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Design of an Automatic Relay-Based Switching System Using Battery and PV Voltage in Off-Grid Solar PV Lighting

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ABSTRACT

The use of solar energy through off-grid photovoltaic (PV) systems to meet energy demands—particularly for DC lighting —still requires further development to address challenges such as weather variability and other limitations. Additionally, an effective control process for valve-regulated lead-acid (VRLA) batteries is crucial to prevent rapid degradation and shorten lifespan. This control ensures charging starts when the depth of discharge (DoD) limit is reached and prevents simultaneous charging and discharging. This study proposes an integrated off-grid PV lighting system with control features. The system uses a low-cost, relay-based automation approach, known as SOL-ARSAT (Solar PV Off-Grid Lighting System with Relay Switching Automation Technology). The system incorporates an AC power source as backup and applies three automatic switching controls based on battery and PV voltage. The results show that the system operates according to the designed control logic (logic 1 = active, 0 = inactive) and successfully manages power transfer between PV and AC sources. The control strategy prevents simultaneous charging and discharging, a prolonged low state of charge (SoC). As a result, the system improves lighting reliability and enhances battery protection, thereby extending the battery lifespan.

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1. INTRODUCTION

Solar PV (photovoltaic) energy in Indonesia has enormous technical, environmental, and economic potential, surpassing all other renewable energy sources. Its potential far exceeds current and future national energy needs if utilized optimally. With increasingly competitive costs, solar energy is a strategic solution for energy transition and long-term energy security [1].

The electrical energy generated by the PV module is highly dependent on weather conditions. The average electrical power generated during cloudy and overcast weather is much smaller than during sunny weather [2, 3]. Two 120 Wp PV modules were able to supply the daily electrical energy needs of the hallway lights of the PSTW of Bengkulu Province during sunny weather. When the weather is cloudy, these PV modules are unable to charge the battery sufficiently to meet the daily electrical energy needs of the hallway lights. In these conditions, a battery charger is used that utilizes PLN electricity sources to meet the daily electrical energy needs of the hallway lights [4]. Three 120 Wp PV modules are capable of charging a 100 Ah battery in sunny weather conditions. However, in cloudy weather

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conditions, battery charging remains insufficient because the charging current stays below 10% of the battery capacity [5].

Besides weather conditions, the physical condition of the PV module can also affect the amount of electrical energy generated by the PV system. These conditions include the layout of the PV module, the area of the PV module, and shadows that block the surface of the PV module. The intensity of light received by the PV module depends on the input power per area, which means that the size of the PV module affects how much electrical energy can be generated. PV modules achieve their highest efficiency when solar irradiance is at its peak, typically between 09:00 and 12:00. In general, PV modules achieve their highest efficiency when solar irradiance is strongest, typically between 09:00 and 12:00. However, from 13:00 to 16:00, the intensity of sunlight decreases, leading to a corresponding decline in the efficiency of the PV [6].

The hybrid system of PLTS with PLN, equipped with an ATS (Automatic Transfer Switch), has been designed on a small scale as a prototype for the lamp load. This hybrid system is designed to reduce dependence on PLN electricity sources for household electricity needs. Solar energy captured by PV modules, serving as the main source of electrical energy, is connected to the SCC (Solar Charge Controller) and LVD (Low Voltage Disconnect). The LVD, which functions as a charge control mechanism to prevent overcharging or deep discharging, is utilized as the control component for an ATS. LVD provides a signal to the relay to change the power source to the PLN as a backup power source when the battery voltage drops to the predefined minimum threshold. The system automatically switches back to the battery once the voltage reaches the predefined maximum level [7].

The ATS panel was designed for an off-grid solar power system (PLTS) supplying a waterwheel motor load at the Vaname shrimp cultivation pond in Sungai Geniot Village, Dumai City. In this study, the ATS panel incorporates two power sources: the solar power system (PLTS) as the primary and the PLN grid as a backup power source. The system operated in two main operation modes. In the first mode, the system utilizes the primary power source, where electrical energy generated by the PLTS is stored in a battery and then converted into AC (alternating current) power by the inverter. The second mode uses AC power supplied entirely by the PLN electricity network as a backup source. This mode is set and used to maintain battery life. When the battery voltage drops below the minimum set-point configured on the LVD, the ATS panel will automatically switch the power source to the PLN network. When the battery position has reached the SoC (State of Charge) value of 100%, the ATS panel will switch the power source position back to the inverter position. [8].

