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Design and Implementation of a Solar Panel-Based Battery Charging System with Protection and Voltage Limiting Circuits

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ABSTRACT

This study aims to design and implement a simple solar panel-based battery charging system equipped with protection and voltage limiting circuits. The study was conducted to address the limitations of a direct solar panel-to-battery connection, which may cause short-circuit risk, reverse current, unstable charging voltage, and excessive battery charging. This research used a design-based experimental approach. The system was developed by preparing a block diagram, dividing it into several functional sub-blocks, and implementing the design into an electronic circuit. The main circuit sections consisted of solar panel protection, voltage limiter, interlocking circuit breaker, power regulator, and voltage divider. The assembled circuit was tested through real-time measurement by observing solar panel output voltage under different time and sky conditions and measuring battery charging time from different initial voltage levels. The results show that the solar panel output voltage varied according to time and weather condition. The lowest measured voltage was 15.0 V under cloudy conditions, while the highest measured voltage was 25.2 V under clear sky conditions around midday. The battery charging test showed that lower initial battery voltage required longer charging time, while voltage closer to the target level required shorter charging time. The evaluation was limited to voltage measurement and charging time; charging current, battery temperature, solar irradiance, and charging efficiency were not measured in detail. The proposed system can be applied for small-scale solar charging, educational practice, and basic renewable energy experiments. The study offers a practical circuit model that integrates protection, interlocking, voltage limiting, and regulation functions using simple and accessible electronic components.

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1. INTRODUCTION

The use of solar panels as an alternative source of electrical energy has increased significantly along with the growing demand for renewable, accessible, and environmentally friendly power systems. Solar photovoltaic systems are widely applied in small-scale electrical systems, lighting units, portable devices, monitoring equipment, and battery-based energy storage systems. However, the direct use of solar panels without energy storage has limitations because photovoltaic output depends on sunlight intensity and weather conditions. Hasan and Altinoluk (2023) explained that photovoltaic systems require battery storage in stand-alone applications because solar energy output is intermittent and affected by environmental conditions.

Photovoltaic technology has developed through several generations based on material composition, conversion efficiency, and operational characteristics. Silicon-based solar cells, including monocrystalline and polycrystalline technologies, remain widely used because of their mature manufacturing process and relatively stable performance. Sharma and Mishra (2025) reviewed the development of photovoltaic cell generations and emphasized that material selection, degradation behavior, temperature stability, and operating conditions strongly influence PV performance.

In tropical environments, photovoltaic performance is affected by temperature, humidity, solar irradiation, and local climate conditions. Femin et al. (2025) compared several photovoltaic technologies under tropical conditions and showed that each technology has different performance characteristics in field operation. Benghanem et al. (2023) also reported that the actual performance of monocrystalline and polycrystalline modules may differ from manufacturer datasheets when panels are operated under high-temperature outdoor conditions. Therefore, the design of a solar-powered battery charging system should consider not only the nominal solar panel voltage but also field variations caused by time and weather.

In addition to conventional silicon-based panels, thin-film, perovskite, tandem, and bifacial photovoltaic technologies have been developed to improve efficiency and broaden the application of solar energy systems. Iturralde Carrera et al. (2025) stated that photovoltaic system efficiency is influenced by interrelated technological, environmental, design, and operational factors. Murillo-Yarce et al. (2020) further emphasized that control techniques in photovoltaic systems are important for obtaining maximum available power and improving energy conversion performance. These developments indicate that the effectiveness of a solar energy system depends not only on the solar panel technology but also on the control and protection system connected to it.

Although commercial solar charge controllers are widely available, the development of a simple and low-cost battery charging system remains important for educational, experimental, and small-scale applications. A solar panel connected directly to a battery may provide a simple charging path, but this configuration can create several technical risks, including reverse current, short circuit, unstable charging voltage, and overcharging. Santosa et al. (2020) showed that solar charge controller design is required to regulate voltage and improve charging performance in solar-powered systems. Sudiharto et al. (2022) also emphasized that overcharging may damage batteries, so the charging process must be controlled properly.

