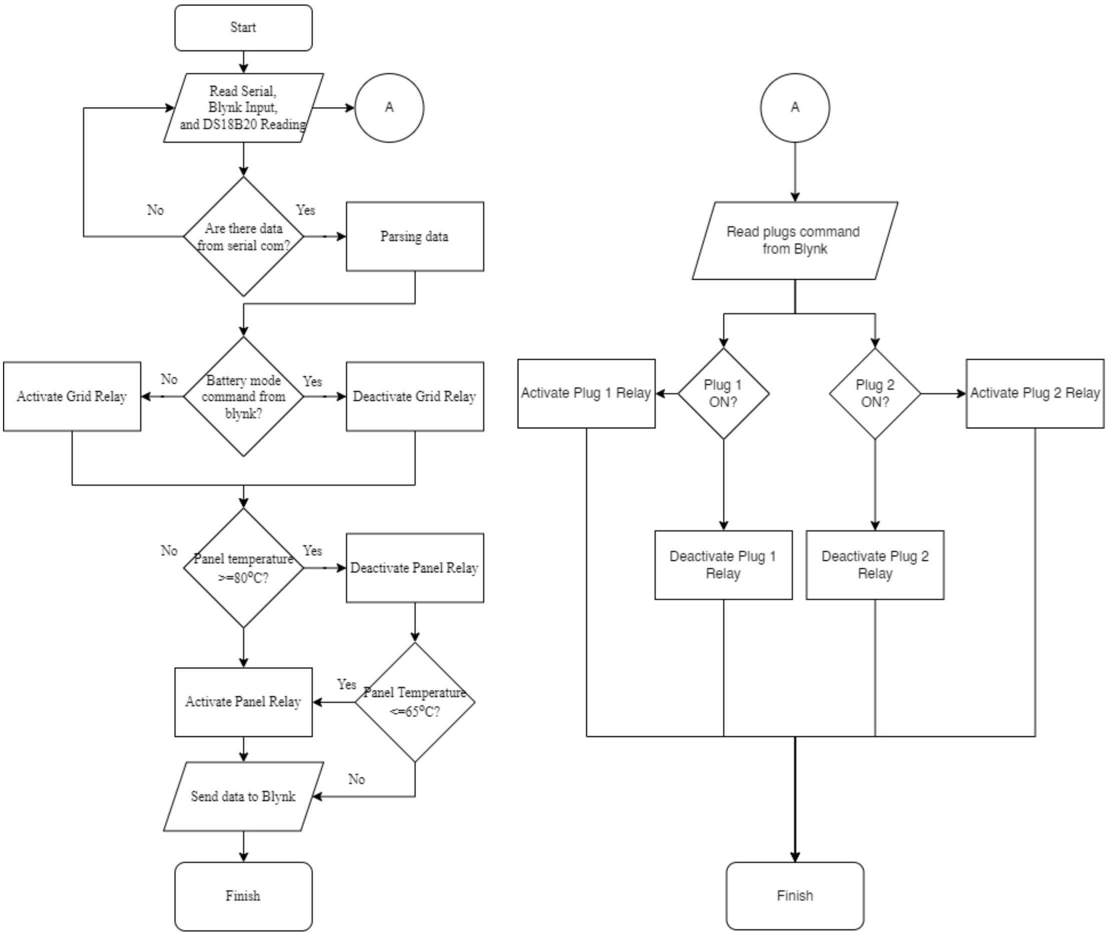
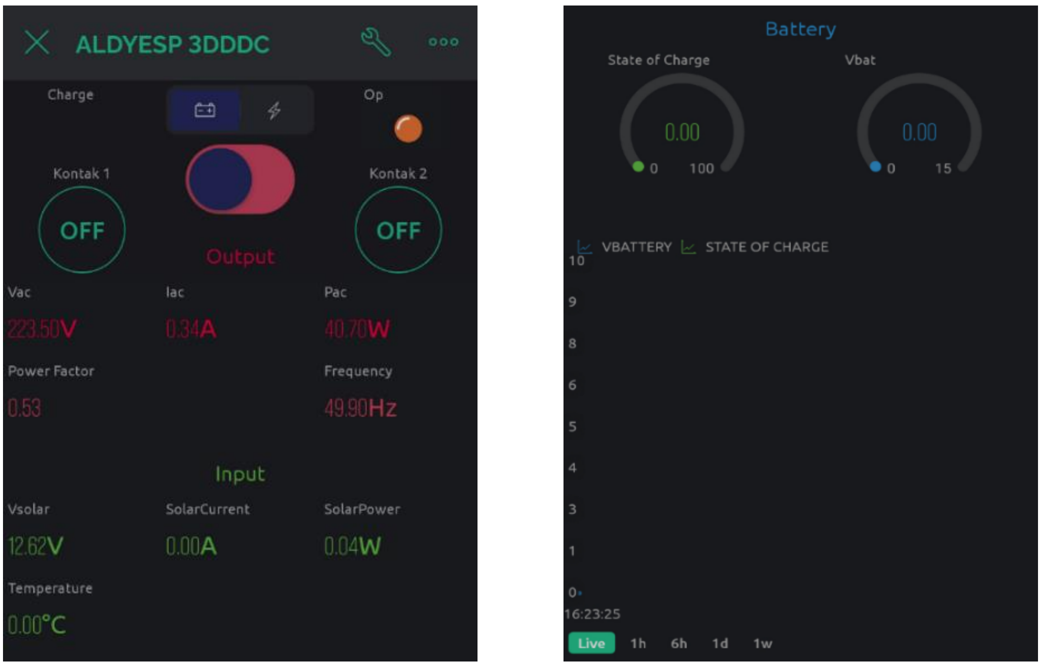


