

Design of Bidirectional DC-DC Converter for Photovoltaic Charging System

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ABSTRACT

This paper proposes a bidirectional DC-DC converter designed for photovoltaic charging systems. The converter aims to efficiently charge batteries while maintaining stable DC voltage and current output. It can convert DC power from solar panels to charge the battery and deliver DC power from the battery to the connected DC bus. The control method for the converter utilizes PI control to achieve a constant output current and voltage. In addition, PI control ensures smooth operation and protects the battery from overcharging or deep discharge. The simulations were conducted using MATLAB/Simulink software, optimizing the converter's topology, parameters, and controls according to the requirements of the PV charging system. Simulations validate the converter's performance under various conditions, including input power fluctuations caused by changes in sunlight intensity, varying input voltage, and load power demand. When varying irradiation, the system has small error, range 0.02%-0.05% and also has good efficiency 95.22% at high irradiation. Then, the system's efficiency increases from 90.65% to a peak of 96.50% at a load power of 175 W, then slightly decreases to 95.08% at a load power of 200 W. That results demonstrate that the bidirectional DC-DC converter effectively operates in charging and discharging modes, maintaining a stable 24V voltage in the DC bus and providing optimal charging performance for the battery.

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1. INTRODUCTION

The global demand for new and renewable energy has surged in response to the urgent need for sustainable solutions driven by climate change [1][2][3][4][5][6]. Solar power plants, utilizing solar energy as the primary source, have emerged as a popular choice to meet the increasing global energy needs [7][8]. The solar photovoltaic (PV) system, comprising essential components such as solar panels, inverters, and batteries, alongside a sophisticated control and monitoring system [9], efficiently converts solar energy into electrical energy, addressing the growing demand for greener energy options [10]. To maximize efficiency and reliability, a cutting-edge charging system integrates DC-DC converter technologies, current and voltage regulation, and control methods to optimize the charging process, enabling batteries to maintain safety, high performance, and an extended lifespan across diverse applications [11][12][13].

PV systems are cutting-edge technologies that directly convert solar energy into electricity, making them one of the most sought-after renewable energy resources [14][15]. However, PV systems face challenges in capturing solar energy due to their intermittent nature, which is affected by several factors such as time, climate, pollution, and seasons [16][17]. However, we can overcome these challenges by utilizing energy storage system technologies like bidirectional DC-DC converters equipped with batteries [18]. These advanced converters store excess energy in batteries, ensuring these converters can be used during periods of lower

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energy capacity [19]. Meanwhile, DC-DC converters play a crucial role in modern electronic circuits by providing stable DC voltage and meeting the needs of various devices. As this technology has continued to evolve since the 20th century, especially with the development of transistor technology in the 1950s, the efficiency of DC-DC converters has significantly improved. Today, these converters are integral in various applications such as solar power systems, automotive, and communications [20].

Bidirectional DC-DC converters play a crucial role in photovoltaic (PV) applications, enabling efficient energy management between PV systems and energy storage devices like batteries. These converters facilitate the transfer of power in both directions, allowing for battery charging when excess solar energy is available and discharging when solar power is insufficient. The design and implementation of such converters are pivotal for optimizing the performance and cost-effectiveness of PV systems. In [21], The bidirectional DC-DC converter used in PV charging systems is a solution to enhance battery charging efficiency by harnessing renewable energy from solar panels. This converter can convert the solar panel's energy to charge the battery, and it can also convert power from the battery to supply electricity to the load bus [22]. Despite the increasing popularity of solar panels as a renewable energy source, the battery charging efficiency of solar panels remains a significant challenge. This is due to fluctuations in sunlight intensity and other environmental conditions that can impact solar panel performance. The bidirectional DC-DC converter plays a crucial role in addressing these challenges and ensuring optimal battery charging efficiency [23]. Another design employs a bidirectional buck/boost converter with soft switching, which reduces switching losses and enhances efficiency through a resonant circuit, minimizing ripple in the inductor current and output voltage [24]. In [25], A novel non-isolated bidirectional three-port converter integrates PV arrays, battery packs, and DC microgrid bus bars, utilizing a KY boost converter and an interleaved boost converter to achieve high efficiency and reduced component count. Also, Design and simulation of a bidirectional DC-DC converter for solar PV system battery charging application is used in [26]. The converter improves efficiency and reduces circuit complexity. A Proportional-Integral Control scheme is implemented to maintain stable battery voltages and load estimation. This paper proposes a bidirectional DC-DC converter with cascaded Proportional-Integral (PI) control for photovoltaic charging systems. The converter aims to efficiently charge batteries while maintaining stable DC voltage and current output. It can convert DC power from solar panels to charge the battery and deliver DC power from the battery to the connected DC bus. The implementation of PI control within the bidirectional converter provides enhanced stability by precisely regulating current and voltage. This control strategy ensures that the system operates smoothly in both charging and discharging modes, maintaining optimal performance while protecting the battery from overcharging or deep discharge.