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Battery charging systems must regulate voltage and current to ensure charging safety, efficiency, and battery durability. The constant current–constant voltage method is commonly applied because it combines faster initial charging with voltage limitation near the full-charge condition. Otong and Khudari (2021) designed a lithium-ion battery charging system using a DC–DC buck converter with a constant current–constant voltage method. Falih et al. (2021) also showed that CC-CV controlled fast charging can reduce overcharging risk by maintaining constant current at the initial stage and constant voltage at the final stage.

The transition between charging stages is also important because inappropriate control may extend charging time or increase battery stress. Faanzir et al. (2021) demonstrated that determining the transition point between constant current and constant voltage based on the state of charge can shorten charging time. Anjani et al. (2023) applied the CC-CV method using an interleaved buck-boost converter and showed that relay-based control can be used to stop the charging process when the battery reaches the required condition. Chen et al. (2023) further compared several lithium-ion battery charging methods and highlighted that charging performance should be evaluated using charging efficiency, battery temperature rise, and charging time.

Battery protection is another essential aspect of a safe charging system. Habib et al. (2023) explained that a battery management system should monitor current, voltage, temperature, charge-discharge conditions, and protection against overcharge, undercharge, and short-circuit conditions. Chen et al. (2024) also emphasized that effective charging techniques should consider charging efficiency, life cycle, charging time, and battery temperature. These studies show that a battery charging system should not only deliver energy but also provide protection and control to prevent unsafe operating conditions.

Based on these considerations, this study aims to design and implement a solar panel-based battery charging system using simple electronic components that are easily available in the market. The proposed system consists of several functional units, including a solar panel input protection circuit, a voltage level detector, a battery charging limiter, an interlocking circuit breaker, and a power regulator. These units are integrated into a single system to protect the solar panel from short-circuit conditions and to prevent the battery from being charged beyond the specified voltage limit.

This study uses an experimental design approach. The research begins with the development of a block diagram, followed by the implementation of each block into an electronic circuit. The circuit is then assembled and tested through direct measurement under outdoor solar panel conditions. The solar panel voltage is observed at different times of the day and under different sky conditions. The battery charging performance is evaluated by measuring the relationship between the initial battery voltage and the charging time required to reach the target voltage.

The main contribution of this study is the development of a simple solar battery charging system equipped with protection and limiting functions. Unlike a basic direct charging circuit, the proposed design includes an interlocking protection mechanism, voltage detection, and a regulator circuit to improve charging safety. The experimental results are expected to show that solar panel voltage varies depending on time and weather conditions, while battery charging time depends on the initial battery voltage. Therefore, this study provides a practical circuit model for safer and more controlled battery charging using a solar panel source.

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2. METHODS

This study was conducted to design a simple and practical battery charging system using a solar panel as the main power source. The purpose of the study was to develop an electronic charging circuit that can transfer electrical energy from a solar panel to a battery while providing basic protection against short-circuit conditions and excessive battery charging. The study was carried out because a direct connection between a solar panel and a battery may be simple, but it does not provide adequate protection for the solar panel or the battery. Therefore, an improved circuit design is needed to make the charging process safer, more controlled, and more reliable for small-scale applications.

The method used in this study was a design-based experimental method. The research began with the preparation of a block diagram as the initial concept of the system. This block diagram was used to describe the relationship between the solar panel, protection circuit, limiter circuit, battery charger circuit, and battery. After the system concept was developed, the block diagram was implemented into an electronic circuit. The circuit was then assembled using electronic components according to the design requirements, and its performance was observed through real-time measurement.

The basic concept of the battery charging circuit is shown in Figure 1. In this basic configuration, the solar panel is used as the electrical energy source and is connected to the battery charging path. However, this simple circuit still has several limitations because it does not include protection against short-circuit conditions, reverse current, or excessive charging voltage. These limitations may cause damage to the solar panel or battery, especially when the system is used continuously.