Fig. 4. Flow diagram of IoT system and solar panel protection



(a) (b)

Fig. 5. GUI design in Android Application (a) Input-output condition (b) Battery condition

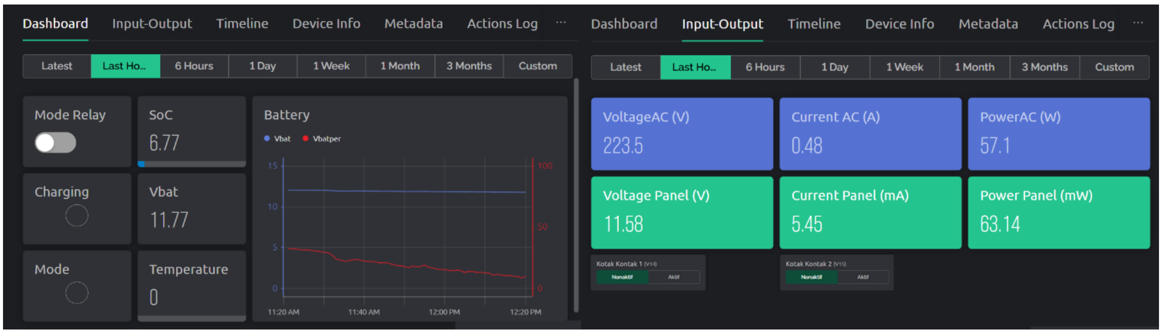


Fig. 6. GUI design Web version

3. Results and Analysis

After the design stage is finished, the hardware is assembled, and the Blynk app is developed. Fig. 7 shows the hardware of the proposed system. The connection between hardware and software was then tested. Next, sensor testing, solar panel system testing, ATS testing, automatic charging testing, and IoT testing are performed.

Fig. 7. The hardware of the proposed system

3.1. Sensor Testing

Sensor testing is carried out to determine the accuracy and precision of the sensor. In this test, a Clamp meter is used as a reference for sensor measurements. By comparing Clamp meter measurements with sensor measurements, it can be detected that there are differences in the measurement values in the Root Mean Square Error (RMSE). The difference in these measurements is used to calculate the accuracy of the sensor. In addition, sensor precision is also tested. If the sensor has readings that are not precise or fluctuate, a filter will be added. Sensor precision testing is carried out by measuring the same conditions many times, which then, based on the results, can be calculated as Relative Standard Deviation (RSD). The equations for RMSE and RSD are shown in (1) and (3). Where the variable used is explained in Table 1.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{((y_i - \hat{y}_i) * 100/y_i)^2}{n}} \quad (1)$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}} \quad (2)$$

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$$RSD = \frac{SD}{\bar{x}} \quad (3)$$

