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Design and Implementation of Battery Control Unit Based Pulse Width Modulation for Lighting System by Solar Cell Module

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Abstract
The utilization of renewable energy has become one of the solutions to addressing the global energy crisis. Along with the continuous rise in energy costs, conventional energy sources are becoming increasingly depleted. One example of renewable energy utilization is the use of solar energy. The energy harnessed from sunlight can be converted into electrical power through photovoltaic technology, which employs solar cells as implemented in solar power plants. However, solar power plants face several challenges, particularly in current and voltage control, which lead to inefficiencies in solar energy utilization. The system is designed to regulate current and voltage during the battery charging and discharging processes using PWM control. The experimental results show a battery charging voltage of 14 VDC and a charging current of 1.2 A, where the charging current corresponds to 10% of the battery capacity. The implemented Battery Control Unit (BCU) achieved an overall efficiency of 92%.
Keywords: *renewable energy, solar cell, pwm control, buck converter, boost converter*

Abstrak
Pemanfaatan energi terbarukan telah menjadi salah satu solusi untuk mengatasi krisis energi global. Seiring dengan terus meningkatnya biaya energi, sumber energi konvensional semakin menipis. Salah satu contoh pemanfaatan energi terbarukan adalah penggunaan energi surya. Energi yang diperoleh dari sinar matahari dapat dikonversi menjadi energi listrik melalui teknologi fotovoltaik, yang menggunakan sel surya sebagaimana diterapkan pada pembangkit listrik tenaga surya. Namun, pembangkit listrik tenaga surya menghadapi beberapa tantangan, terutama dalam pengendalian arus dan tegangan, yang menyebabkan rendahnya efisiensi dalam pemanfaatan energi surya. Sistem ini dirancang untuk mengatur arus dan tegangan selama proses pengisian dan pengosongan baterai menggunakan kendali PWM. Hasil pengujian menunjukkan bahwa tegangan pengisian baterai sebesar 14 VDC dan arus pengisian sebesar 1,2 A, di mana arus pengisian tersebut setara dengan 10% dari kapasitas baterai. Unit Kendali Baterai (*Battery Control Unit*/BCU) yang diterapkan mencapai efisiensi keseluruhan sebesar 92%.
Kata Kunci: *energi terbarukan, energi surya, kontrol pwm, buck converter, boost converter*

1. Introduction

Along with the rapid advancement of technology, the demand for electrical energy continues to increase. The growing need for electricity has driven researchers to develop technologies that utilize renewable energy sources, one of which is solar energy [4]. Indonesia, as a tropical country based on its geographical location, has great potential to harness solar power as an alternative energy source. Although Indonesia possesses abundant oil and natural gas reserves, these resources are non-renewable and will eventually be depleted.

By utilizing sunlight, numerous Solar Power Plants have been developed. However, in Indonesia, the use of solar energy as an electricity source remains relatively limited. In fact, Solar Power Plants are environmentally friendly, require minimal maintenance, and provide an inexhaustible energy supply. One of the main challenges, however, lies in the high initial investment cost required for their development [9][10].

The construction of a Solar Power Plant involves several essential components, such as solar cells, Battery Control Units (BCU), inverters, batteries, and loads. In this study, a Battery Control Unit (BCU) is designed as one of the key components in the solar power generation system. The distribution of current and power from the solar cells to the battery is a critical issue that must be carefully addressed, as improper distribution may lead to battery damage. The BCU functions to regulate the electrical current from the solar cells to the battery and from the battery to the load. In addition, it also manages excess voltage from the solar cells that may reduce battery lifespan [5].

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Recent studies highlight the importance of proper charge controllers in solar-battery systems to optimize performance and extend battery life.[1] implemented a PWM-type solar charge controller and successfully regulated PV input to a 12 V battery system, achieving output stability at approximately 14 V. Further comparative evaluations reveal that PWM charge controllers are less efficient than MPPT controllers under variable irradiation conditions, yet they remain cost-effective and widely used in small-scale off-grid systems [2][3]. Therefore, the design of a PWM-based Battery Control Unit (BCU), as proposed in this study, addresses both practical cost constraints and the need for reliability in lighting systems powered by solar modules.

The outcome of this study is the design and implementation of a PWM (Pulse Width Modulation)-based Battery Control Unit, which is expected to effectively control the charging and discharging processes of the battery, and subsequently be applied in a Solar Power Plant system.