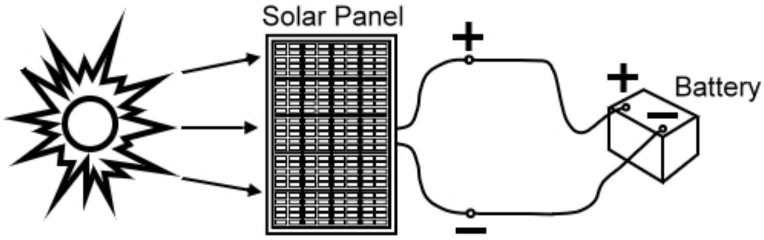

Figure 1. Basic battery charger circuit

To overcome these limitations, the basic charging circuit was developed into a more complete solar panel-based battery charging system. The proposed system includes several additional electronic circuits that function as protection and control units. These circuits are designed to protect the solar panel from short-circuit conditions at the input stage and to protect the battery from overcharging or short-circuit conditions during the charging process. The general block diagram of the proposed system is shown in Figure 2.

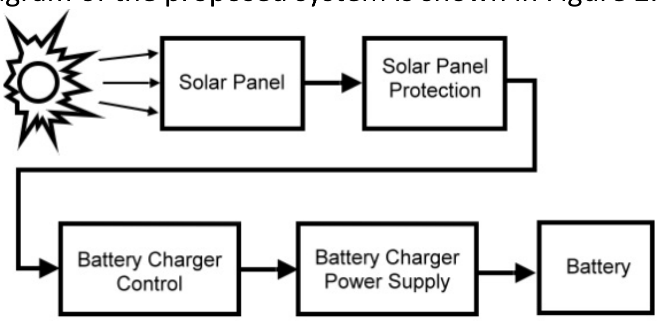

Figure 2. Block diagram of power charger using solar panel

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Volume 2 Issue 1 May 2026 Page 13-24

After the main block diagram was prepared, the system was divided into several more detailed sub-block diagrams. This stage was conducted to explain the function of each circuit section before it was implemented into an electronic circuit. The first sub-block diagram is the solar panel protection section, as shown in Figure 3. This section consists of an on-off switch, a push-button switch, and a relay. These components are arranged to support a protection mechanism that can disconnect the solar panel from the charging circuit when an unsafe condition occurs.

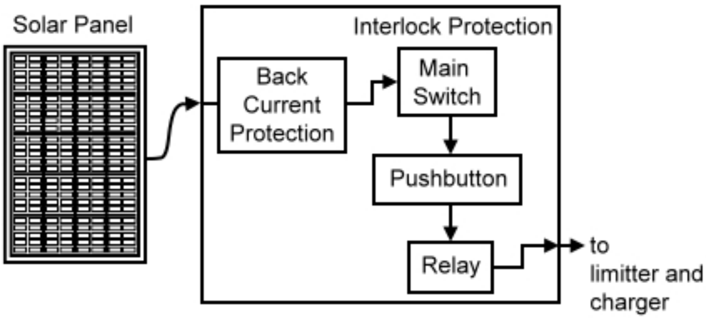

Figure 3. Sub-block diagram of solar panel protection

The second sub-block diagram is the limiter section, as shown in Figure 4. This section was designed to limit the battery charging voltage by detecting the battery voltage level. The limiter identifies whether the battery is in a low-voltage or high-voltage condition by comparing the detected battery voltage with a predetermined reference voltage. The comparison result is then used as a control signal to trigger the power breaker circuit and regulate the continuation or termination of the charging process.

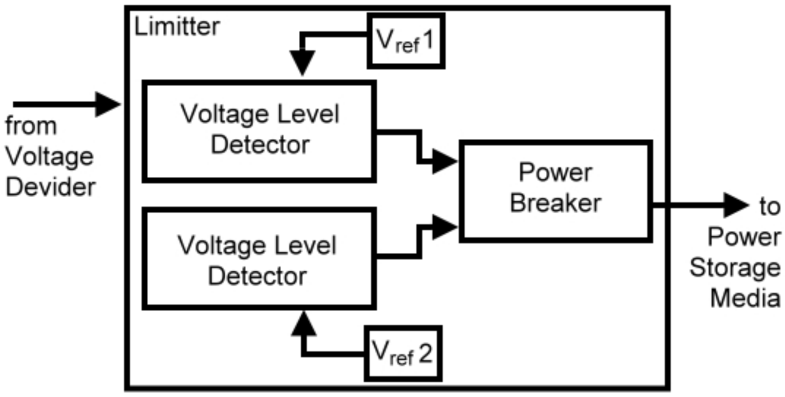

Figure 4. Limiter sub-block diagram

The third sub-block diagram is the battery charger section, as shown in Figure 5. This section contains the charging path and a voltage divider circuit. The voltage divider is used to detect the battery voltage level during the charging process. The detected voltage becomes an important input for the limiter and protection circuits, allowing the system to monitor the battery condition and control the charging process more safely.