An ATS system is designed to transfer the main power (PLN electricity source) to the backup power source (PLTS battery). This ATS system utilizes Inverter Standby Mode (ISM) and Inverter Off Mode (IOM) to automatically manage the switching process between the PLN and PLTS power sources. ISM is used to manage the distribution of electrical energy based on a switching mechanism, while Inverter Off Mode (IOM) functions to conserve battery power during inverter-based energy distribution. The switching technique is executed as quickly as possible to prevent potential damage to the equipment. The distribution of electrical energy from the inverter is regulated by the LVD so that when the battery cannot distribute electrical energy to the load, the ATS will switch to the PLN electricity source [9].

A study has examined the degradation mechanism of VRLA (Valve-Regulated Lead-Acid) batteries. Sulfation is a major challenge in the use of VRLA batteries. Heavy sulfation and water loss are the main causes of increased internal resistance (ohmic, charge-transfer, and mass-transport resistances). The capacity decrease is in line with the increase in internal resistance in all duty cycles, with the same general trend. Sulfation mitigation should be a top priority in VRLA battery management. VRLA batteries that are not promptly recharged after reaching their Depth of Discharge (DoD) limit and are left in a low SoC condition are at high risk of sulfation, which is a major cause of degradation and increased internal resistance [10, 11].

In a renewable energy system, VRLA batteries are an important component of an off-grid PV system. It acts as a component of electrical energy storage. If this system cannot properly manage the charging and discharging processes, it significantly accelerates battery degradation and reduces its service life. Therefore, an effective charging and discharging control method is essential to protect the battery and extend its lifespan [12].

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A prototype control system that combines grid (PLN) and off-grid PV power sources has been designed to accelerate battery charging at the Base Transceiver Station (BTS). The grid serves as the primary power source for battery charging in this system. Meanwhile, the backup energy source is taken from the PV system. When the battery reaches the empty limit, it will be charged by a combination of PLN electricity and the off-grid PV system while the PLN electricity source is on. Conversely, when the PLN electricity source is off, the battery will be charged by the off-grid PV system [13].

Based on various research findings, the utilization of solar energy, particularly through off-grid PV systems, for meeting electricity demands requires further development to address any constraints. Moreover, VRLA batteries that are discharged to their deepest DoD and not quickly restored to an optimal SoC tend to undergo accelerated degradation, significantly shortening their cycle life. To prevent this, it is essential to implement a control process for the VRLA battery to ensure charging begins promptly once the DoD limit is attained, thereby preventing simultaneous charging and discharging operations. Based on these considerations, this research conceptually designs a solar PV off-grid DC lighting control system, governed by the voltage of the VRLA battery and the PV module, which uses a relay-based switching mechanism as an actuator, hereafter referred to as the SOL-ARSAT (Solar PV Off-Grid Lighting System with Relay Switching Automation Technology). The SOL-ARSAT is designed as an independent control unit that can be integrated with various types of backup power to increase battery life and ensure uninterrupted DC (direct current) lighting availability using a low-cost relay-based automation approach. The system also allows alternating VRLA battery charge-discharge control, so that the battery operates in only one mode at a time. Backup energy can be operated while the VRLA battery is charging, either to maintain a continuous power supply to DC lighting loads or to assist VRLA battery charging when PV energy is insufficient.

2. RESEARCH METHOD

This research is an applied study aimed at addressing practical, real-world problems—specifically, the implementation of automatic switching technology in the utilization of solar energy through off-grid PV systems for 12 V DC lighting applications. This research employs a conceptual system analysis and design method, focusing on developing a conceptual design for the SOL-ARSAT using a state control logic approach. The selection of energy sources for charging and discharging the VRLA battery is adaptively based on voltages of both the VRLA battery and the PV module. The research stages include system requirements analysis, block diagram design, flowchart design, wiring diagram design, and the SOL-ARSAT state tables based on implemented control logic.