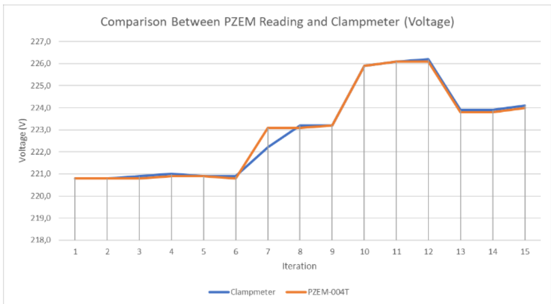
Table 1. Variable explanation

Variable	Remark
RMSE	Root mean square error (%)
SD	Standart deviation
RSD	Relative standart deviation (%)
y_i	Set-point value
$\hat{y}_i$	Measured value
n	The number of data
x_i	Measured value
$\bar{x}$	Mean of x

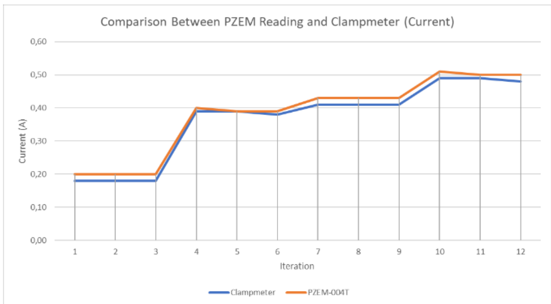
3.1.1. PZEM-004T Sensor

Testing the accuracy of the PZEM-004T-V3 AC energy sensor was carried out by comparing the sensor measurement results under several conditions with the UNI-T UT204+ Clamp meter measurement results. In comparison, the precision test is carried out by measuring the same condition thirty-five times of testing to obtain the relative standard deviation level, which is used to calculate the sensor precision. Power accuracy testing is carried out by comparing the power value measured by the sensor with the multiplication of the voltage, current, and power factor of the sensor after measuring the sensor voltage and current is tested for accuracy.

Fig. 8 shows the comparison between PZEM-004T-V3 and the Clamp meter measurement. It can be concluded that the PZEM sensor has worked well with each level of accuracy for voltage, current, and power of 99.89%, 93, 59%, and 98.02%, respectively. Therefore, the PZEM sensor does not need to be recalibrated. At the same time, the results of the PZEM-004T sensor precision test for measurements obtained a good level of precision which is 99.91% for voltage measurements, 98.56% for current measurements, and 98.88% for power measurements, so there is no need to add filters.



(a)



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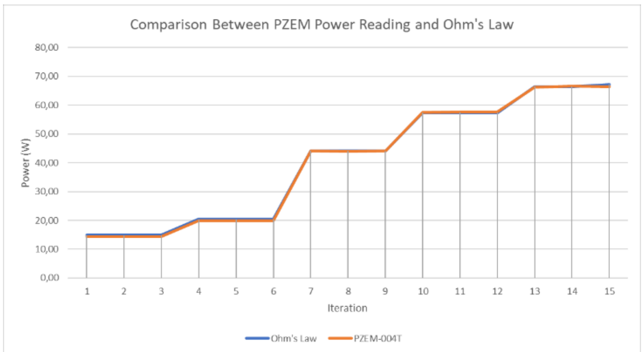
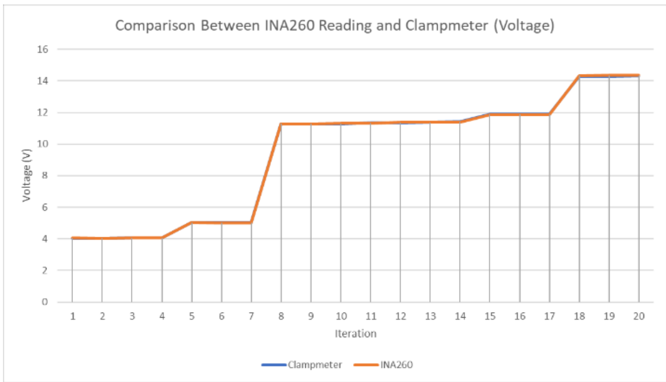


(c)