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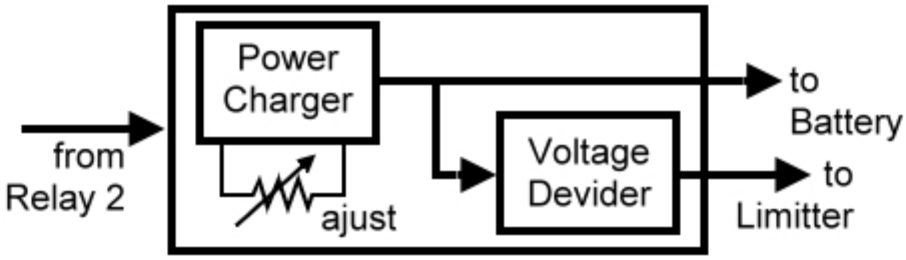

Figure 5. Sub-block diagram of battery charger

The expected finding of this methodological design is that the proposed circuit can provide a safer charging process than a basic direct charging circuit. By combining the solar panel protection circuit, limiter circuit, power breaker, and voltage detection section, the system is expected to prevent short-circuit conditions and reduce the risk of excessive battery charging. The real-time measurement stage is used to observe whether the circuit can operate according to its intended function and whether the battery charging process can be controlled through the designed protection and limiter mechanisms.

3. RESULTS

The implementation of the block diagram was carried out by converting the system concept into an electronic circuit used for battery charging. The circuit was assembled using common electronic components that are easily available in the market. The following results present the circuit design and measurement data obtained from the solar panel-based battery charging system.

Referring to the block diagram in Figure 3, the system includes a main switch that functions as the initial connection between the solar panel and the battery charging control circuit. Before the current reaches the charging circuit, it passes through an interlock protection system. This protection system is used to disconnect the connection between the solar panel and the battery charging line when a short-circuit condition occurs at the input side.

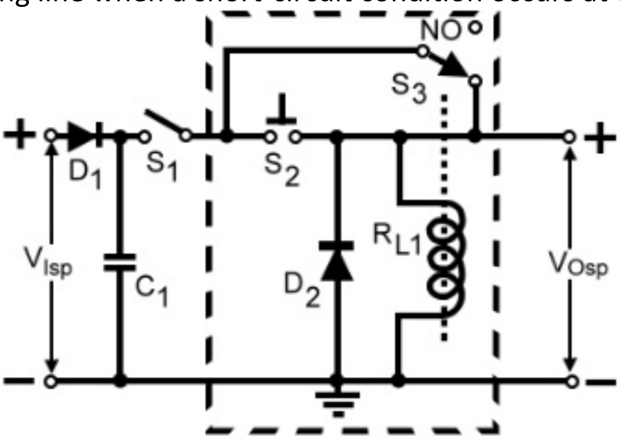

Figure 6. Simple schematic of solar panel protection

Figure 6 shows the implementation of the solar panel protection block into a simple electronic circuit. The circuit uses relay RL1 and push-button S2 to form an interlocking mechanism. The circuit also includes a diode and capacitor as reverse-current protection and voltage spike suppression components. Switch S1 functions as an on-off switch that allows current from the solar panel to enter the interlock protection circuit before being supplied to

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Volume 2 Issue 1 May 2026 Page 13-24

the load. Therefore, the output of this circuit becomes the power supply for the next circuit sections.