2. Material and Methods

Battery Charging and Control System

In general, the block diagram of the Battery Control Unit design can be seen in the **Figure 1**.

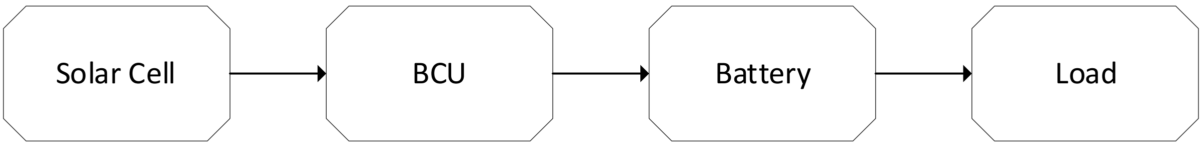

Figure 1: Block Diagram BCU System

1. The solar panel converts solar energy into electrical energy.
2. The converter detects the voltage level from the solar cells.
3. After detecting the voltage from the solar cells, the converter adjusts the voltage—either increasing or decreasing it—according to the battery's requirements, which range between 13.7V and 13.9V.
4. Once the voltage is appropriate, it is supplied for battery charging.
5. The power from the battery is then distributed to the 12V DC lamp load.
6. The charging process continues to ensure the battery remains fully charged.
7. The current and voltage sensor signals provide data regarding the current and voltage from the solar cells as well as the battery condition.

Photovoltaic

Photovoltaic, also known as a solar cell, is an electronic device that converts direct sunlight into electricity. Sunlight is processed by the photovoltaic system and converted into DC electrical energy. The material commonly used in solar cells is a semiconductor. Solar cells are typically made from silicon-based semiconductor materials, which act as insulators at low temperatures and as conductors when exposed to energy and heat.

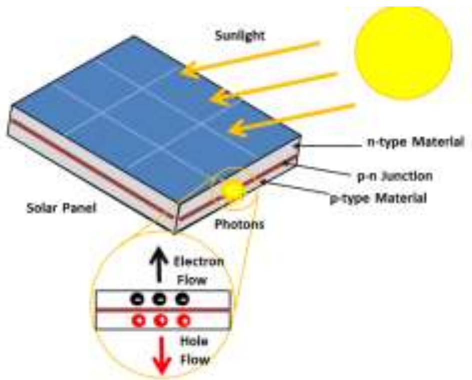

Figure 2: Diagram Showing the Photovoltaic Effect

The photovoltaic effect occurs in solar cells made of two types of semiconductors, p-type and n-type, forming a p–n junction. At this junction, an electric field is created that separates charges. When light hits the cell, photons transfer energy to electrons, causing them to move to the conduction band and leave behind holes in the valence band. Due to the electric field, electrons move toward the n-side and holes toward the p-side, generating an electric current in the solar cell [8].

Lead Acid Storage Battery

The electrolyte used in a lead-acid battery is a sulfuric acid (H_2SO_4) solution. In a lead-acid battery, the electrodes consist of lead peroxide (PbO_2) plates serving as the anode (positive terminal) and pure lead (Pb) plates serving as the cathode (negative terminal) [7].

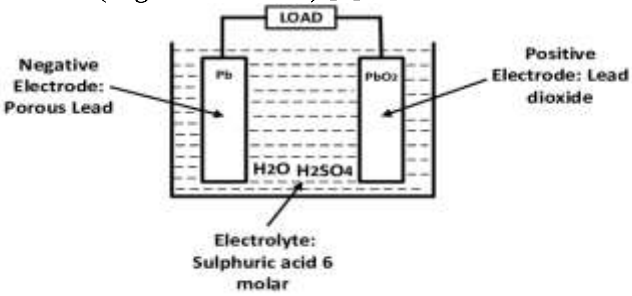

Figure 3. Lead Acid Battery Construction

Buck Converter

A Buck Converter is one type of DC-DC converter that functions to step down the DC voltage. The output voltage of a buck converter is lower than its input voltage. A simple circuit diagram of the buck converter is shown in the **Figure 4**.