The novelty of this research lies in the formulation of a finite-state control logic design that clearly separates the charging and discharging modes of the VRLA battery. The main contribution of this research is the design of the SOL-ARSAT control system that can maintain the operation of the VRLA battery by switching between charging and discharging modes in a coordinated manner, while ensuring the continuity of power supply to the off-grid PV DC lighting system and the VRLA battery charging through the integration of the external backup energy sources.

The SOL-ARSAT design comprises several subsystems, as illustrated in the block diagram in Figure 1. The SOL-ARSAT is a friendly energy source for the environment. It uses solar as the primary source, with a backup power activated when needed. In this research, the backup power source is a 220 V AC, operated automatically when solar energy is insufficient to meet the demands of battery charging and powering the 12 DC lighting system. This function is managed by switching automation through battery charging and load power supply controls to maintain continuity and operational efficiency of the off-grid PV system.

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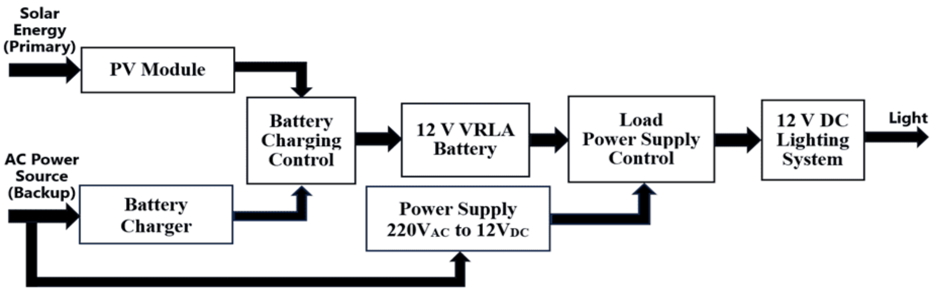

Figure 1. Block diagram design of the SOL-ARSAT with the AC backup power source

Furthermore, simultaneous charging and discharging should be avoided during VRLA battery operation, as this can accelerate degradation processes [14-16]. In this research, the SOL-ARSAT is designed to operate alternately in two distinct modes: discharge and charge. This alternating operation prevents the battery from undergoing charging and discharging processes simultaneously. In discharge mode, the system supplies electrical energy to the load (12 V DC lighting system) from the VRLA battery as the primary source or an AC backup power source, which does not undergo charging during this process. Conversely, in charge mode, the SOL-ARSAT charges the battery without connecting it to the load, using a power source to charge the VRLA battery from the PV off-grid system as a primary or an AC backup.

The SoC represents the usable battery capacity, and the DoD represents the used battery capacity. They are usually expressed as percentages, e.g., when a battery is fully charged, the SoC is 100%, and the DoD is 0%. Based on the recommendation from the VRLA batteries manufactory, the DoD is limited to 80% to preserve battery longevity. Nevertheless, experimental findings suggest that maintaining the DoD of approximately 60% offers more favorable conditions for prolonged battery life [17].

The work process algorithm of the SOL-ARSAT is presented in the flowchart in Figure 2. The value of SoC or DoD becomes the key control parameter in deciding the operating mode. In this process, SoC or DoD is represented by the battery voltage (V_B). It begins with V_B monitoring. As shown in the flowchart, when V_B exceeds the lower threshold voltage (V_{BL}), the system operates in discharge mode, indicating that the battery DoD is between 0% to 60%. Conversely, when V_B falls below V_{BL} and up to the upper threshold voltage (V_{BH}), the system switches to charge mode, corresponding to a battery SoC range of 40% to 100%. The transition between these operating modes is automatically regulated by the operation mode control subsystem, ensuring appropriate switching based on real-time battery conditions. The relationship between SoC and DoD values can be analyzed using Equations (1) and (2).

$$DoD\ (t) = 100\% - SoC\ (t) \quad (1)$$

$$SoC\ (t) = \frac{V_B - V_{Bmin}}{V_{Bmax} - V_{Bmin}} \cdot 100\% \quad (2)$$

Where V_B is battery voltage at t, V_{Bmin} is the minimum battery voltage when SoC is 0%, and V_{Bmax} is the maximum battery voltage when SoC is 100%.