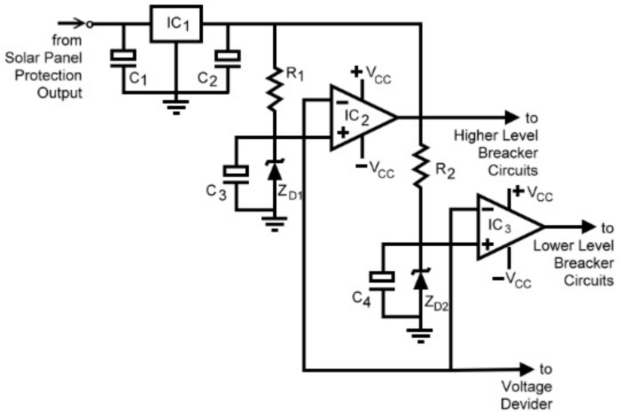

Figure 7. Schematic diagram of limiter circuit

Figure 7 shows the battery charging limiter circuit. The full-charge condition is determined when the battery voltage reaches the maximum voltage level according to the battery specification. This voltage limit is set using zener diode ZD1. Meanwhile, the low-voltage condition is determined based on the lower voltage limit set by zener diode ZD2. Through this configuration, the circuit can detect whether the battery voltage is still low or has reached the charging limit.

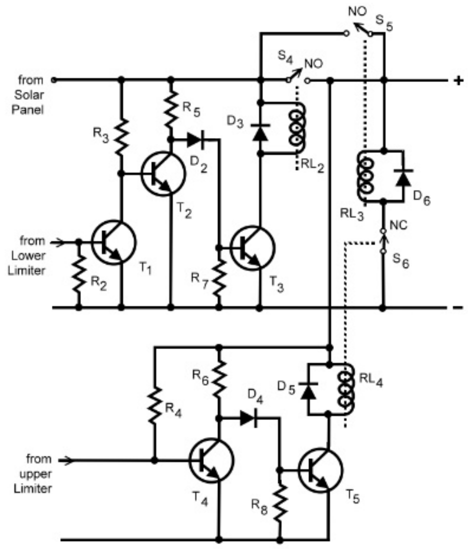

Figure 8. Schematic diagram of interlocking circuit breaker

Figure 8 shows the interlocking circuit breaker used to start or stop the battery charging process. In this circuit, relays RL2, RL3, and RL4 form a chained interlocking system. These relays lock each other during operation, and the interlock condition can only be released when RL4 is activated, even for a short moment. The positive and negative output terminals on the upper right side of the circuit indicate the protected power output that has passed through the interlock protection mechanism.

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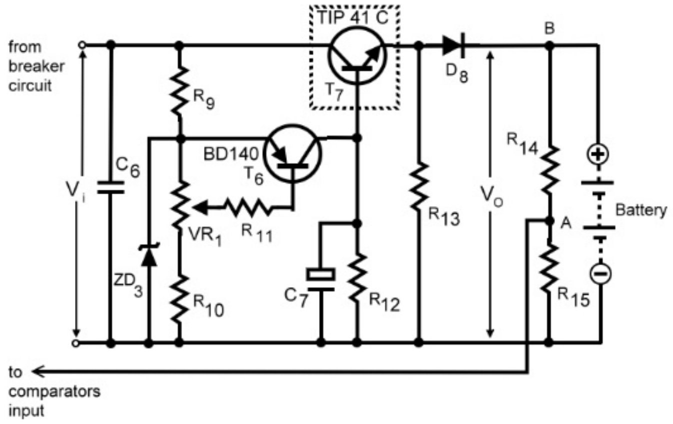

Figure 9. Schematic diagram of power regulator circuit and voltage divider

Figure 9 shows the power regulator circuit and voltage divider used in the battery charging system. The DC current passing through transistor T7 produces the output voltage, Vo, after passing through diode D7. This output voltage is used as the battery charging voltage. Diode D7 functions as a reverse-current blocking component when the charging process has stopped and the relays have disconnected the solar panel from the charging circuit. The voltage divider connected between the battery and the regulator provides a voltage signal to the comparator, allowing the system to detect whether the battery is still fully charged or has dropped to a low-voltage condition.

The first measurement was conducted by testing the solar panel outdoors in an open area. The solar panel output voltage was measured at different times of the day under different sky conditions. The measurement results are presented in Table 1.