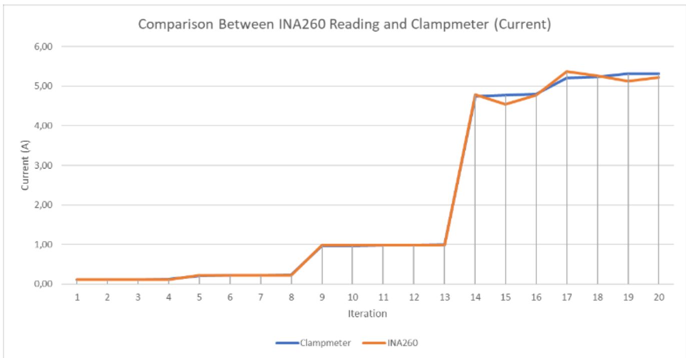
Fig. 8. Comparison between PZEM-004T-V3 and Clamp meter measurement (a) Voltage (b) Current

3.1.2. INA260 Sensor

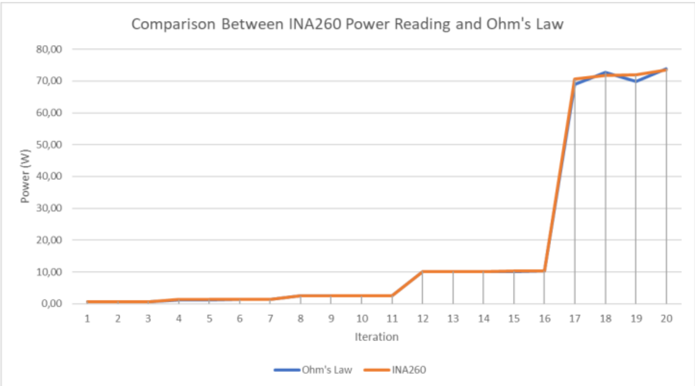
Accuracy testing was carried out on varying voltages using a VRLA battery and Arduino, which was given a resistive load and no load. The result is shown in Fig. 9. The test results for the INA260 sensor have an accuracy rate of 99.83% in measuring voltage, 93.32% for measuring current, and 96.13% for measuring power. Based on the results of the accuracy test, recalibration is not necessary because it has an accuracy of more than 90%. The results of the INA260 sensor precision test obtained a precision of 99.58% for voltage, 98.85% for current, and 99.59% for power. Based on these data, the INA260 sensor has very good precision, so no filter is needed.



(a) Voltage



(b) Current



(c) Power

Fig. 9. Comparison between INA260 sensor reading with Clamp meter

3.1.3. Voltage Sensor

The battery used in this system is a 12V 33Ah VRLA battery where the 12V VRLA battery has a maximum voltage when in the float charging process with a voltage of 14.5V, so a voltage divider circuit is designed considering the maximum input voltage value of 15V for a maximum output of 4.5V. A voltage divider circuit can be designed using (4). The accuracy test was carried out 20 times at 4 different voltages. A measurement accuracy of 98.37% was obtained, while the results of the precision test showed that the sensor had a precision of 99.91%, so it can be concluded that the voltage divider circuit has good accuracy and precision. The testing result is shown in Fig. 10.

$$V_o = \frac{V_i x R_2}{(R_2 + R_1)} \tag{4}$$

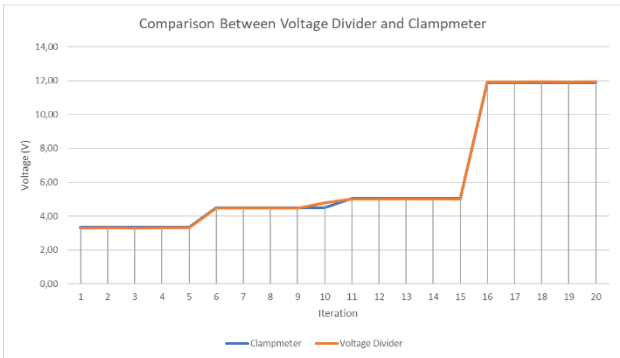


Fig. 10. Comparison between voltage divider sensor and Clamp meter

3.1.4. DS18B20 Sensor

In testing the accuracy of the DS18B20 temperature sensor, the UT204+ Clamp meter uses a special probe for temperature measurement. Based on the results of accuracy testing and precision testing, Fig. 11, it can be concluded that the DS18B20 temperature sensor used already has good accuracy and precision of 97.99% and 99.74%, respectively, so it does not need to be calibrated again. The solar panel data sheet shows that the solar panel has an operating temperature of up to +85ºC, so by using the DS18B20 sensor, before the solar panel reaches that temperature, ESP32 disconnects the solar panel from the Solar Charge Controller (SCC).