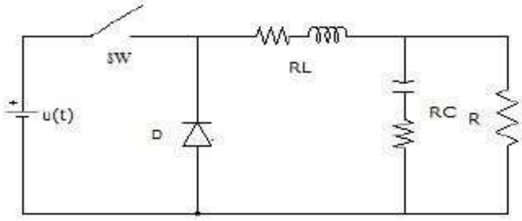

Figure 4. Buck Converter

The working principle of a buck converter is based on switching control. The switch, which can be a transistor or MOSFET, operates by alternating between open and closed states. These switching conditions are determined by the PWM (Pulse Width Modulation) signal and the duty cycle, which control the switching frequency and operation speed [12].

Boost Converter

A boost converter functions to produce an output voltage that is higher than its input voltage, and is therefore commonly referred to as a step-up converter. This type of converter is widely used in applications such as solar power generation and wind turbines [13]. The circuit diagram of the boost converter is shown in **Figure 5**.

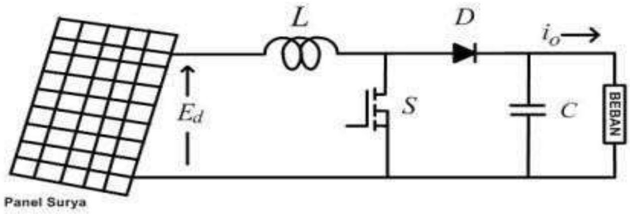

Figure 5. Boost Converter

In renewable energy systems, especially photovoltaic (PV) applications, the boost converter plays a crucial role in increasing the DC voltage generated by solar panels to a suitable level for charging batteries or supplying inverters [14]. The converter operates by storing energy in an inductor during the ON state of the switching device and releasing it to the load during the OFF state, thus boosting the voltage [15].

Pulse Width Modulation

PWM (Pulse Width Modulation) is a modulation technique used to control the width of output pulses. In a microcontroller, the pulse source is generated through an internal clock and then modulated with a waveform produced by a wave generator [16].

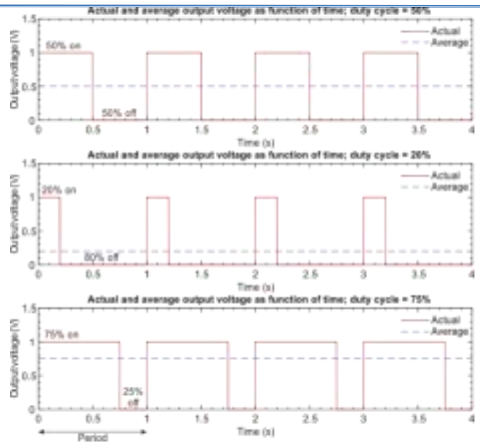

Figure 6. PWM Signal

System Flow Diagram

A 12-volt battery consists of six cells. The voltage limit of a single cell generally ranges from 2.30 V to 2.45 V. Therefore, the actual voltage of a 12 V battery is between 13.8 V and 14.7 V. By assuming the battery voltage to be 14 V, the flowchart will use 14 V as the reference voltage for the system.