Table 1. Solar Panel Observation

No.	Time	Sky Condition	Voltage (V)	Time	Sky Condition	Voltage (V)	Time	Sky Condition	Voltage (V)
1	06:00	Cloudy	15.0	10:00	Cloudy	19.8	14:00	Clear	25.2
2	06:30	Cloudy	15.6	10:30	Cloudy	19.2	14:30	Cloudy	23.4
3	07:00	Cloudy	16.5	11:00	Cloudy	19.8	15:00	Cloudy	16.5
4	07:30	Cloudy	18.0	11:30	Cloudy	23.4	15:30	Cloudy	16.5
5	08:00	Cloudy	17.7	12:00	Clear	25.2	16:00	Cloudy	17.4
6	08:30	Cloudy	18.6	12:30	Clear	25.2	16:30	Cloudy	18.0
7	09:00	Clear	24.0	13:00	Cloudy	19.2	17:00	Cloudy	16.8
8	09:30	Clear	24.6	13:30	Clear	25.2	17:30	Cloudy	15.0

Based on the solar panel observation results, the output voltage varied according to the time of observation and sky condition. The lowest measured voltage was 15.0 V, recorded at 06:00 and 17:30 under cloudy conditions. The highest measured voltage was 25.2 V, recorded at 12:00, 12:30, 13:30, and 14:00 under clear sky conditions. These results indicate that the solar panel produced higher voltage around midday, especially when the sky was clear.
The second measurement was conducted to determine the relationship between the initial battery voltage and the charging time required to reach the target voltage. The results are presented in Table 2.

Table 2. Battery Initial Voltage and Charging Time

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Volume 2 Issue 1 May 2026 Page 13-24

No.	Initial Voltage Condition (V)	Charging Time (minutes)
1	9.0	17
2	9.5	13
3	10.0	9
4	10.5	6
5	11.0	3
6	11.1	0

Table 2 shows that the charging time decreased as the initial battery voltage increased. When the initial battery voltage was 9.0 V, the charging process required 17 minutes to reach the target voltage. At an initial voltage of 10.0 V, the required charging time decreased to 9 minutes. When the battery voltage reached 11.1 V, no additional charging time was required. These results indicate that the initial battery voltage directly affected the duration of the charging process.

4. DISCUSSION

The results show that the proposed solar panel-based battery charging system can be implemented as a simple circuit consisting of protection, limiting, switching, regulation, and voltage detection sections. The implementation of the circuit design indicates that a basic solar battery charger requires additional protection mechanisms to make the charging process safer and more controlled. Without these additional circuits, the direct connection between a solar panel and a battery may expose both components to short-circuit conditions, reverse current, and excessive charging voltage.

The solar panel protection circuit shown in Figure 6 plays an important role in securing the input side of the system. The use of relay RL1 and push-button S2 creates an interlocking mechanism that can disconnect the solar panel from the charging circuit when an unsafe condition occurs. This mechanism is important because the solar panel acts as the main energy source, and any disturbance at the input side may affect the entire charging system. The addition of a diode and capacitor also strengthens the protection function by reducing the possibility of reverse current and voltage spikes flowing back to the solar panel.

The limiter circuit shown in Figure 7 functions as the voltage detection and limitation stage. The use of zener diodes ZD1 and ZD2 allows the system to identify high-voltage and low-voltage battery conditions based on predetermined voltage thresholds. This condition is important because battery charging must be stopped or limited when the battery reaches its maximum allowable voltage. If the charging process continues beyond this limit, the battery may experience overcharging, which can reduce battery performance and service life. Therefore, the limiter circuit contributes to maintaining the battery within a safer operating range.

The interlocking circuit breaker shown in Figure 8 supports the control function of the charging system. Relays RL2, RL3, and RL4 form a chained interlocking system that allows the charging process to be started or stopped according to the detected battery condition. This design shows that the system does not rely only on a manual switch, but also uses a protection logic that can disconnect the charging path when required. The protected positive and

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negative output terminals indicate that the power supplied to the next stage has passed through the safety mechanism.

The power regulator and voltage divider circuit shown in Figure 9 further support the charging control process. The regulator section provides the charging voltage to the battery, while diode D7 blocks reverse current from the battery when the charging process stops. The voltage divider connected to the battery provides feedback to the comparator or detection circuit. This feedback is necessary because the system must continuously recognize whether the battery voltage is still low or has reached the charging limit. Therefore, the combination of the regulator and voltage divider improves the monitoring function of the charging system.