The development of bidirectional DC-DC converters, particularly in charging systems, holds immense potential for enhancing the energy efficiency and sustainability of PV systems. Through continued development and implementation of these technologies, we can effectively meet the global energy demand in an environmentally friendly and sustainable manner, while tackling the challenges of climate change and the limitations of conventional energy resources.

2. DESIGN OF BIDIRECTIONAL DC-DC CONVERTER

This paper proposes energy storage systems which focuses on using a solar panel as a voltage source and a buck converter to reduce the voltage for the DC bus. The buck converter steps down the voltage from the solar panel to 24V to supply the DC bus voltage. Additionally, a bidirectional DC-DC converter is utilized for energy storage systems to charge and discharge batteries. During the buck mode of the bidirectional DC-DC converter, the voltage from the DC bus is reduced to 14.4V to charge a 12V 40Ah battery. The charging voltage is set to 13.8V – 14.4V to provide energy to the battery and prevent overcharging. When the power from the solar panel is insufficient to meet the load demand, the bidirectional DC-DC converter operates in boost mode. It steps up the battery voltage from 12V to 24V for the DC bus. The block diagram of the proposed system is shown in Figure 1.

The modeling of bidirectional DC-DC converters involves using a non-isolated half-bridge converter, as depicted in Figure 2. The converter comprises an inductor, filter capacitors, and 2 switching devices. This circuit enables power to flow in both directions, allowing for bidirectional power flow.

Depending on the operating mode, the bidirectional converter can either step up or step down the voltage in either direction [27][28]. The duty cycle of the bidirectional converter in buck and boost mode can be calculated as follows:

$$D_{buckbdc} = \frac{V_{buckbdc}}{V_{bus}} = \frac{14.4}{24} = 0.6 \quad (1)$$

$$D_{boostbdc} = 1 - \frac{V_{batt}}{V_{boostbdc}} = 1 - \frac{12}{24} = 0.5 \quad (2)$$