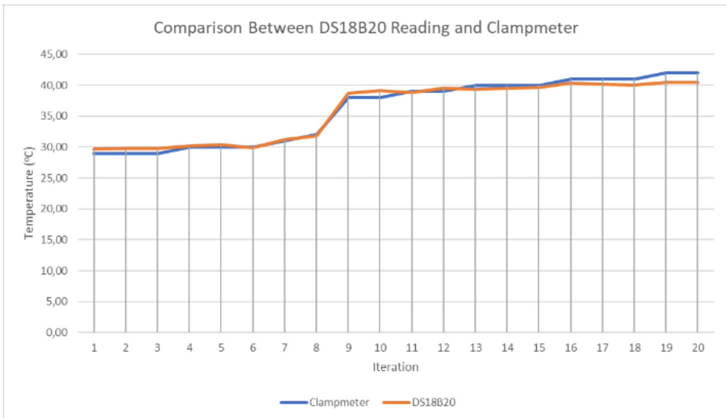


Fig. 11. Comparison between DS18B20 sensor with Clamp meter

3.2. Solar Panel Testing

The average test results carried out four times on May 18, 2022, May 19, 2022, June 2, 2022, and June 10, 2022, are shown in Fig. 12. The maximum output voltage of the solar panel is 21.54V on May 18, 2022, at 13:40, when it is sunny. Meanwhile, the minimum panel output was obtained on May 18, 2022, at 16:40 at a voltage of 16:34 with overcast conditions, almost raining. Based on the test results of the open-loop solar panel, it is determined that the lower limit of charge using solar energy at a voltage of 17.5V with the consideration that charging using solar panels can be done throughout the day if the solar panel can still absorb solar energy.

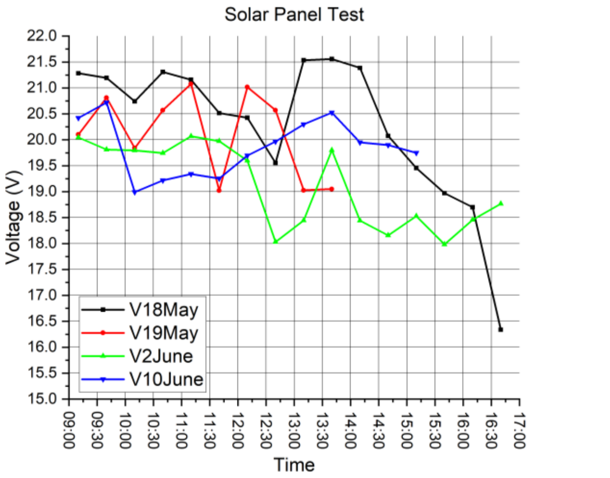
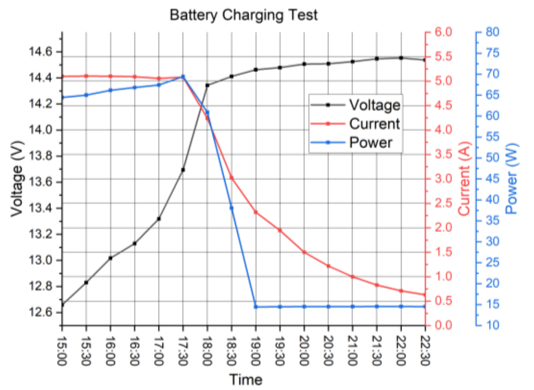
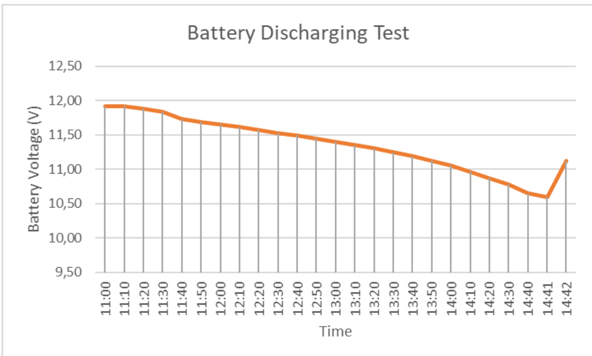