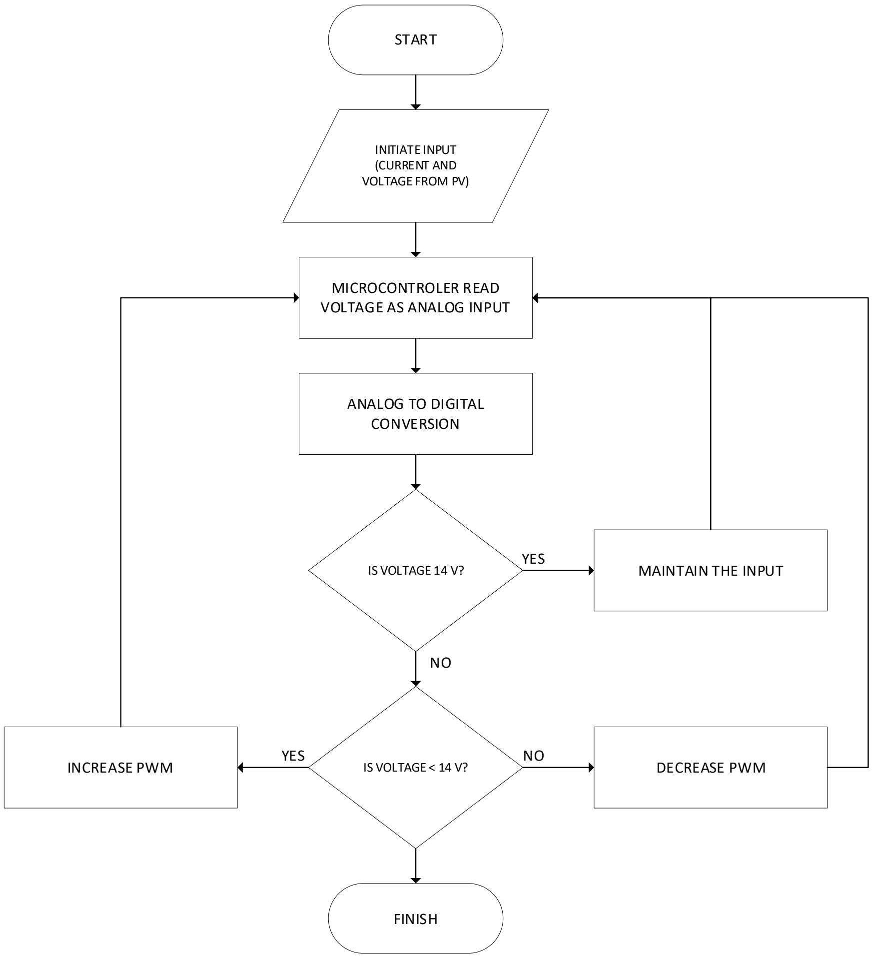

Figure 7. System Flow Diagram

3. Results and Discussion

This test was carried out to charge the battery, also referred to as the power transfer process from the photovoltaic module to the battery. The purpose of this test is to determine whether the charging process operates as expected. The test is conducted by connecting the photovoltaic module to the Battery Control Unit (BCU) to regulate the voltage according to the reference voltage of 14 V and to enable sensor readings for monitoring. Afterward, the output from the BCU is connected to a 12 V battery for the charging process.

In the 12 V battery charging test, measurements of the battery's voltage and current were taken over time (hours). The test began when the battery voltage was at 10.80 V. The test results are presented as follows.

Table 1. Measurement results during the charging process.

Time	*Solar Cell* Voltage (V)	*Solar Cell Current* (A)	*Solar Cell* Power (W)	BCU Voltage *Output* (V)	BCU Current *Output* (A)	Battery Voltage (V)
6.00	14.37	1.22	17.53	14.00	1.27	10.80
7.00	17.19	1.36	23.38	14.00	1.26	11.20
8.00	18.75	1.40	26.25	14.00	1.25	11.40
9.00	19.53	1.94	37.89	14.00	1.20	11.70
10.00	20.44	1.98	40.47	14.00	1.19	11.90
11.00	20.97	2.04	43.83	14.00	1.17	12.00
12.00	21.76	2.11	46.78	14.00	0.90	12.10
13.00	21.41	2.08	45.60	14.00	0.82	12.15
14.00	21.02	1.81	38.05	14.00	0.71	12.18
15.00	19.04	1.67	31.80	14.00	0.52	12.19
16.00	15.18	1.53	23.23	14.00	0.31	12.20

From **Table 1**, it can be seen that the battery charging process started when the battery voltage was at 10.80 V, and after 11 hours of charging, the battery reached a voltage of 12.20 V. The charging current at the beginning of the process was 1.27A and gradually decreased as the battery approached full capacity.

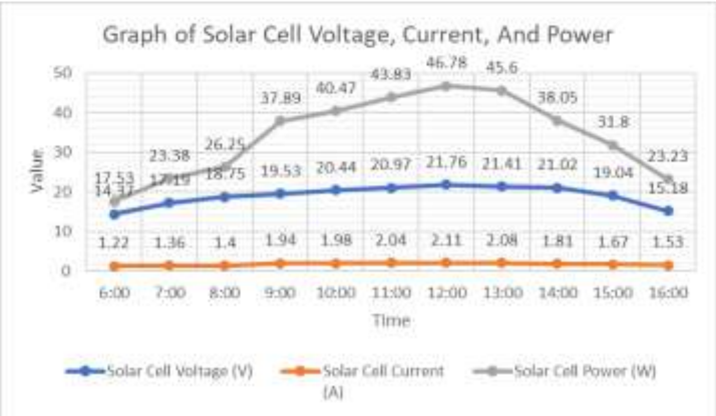

Figure 8. Graph of Solar Cell Voltage and Current versus Time

From **Figure 8**, it can be seen that the voltage and current output generated by the solar cell during the charging process vary over time. The highest output power was recorded at 12:00 PM, reaching 46.78 W. **Figure 9** shows the output current from the BCU to the battery during the charging process. At the beginning of charging, the current entering the battery is 1.27 A, and it gradually decreases to 0.31 A as the battery becomes fully charged.