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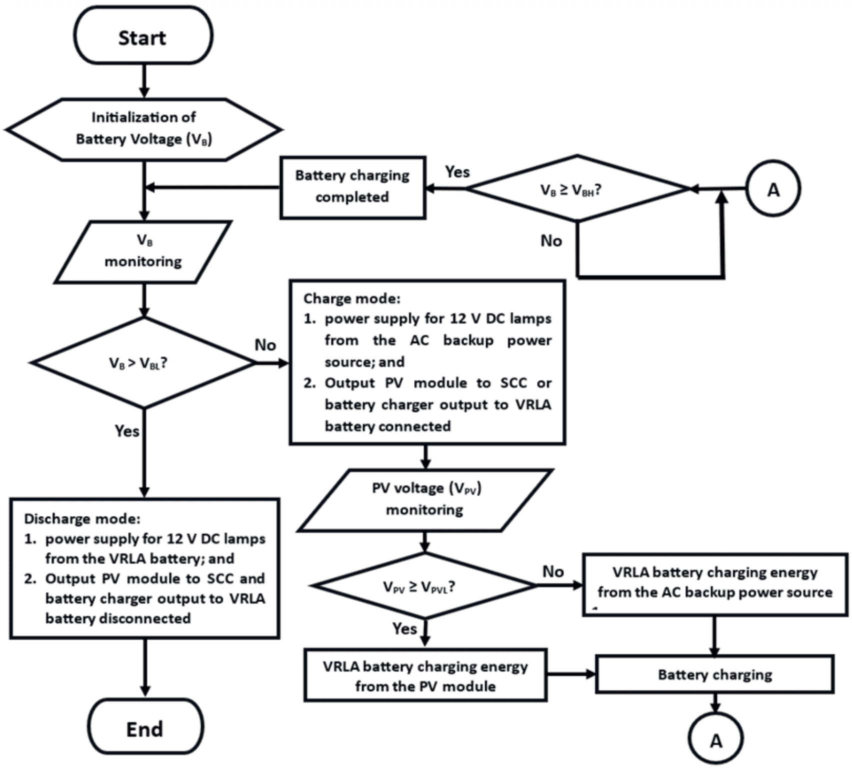

Figure 2. Flowchart of the SOL-ARSAT with the AC backup power source

Table 1. The state of the SOL-ARSAT operation mode control

State	VRLA Battery Voltage (V_B)	Control Logic	Operation Mode
State A1	Decreases from V_{BH} to > V_{BL}	1	Discharge mode
State A2	≤ V_{BL}	0	Discharge to Charge mode transition
State A3	Increases from ≤V_{BL} to < V_{BH}	0	Charge mode
State A4	≥ V_{BH}	1	Charge to Discharge mode transition

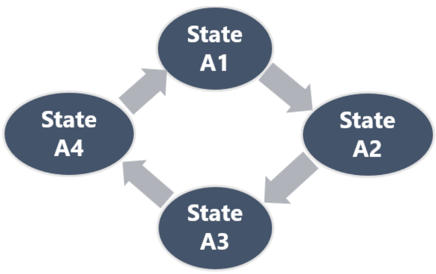

Figure 3. State cycle of the SOL-ARSAT operation mode control

Based on these SoC and DoD thresholds, the operation mode control is implemented using finite state control logic. In this approach, each operation condition of the SOL-ARSAT is represented as a distinct state, defined by specific voltage ranges corresponding to the battery's SoC and DoD levels. The operation mode control can be categorized into four state control logics, with the conditions of each state as in Table 1. This state of control logic condition establishes a repetitive operating cycle, as illustrated in Figure 3.

The control logic comprises four primary states: State A1, State A2, State A3, and State A4, each with clearly defined transition conditions to prevent overlap and unstable switching. State transitions are triggered when the battery voltage crosses predefined threshold values, the lowest V_B (V_{BL}) and the

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highest V_B (V_{BH}). This formulation ensures deterministic mode selection and eliminates ambiguity in the control decision process.

The SOL-ARSAT is designed to operate in discharge mode when the V_B exceeds the specified V_{BL}, which occurs when the VRLA battery DoD is 0% to 60%. When operating in this mode, the load is supplied by the VRLA battery as the primary power source. To prevent the VRLA battery from being charged while in this mode, the PV module output to the SCC and the battery charger output to the VRLA battery are disconnected.