The solar panel observation results in Table 1 show that the output voltage varied according to time and sky condition. The lowest voltage was 15.0 V, recorded at 06:00 and 17:30 under cloudy conditions. Meanwhile, the highest voltage was 25.2 V, recorded at several midday observations under clear sky conditions. This result confirms that the solar panel produced higher voltage when sunlight intensity was stronger. The voltage tended to increase from morning to midday and decreased again in the afternoon, especially under cloudy conditions.

These findings indicate that the best charging opportunity occurred around midday when the sky was clear. This condition is reasonable because solar radiation is generally stronger during the middle of the day, allowing the solar panel to produce a higher output voltage. However, the data also show that cloudy conditions can reduce the output voltage even during daytime. For example, at 13:00, the voltage dropped to 19.2 V under cloudy conditions, while at 13:30 under clear sky conditions, the voltage increased to 25.2 V. This difference shows that weather condition is one of the key factors affecting the effectiveness of solar panel-based charging.

The battery charging results in Table 2 show that charging time decreased as the initial battery voltage increased. When the initial battery voltage was 9.0 V, the charging process required 17 minutes to reach the target voltage. When the initial voltage increased to 10.0 V, the charging time decreased to 9 minutes. At 11.0 V, the charging time was only 3 minutes, and when the battery voltage reached 11.1 V, no additional charging time was required. This pattern indicates that the charging duration is strongly influenced by the initial battery voltage condition.

The relationship between initial voltage and charging time suggests that a battery with a lower voltage condition requires a longer charging duration because more energy must be supplied to reach the target voltage. In contrast, a battery that is already close to the target voltage requires a shorter charging time. This result also shows that the voltage detection and limiter circuit are important for identifying the battery condition during charging. By detecting the voltage level, the system can determine whether charging should continue or stop.

Overall, the results demonstrate that the proposed circuit can improve the safety and control of a simple solar panel-based battery charging system. The circuit does not only transfer energy from the solar panel to the battery, but also provides protection against short-circuit conditions, reverse current, and excessive charging voltage. The use of commonly available components also makes the design suitable for educational purposes, laboratory practice, and small-scale renewable energy applications.

However, this study still has several limitations. The testing was mainly based on voltage observation and charging time measurement. Other important parameters, such as charging current, battery capacity, solar irradiance, battery temperature, and charging efficiency, were not yet presented in detail. Therefore, future studies should include more complete

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measurements to evaluate system performance more comprehensively. In addition, the circuit can be further improved by adding current sensing, temperature monitoring, and automatic control based on a microcontroller or maximum power point tracking technique.

Based on the discussion, the proposed solar panel-based battery charging system has shown practical potential as a simple and safer charging circuit. The combination of protection, limiter, interlocking breaker, regulator, and voltage divider circuits allows the system to operate in a more controlled manner than a basic direct charging circuit. These findings support the objective of the study, which is to design a simple battery charging system from a solar panel source with additional protection for both the solar panel and the battery.

5. CONCLUSION

This study designed and implemented a solar panel-based battery charging system using simple electronic components. The system consists of several main sections, including solar panel protection, voltage limiter, interlocking circuit breaker, power regulator, and voltage divider. The results show that the proposed system can support a more controlled charging process than a basic direct charging circuit because it provides protection against short-circuit conditions, reverse current, and excessive battery charging.

The solar panel observation showed that the output voltage was affected by time and sky condition. The lowest voltage was 15.0 V under cloudy conditions, while the highest voltage was 25.2 V under clear sky conditions around midday. The battery charging test also showed that the initial battery voltage influenced the charging duration. A lower initial battery voltage required a longer charging time, while a battery voltage closer to the target value required a shorter charging time.

This study still has several limitations. The evaluation was mainly based on voltage measurement and charging time, while charging current, battery capacity, solar irradiance, battery temperature, and charging efficiency were not measured in detail. This limitation is related to the method and may affect the completeness of the performance evaluation. Future research should include more complete electrical measurements and controlled testing conditions. The system can also be improved by adding current sensors, temperature protection, automatic cut-off control, battery management features, and maximum power point tracking to improve charging efficiency and system reliability.

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