From **Figure 10**, it can be seen that the graph shows the battery voltage during the charging process. At the beginning of charging, the battery voltage is 10.80V, and after 12 hours of charging, the voltage reaches approximately 12V. This indicates that the battery charging process has proceeded as expected.

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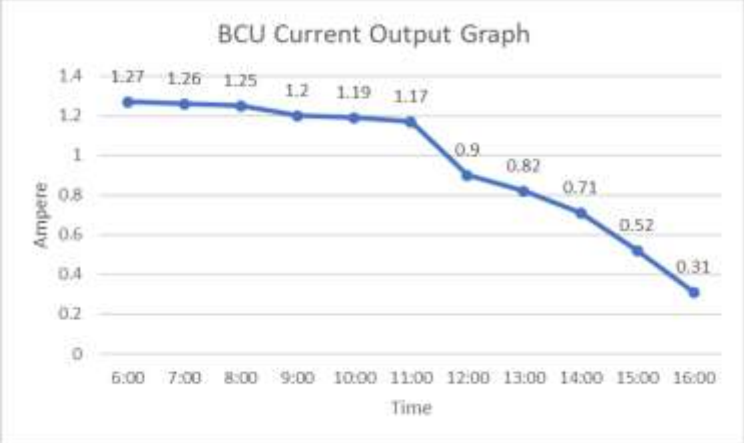

Figure 9. Charging current versus time graph

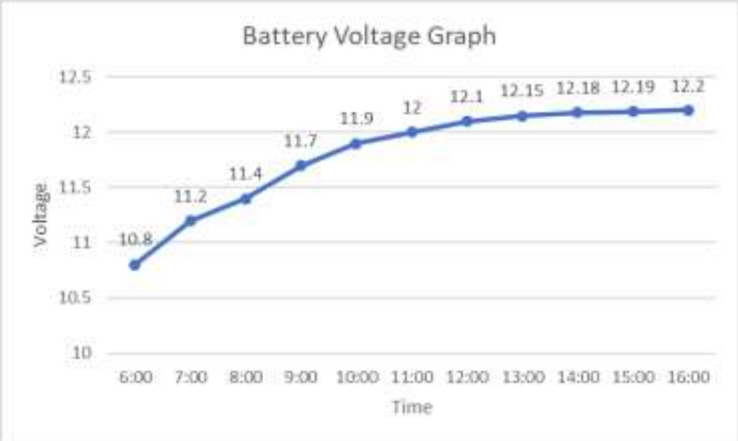

Figure 10. Battery voltage versus time graph

Buck Boost Converter XL6009 Testing

This test was conducted to determine whether the XL6009 buck-boost converter module used in the BCU can properly regulate the output voltage, which will then be supplied to the battery for charging.

Result

Table 2 shows the test results of the buck-boost converter using a 24Ω resistive load, with the output voltage set to 14V. The highest power efficiency achieved was 92%, with an input power (Pi) of 8.820W and an output power (Po) of 8.12W.

Table 2. Buck Boost Converter Testing

Vi	Ii	Pi	Vo	Io	Po	Power Efficiency (%)
9.51	0.98	9.320	14	0.58	8.12	87%
9.96	0.92	9.163	14	0.58	8.12	89%
10.90	0.83	9.047	14	0.58	8.12	90%
11.41	0.79	9.014	14	0.58	8.12	90%
12.60	0.70	8.820	14	0.58	8.12	92%
15.00	0.60	9.000	14	0.58	8.12	90%
16.10	0.56	9.016	14	0.57	7.98	89%
17.20	0.53	9.116	14	0.58	8.12	89%
18.20	0.49	8.918	14	0.58	8.12	91%
19.70	0.47	9.259	14	0.57	7.98	86%

Sollar Cell (Photovoltaic) Testing

The solar cell voltage test was conducted to determine whether the output of the solar cell corresponds to its specified performance.