When the battery energy is insufficient for discharge, which occurs when V_B is lower than V_{BL} or the VRLA battery's DoD exceeds 60%, the SOL-ARSAT is designed to change to charge mode, and an AC backup power source is used to maintain power to the load. The AC power source is connected to a power supply unit that converts the 220 V_{AC} input into the 12 V_{DC} output, enabling it to power the load. To enable automatic switching between the battery and the backup power source, the load power supply control is implemented. This control system can be categorized into two state control logics: State A3 and A4, as in Table 2, which are the repetitive cycles.

Table 2. The state of the SOL-ARSAT load power supply control

State	VRLA Battery Voltage (V_B)	Control Logic	Load Power Supply Source
State A3	Decreases from V_{BH} to > V_{BL}	1	VRLA battery
State A4	Increases from ≤V_{BL} to < V_{BH}	0	AC Backup power supply

Table 3. The state of the SOL-ARSAT battery charge control

State	PV Module Voltage (V_{PV})	Control Logic	Battery Charge Source
State B1	Decreases from V_{PVH} to > V_{PVL}	1	PV module
State B2	≤ V_{PVL}	0	PV module to AC power source transition
State B3	Increases from ≤V_{PVL} to < V_{PVH}	0	AC Power Source
State B4	≥ V_{PVH}	1	AC Power Source to PV module transition

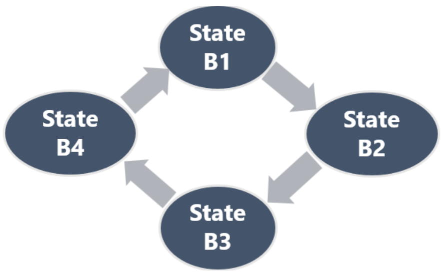

Figure 4. State cycle of battery charge control

In the charge mode of the SOL-ARSAT design, the primary power source to charge the VRLA battery is the PV module by SCC. When the PV module's energy is insufficient to charge the VRLA battery, which occurs when the PV module voltage (V_{PV}) is lower than the specified lowest V_{PV} (V_{PVL}), the AC backup power source is used. The AC power source is connected to a battery charger, which converts AC power into the required DC power to charge the VRLA battery. When the V_{PV} is above the specified highest V_{PV} (V_{PVH}), the primary source is back. The transition between the primary and backup power sources in the charge mode of the SOL-ARSAT is automatically controlled by the battery charge control, which is categorized into four control states as in Table 3. Figure 4 illustrates that the control condition establishes a repetitive operating cycle. To prevent the VRLA battery discharge while in this mode, the VRLA battery is disconnected from the load. Once the V_{BH} is reached, the SOL-ARSAT is designed to switch to discharge mode.

3. RESULTS AND DISCUSSION

The results of this research present a conceptual wiring diagram for the relay-based switching control actuator implementation of the proposed state control logic, as illustrated in Figure 5. The design

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clearly separates the charging and discharging states of the VRLA battery, establishing voltage-dependent transition conditions based on the PV module and battery parameters. Unlike conventional PV charge control systems that typically rely on microcontroller-based architectures, the developed design adopts a purely electromechanical control strategy using LVDs and electromechanical relays.