Fig. 12. Solar panel output voltage testing

The results of the battery charging test show that the charging voltage reaches 14.55V, so it can be set as 100% voltage when charging. After removing the charger and waiting a few hours, the battery voltage stabilizes at 12.90V so that 12.90V is considered the 100% SoC value of the battery in standby condition. Charging starts from 11.88V. Charging through two stages of VRLA batteries, namely bulk charging and floating charging, where bulk charging has increased voltage characteristics and a constant current. After reaching 14.4V charging changes to floating charging which can be seen in Fig. 13 (a). Based on the datasheet of the SUOER 20A+ charger, the battery reaches 100% capacity when the current displayed by the charger reaches less than 1A.

The battery discharge test aims to determine the lower limit of the battery after the battery is used up. Based on the test results presented in Fig. 13 (b), the battery runs out at 10.60V, and the inverter issues a warning sound and automatically disconnects. Shortly after the inverter turns off and the load is disconnected, the battery voltage rises to 11.12V and continues to rise slowly and steadily at 11.42V. Based on the results of this test, the authors assume that the lower limit value of the battery voltage used is 11.40V when the battery is in standby mode and 10.60V for the battery in the discharge state. In addition, from this test, by comparing the output of the battery and the output of the inverter, inverter efficiency was obtained in the range of 80.33% to 85.09%, so the efficiency of the inverter used is 80%.





(a) (b)

Fig. 13. Battery testing results (a) Charging (b) Discharging

The results of testing battery charging with solar panels are shown in Fig. 14. It is concluded that solar panels can be used to charge bulk up to a predetermined cut-off setpoint with a charging current that is smaller than the charging current of the charger.

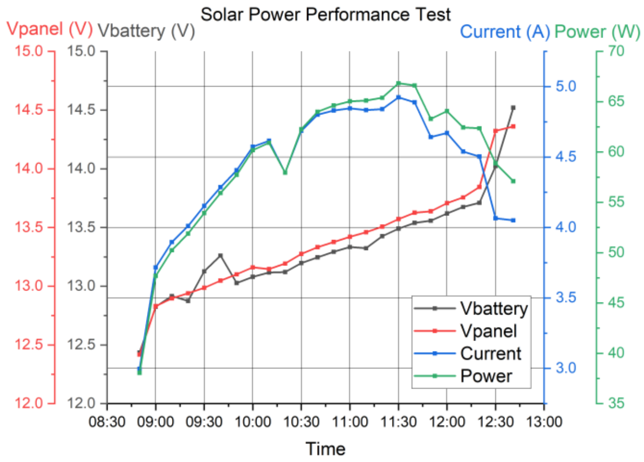


Fig. 14. Solar panel performance for battery charging

3.2. Automatic Transfer Switch (ATS) Testing

The test results, Table 2, show that the ATS with grid and inverter power sources has been successfully designed and works well. When the grid is ON, and the inverter is turned OFF, the load power is supplied by the grid. This can be seen in the relay that turns on when the grid is ON so that the inverter circuit is disconnected. When the load is supplied by the inverter, namely, the grid condition is OFF, and the inverter is ON, the 220VAC relay does not turn ON so that the inverter circuit is not interrupted. In the condition that both power sources are ON, the 220VAC relay is ON so that the ATS is successfully designed with grid resource priority. When ATS operates in grid mode, then switching occurs so that the operating mode changes to inverter mode and a 20ms time difference is detected, whereas when ATS operates in inverter mode, then the grid turns ON again, so ATS automatically switches to grid mode and detects a 26ms time difference.

Table 2. ATS Testing results

Condition	Input Condition		Output Condition	
	Grid	Inverter	Relay	Lamp
1	OFF	OFF	OFF	OFF
2	OFF	ON	OFF	ON
3	ON	OFF	ON	ON
4	ON	ON	ON	ON

3.3. Automatic Charging Testing

Table 3 resumes the results of the automatic charging testing. In condition 1, the relay that connects the solar panel to the SCC is ON, which means charging is done using the solar panel output. In condition 2, the relay that connects the charger to the battery is ON, so charging is done using the charger. While in other conditions charging is not carried out because charging is only done when the system is working with a grid power source and when the battery is at SoC below 55% and ends at 85%. In addition, a charging mode lock function is also added where the charging mode cannot be changed from the solar panel to the charger or vice versa until the battery SoC reaches 85%, or the grid turns OFF. When charging using a solar panel, the solar panel voltage will drop close to the battery voltage so that it can trigger charging with a charger. Based on the results of this test, it can be concluded that the automatic charging system has worked well according to the design.