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Result

The test was carried out using 24 Ω and 35 Ω resistors on different days. The following are the results of the solar cell module testing.

Table 3. Testing with resistor 24 Ω

Time (Hour)	Voltage (V)	Current (A)	P (W)
6.00	14.12	0.588	8.31
7.00	16.17	0.674	10.89
8.00	19.20	0.800	15.36
9.00	19.81	0.825	16.35
10.00	20.00	0.833	16.67
11.00	20.31	0.846	17.19
12.00	20.73	0.864	17.91
13.00	21.10	0.879	18.55
14.00	21.30	0.888	18.90
15.00	18.42	0.768	14.14
16.00	14.77	0.615	9.09

Table 3 presents data collected, showing the maximum and minimum voltages produced by the photovoltaic module. The maximum voltage recorded was 21.30 VDC at 2:00 PM, while the minimum voltage recorded was 14.12 VDC at 6:00 AM.

Table 4. Testing with resistor 32 Ω

Time (Hour)	Voltage (V)	Current (A)	P (W)
6.00	10.79	0.308	3.33
7.00	16.35	0.467	7.64
8.00	20.14	0.575	11.59
9.00	20.52	0.586	12.03
10.00	20.76	0.593	12.31
11.00	20.91	0.597	12.49
12.00	21.22	0.606	12.87
13.00	21.54	0.615	13.26
14.00	20.72	0.592	12.27
15.00	18.55	0.530	9.83
16.00	16.67	0.476	7.94

Table 4 presents data collected on April 25, 2019, showing that the maximum voltage produced by the solar cell module was 21.54 VDC at 1:00 PM, while the minimum voltage recorded was 10.79 VDC at 6:00 AM.

Protection Circuit Testing

This test was carried out to evaluate the performance of the protection circuit that uses a diode IN4002. The testing was conducted by measuring the voltage and current supplied to the load when the diode was installed in the forward direction and when it was installed in reverse.

Result

From the voltage measurement test with the diode connected in the forward direction toward the load, the results shown in **Table 5** indicate that the diode was able to conduct voltage properly to the load. In **Table 5**, the voltage measurement with the diode connected in the reverse direction toward the load can be seen. It shows that the voltage supplied to the load is 0 V, indicating that the diode is able to block reverse or non-directional voltage effectively.

Table 5. Forward-biased and Reverse-Biased diode condition

Power Supply (V)	Voltage to Load Forward- Biased (V)	Voltage to Load Reverse-Biased (V)
10.66	10.29	0
12.33	11.97	0
14.25	13.92	0
16.72	16.37	0
17.52	17.15	0

4. Conclusion

The designed Battery Control Unit (BCU) successfully regulates the charging process of a 12 V battery supplied by a photovoltaic module using Pulse Width Modulation (PWM) control. The system maintains a stable output voltage of 14 V throughout the charging process, ensuring the voltage remains within the reference range. Based on the test results, the battery voltage increased from 10.80 V to 12.20 V after 11 hours of charging, while the current gradually decreased from 1.27 A to 0.31 A as the battery reached full capacity. This indicates that the BCU effectively manages the charging voltage and current, allowing the battery to charge efficiently and safely under varying solar irradiance conditions.

The XL6009 buck-boost converter implemented in the Battery Control Unit (BCU) demonstrated stable voltage regulation performance during testing. With a resistive load of 24 Ω and an output voltage set to 14 V, the converter successfully maintained a consistent output despite variations in input voltage. The test results indicated that the system achieved a maximum power efficiency of 92%, corresponding to an input power of 8.82 W and an output power of 8.12 W. This high level of efficiency confirms that the XL6009 module is capable of effectively managing voltage conversion between the photovoltaic source and the battery, ensuring minimal power loss and reliable energy transfer during operation.

Based on the protection circuit testing, the IN4002 diode successfully performed its function as a protection component in the system. The diode was able to conduct voltage properly in the forward-biased condition and effectively block voltage in the reverse-biased condition, ensuring that no reverse current flowed to the load. This result indicates that the protection circuit can safeguard the system from reverse polarity and potential damage to sensitive components, thereby increasing the reliability and safety of the overall circuit.

5. Abbreviations

A	Ampere
BCU	Battery Control Unit
DC	Direct Current
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
PWM	Pulse Width Modulation
V	Voltage
VDC	Voltage Direct Current
W	Watt

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