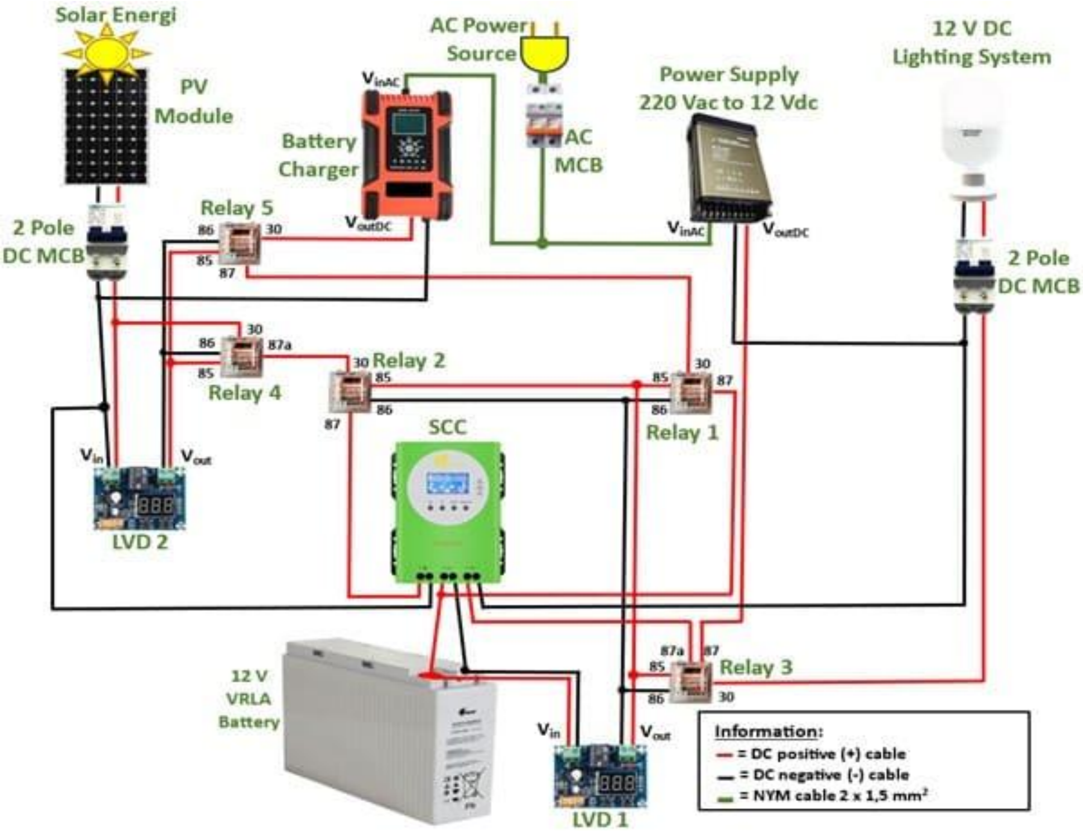

Figure 5. Wiring diagram of the SOL-ARSAT design with AC backup power source

LVDs are selected as the primary sensing elements because the control decision is based on voltage thresholds of the VRLA battery and PV module. Meanwhile, relays are used as switching devices due to their structural simplicity, inherent electrical isolation, high reliability in low-voltage DC applications, and suitability for cost-sensitive off-grid environments. This hardware realization enables state transitions control without requiring programmable control units, thereby reducing system complexity while maintaining operational robustness and power supply continuity for the load.

An LVD is an electronic module that operates based on the voltage at its input and output terminals (positive and negative). The LVD output voltage cuts off when the input voltage falls below the specified low limit, and is restored when the high voltage limit is reached. The LVD has a button to set the low and high voltage. The output voltage generated by the LVD matches the input provided. This LVD operating principle is very suitable for generating control logic in the design of SOL-ARSAT systems. In this design, two LVDs are used, namely LVD 1 and LVD 2, as shown in Figure 5.

LVD 1 functions as a VRLA battery voltage sensor for the operation mode control and the load power supply control. LVD 1 sets a low-voltage reference threshold corresponding to V_{BL} and a high-voltage reference threshold corresponding to V_{BH}. LVD 2 functions as a voltage sensor for the battery charge control, sensing the voltage generated by the PV module. LVD 2 sets a low-voltage reference threshold corresponding to V_{PVL} and a high-voltage reference threshold corresponding to V_{PVH}.

The SOL-ARSAT system is designed with 5 (five) relays to perform control operations based on control signals from the output voltage of LVD 1 and LVD 2. This control signal is the state control logic in the SOL-ARSAT system control logic design. In Figure 5, it can be seen that the relays consist of 3 (three) 4-pin relays (Relay 1, Relay 2, and Relay 5) and 2 (two) 5-pin relays (Relay 3 and Relay 4).

The control signal is connected to pin 85 (positive) and pin 86 (negative). In the absence of a control signal at these pins, the relay remains in its default state: pin 87 is in a Normally Open (NO) position and disconnected from pin 30, whereas pin 87a is in a Normally Closed (NC) position and connected to pin 30. Conversely, when a control signal is applied, the relay switches state, pin 87 connects to pin 30, and pin 87a is disconnected. Relay 1, Relay 2, and Relay 3 receive control signals from LVD 1, while Relay 4 and Relay 5 receive control signals from LVD 2. Relay 1 and Relay 2 act as switching devices for the operation mode control, Relay 3 acts as a switching device for the operation mode and the load power supply control, Relay 4 and Relay 5 act as switching devices for the battery charge control.