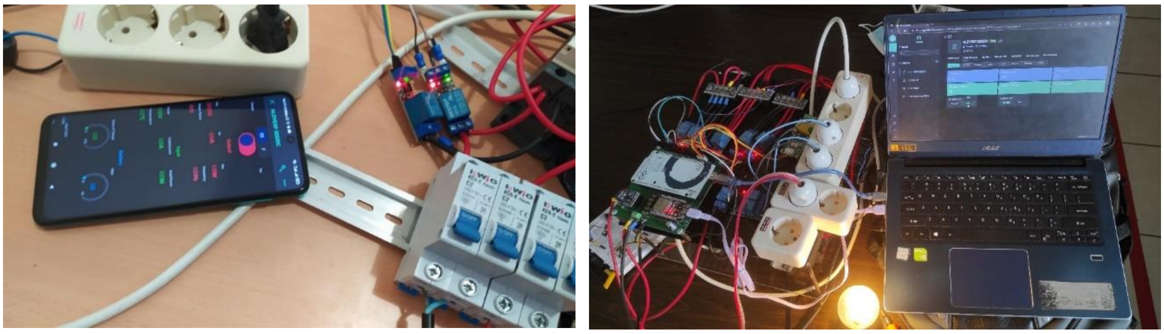
Table 3. Automatic charging testing

Condition	Input Condition		Output Condition	
	Grid	Battery SoC (%)	The Solar Panel (V)	Charging Mode
1	ON	<55%	>17.5	Solar panel
2	ON	<55%	<17.5	*Charger*
3	ON	>85%	>17.5	OFF
4	ON	>85%	<17.5	OFF
5	OFF	<55%	>17.5	OFF
6	OFF	<55%	<17.5	OFF
7	OFF	>85%	>17.5	OFF
8	OFF	>85%	<17.5	OFF

3.4. IoT System Testing

ATS remote control via IoT was successfully carried out with the relay's LED on the indicator shown in Fig. 15. When the button is pressed and it changes to battery mode, the relay is active and disconnects the grid power source, which is assembled on the NC pole. When the button is pressed, and it changes to grid mode, the relay's LED turns OFF, and the grid source is reconnected. If the system reaches a total blackout because the battery runs out because the relay and the grid source are wired at the NC pole, the system will immediately turn ON if the grid source is not extinguished.

Switching via IoT is tested by pressing the button on Blynk Apps to change the ATS operating mode and calculate the interval. Based on the test results, it is obtained that the average time to activate the relay is 303.33 ms, while to deactivate the relay, it takes an average time of 185 ms. Table 4 resumes the result of IoT testing, which shows the input-output condition. It shows that the output condition matches the given input condition, which means that the system works well.



(a) (b)

Fig. 15. IoT testing (a) App Control (b) Website Control

Table 4. IoT testing results

Condition	Input condition		Output condition	
	Contact-1	Contact-2	Contact-1	Contact-2
1	OFF	OFF	OFF	OFF
2	OFF	ON	OFF	ON
3	ON	OFF	ON	OFF
4	ON	ON	ON	ON

4. Conclusion

The Automatic Transfer Switch system was successfully designed using two contactors, 4 MCBs, and 1 AC 220V relay. The designed ATS successfully performs switching with 20ms grid-inverter and 26ms inverter-grid switching intervals. Remote monitoring with IoT technology is carried out on temperature, voltage, current, power factor, frequency, solar panel temperature, and battery SoC. Meanwhile, the control function is carried out by providing a dual-state button on the IoT interface to change the ATS operating mode via IoT. In its implementation, it has an average delay of 303.33ms to activate the relay and 185ms to deactivate the relay. Based on the results of the tests that have been carried out, it can be concluded that the proposed system has worked according to design. In the future, this system can be improved by adding solar panel capacity and the connected load. Therefore, this system can be used for the whole electrical load at home.

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