Relay 1 prevents the battery charger output from connecting to the VRLA battery in discharge mode on the SOL-ARSAT. Pin 30 is connected to pin 87 when there is no control signal on Relay 1, so the battery charger output is only connected to the VRLA battery when the SOL-ARSAT is in charge mode. Similarly, Relay 2 prevents the PV module output from connecting to the VRLA battery via the SCC input in discharge mode on the SOL-ARSAT. Pin 30 is connected to pin 87 when there is no control signal on Relay 2, so the PV module output is only connected to the SCC input for battery charging when the SOL-ARSAT is in charge mode.

When the control signal is applied to Relay 3, pin 87a is connected to pin 30, thereby connecting the VRLA battery through the SCC output as the primary source of the load, thus putting the SOL-ARSAT operation in discharge mode. Conversely, when there is no control signal, pin 87 is connected to pin 30, the SOL-ARSAT operation changes to charge mode, and the AC backup power through the power supply becomes the load power source. Thus, the SOL-ARSAT can maintain the availability of the load power supply even though the VRLA battery power is insufficient. This functionality is made possible by the automatic switching mechanism for the load backup power source.

Pin 30 of Relay 4 is connected to the positive terminal of the PV module output, serving as the primary source of battery charging. Pin 87a of Relay 4 is connected to pin 30 of Relay 2 so that when SOL-ARSAT is in charge mode, and the PV module voltage is sufficient to charge the battery, the PV module is connected to the positive input of the SCC. In the opposite condition, the PV module will be disconnected from the SCC, and the backup power source will charge the VRLA battery.

Pin 30 of Relay 5 is connected to the positive pole of the battery charger output as a backup source for battery charging. Pin 87 of Relay 5 is connected to pin 30 of Relay 1 so that when SOL-ARSAT is in charge mode, and the PV voltage is insufficient to charge the battery, the backup source is connected to the positive input of the VRLA battery. In the opposite condition, the backup power source will be disconnected from the positive input of the VRLA battery because charging is done through the SCC.

Table 5. The SOL-ARSAT state based on implemented control logic

Control Logic		Operation Mode		Load Power Source		Battery Charge Source	
LVD 1	**LVD 2**	**Discharge**	**Charge**	**Primary**	**Backup**	**Primary**	**Backup**
0	0	0	1	0	1	0	1
0	1	0	1	0	1	1	0
1	0	1	0	1	0	0	0
1	1	1	0	1	0	0	0

The state of the SOL-ARSAT, successfully designed based on the control logic used in this research, is presented in Table 5. Logic 1 means active, and logic 0 means inactive. The SOL-ARSAT system, integrated with an AC backup power source, was successfully designed. This system automatically manages the power supply for battery charging and load power supply between the primary and backup power sources as needed. With the SOL-ARSAT managing battery charging and discharging, the battery is better protected, potentially extending its life cycle. It allows for avoiding simultaneous charging and discharging, as well as low SoC conditions, for extended periods.

4. CONCLUSION

This research successfully designed the SOL-ARSAT system, which uses an off-grid PV system as its primary energy source and incorporates an AC power supply as a backup. The SOL-ARSAT consists of three automatic switching control systems: the operation mode control, the battery charge control,

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and the load power supply control. These are implemented using a control circuit comprising two LVDs and five electromechanical relays. The battery voltage serves as the basis for both the operation mode and the load power supply control. The battery charge control is based on the PV module voltage. Through the SOL-ARSAT control mechanism, which ensures that charging and discharging processes do not occur simultaneously and that the battery is not left in a low SoC. This research contributes to the development of control for battery protection. This conceptual design can be implemented easily and at a low cost. Furthermore, in off-grid PV lighting, it maintains the battery's lifespan. Therefore, the proposed system constitutes a feasible and scalable solution for rural and standalone applications, where reliability and cost efficiency are critical.

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