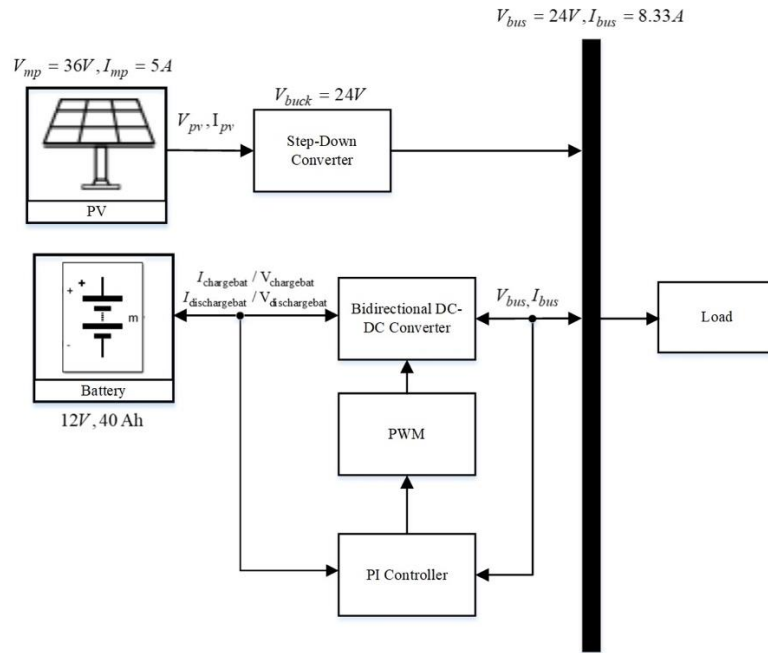


Figure 1. Block diagram of the proposed photovoltaic system

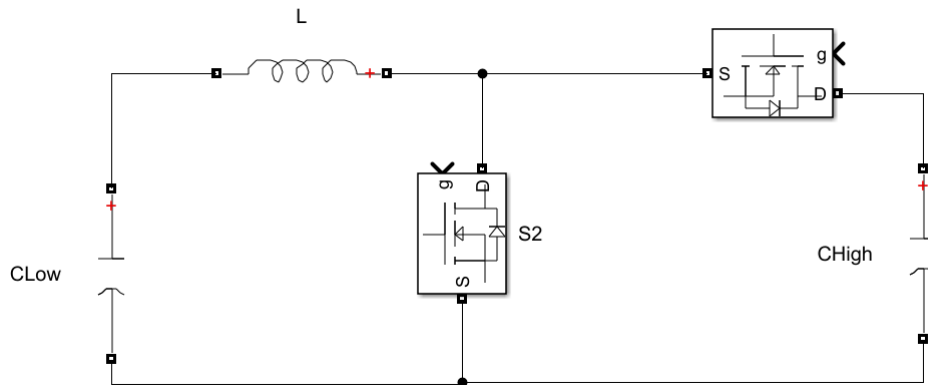


Figure 2. The circuit of bidirectional DC-DC converter

Where $D_{buckbdc}$ and $V_{buckbdc}$ are the duty cycle and voltage in the buck mode, V_{bus} is the DC bus voltage, V_{batt} is the battery voltage, and $V_{boostdc}$ is the voltage in the boost mode. In general, the safe charging current is 10% to 30% of the rated capacity of the battery. The charging current is chosen as 20% of the rated capacity on the battery [29] as follows:

$$I_{chargebatt} = 20\% \cdot 40 = 8 \text{ A} \quad (3)$$

Where $I_{chargebatt}$ is the charging battery current. Then, the value of the inductor current ripple in buck mode is determined as follows:

$$\Delta I_{Lbuckbdc} = 10\% \cdot I_{chargebatt} = 10\% \cdot 8 = 0.8 \text{ A} \quad (4)$$

From the inductor ripple, one can calculate the value of the inductor in buck mode as follows:

$$L_{buckbdc} = \frac{D_{buckbdc} \cdot T_s \cdot (V_{bus} - V_{buckbdc})}{\Delta I_{Lbuckbdc}} = \frac{0.625 \cdot 10^{-6} \cdot (24 - 14.4)}{0.8} = 0.0002 \text{ H} \quad (5)$$

Where $\Delta I_{Lbuckbdc}$ and $L_{buckbdc}$ are the changing inductor current and inductor value in buck mode, T_s is the sampling. The value of the inductor current ripple in boost mode with a current ripple of 10% is determined as follows:

$$\Delta I_{Lbuckbdc} = 10\% \cdot I_{bus} = 10\% \cdot 8.33 = 0.833 \text{ A} \quad (6)$$

The inductor value in boost mode, $L_{boostbdc}$, can be calculated as follows:

$$L_{boostbdc} = \frac{D_{boostbdc} \cdot T_s \cdot V_{buckbdc}}{\Delta I_{Lboostbdc}} = \frac{0.4 \cdot 25 \cdot 10^{-6} \cdot 14.4}{0.833} = 0.0002 \text{ H} \quad (7)$$

Based on Figure 1, it is evident that the bidirectional converter incorporates a single inductor. The inductor value for both buck and boost modes are selected to be 0.0002 H. When determining capacitor output voltage changing, $\Delta V_{Obuckbdc}$, it is important to note that a 1% voltage ripple is designed for the buck mode, which results in the following output ripple.

$$\Delta V_{Obuckbdc} = 1\% \cdot V_{Obuckbdc} = 1\% \cdot 14.4 = 0.144 \text{ V} \quad (8)$$

Then, the value of the output capacitor in buck mode, $C_{Obuckbdc}$, can be calculated as follows:

$$C_{Obuckbdc} = \frac{(1-D_{buckbdc}) \cdot V_{buckbdc} \cdot T_s^2}{8 \cdot L_{buckbdc} \cdot \Delta V_{Obuckbdc}} = \frac{(1-0.6) \cdot 14.4 \cdot (25 \cdot 10^{-6})^2}{8 \cdot 0.0002 \cdot 0.144} = 0.0000156 \text{ F} \quad (9)$$

The output ripple in boost mode, $\Delta V_{Oboostbdc}$, with a voltage ripple of 1% is as follows:

$$\Delta V_{Oboostbdc} = 1\% \cdot V_{bus} = 1\% \cdot 24 = 0.24 \text{ V} \quad (10)$$

Finally, the value of the output capacitor in boost mode, $C_{Oboostbdc}$, can be calculated as follows:

$$C_{Oboostbdc} = \frac{V_{bus} \cdot D_{boostbdc}}{8 \cdot \Delta V_{Oboostbdc}} = \frac{8.33 \cdot 0.4}{40000 \cdot 0.24} = 0.00034 \text{ F} \quad (11)$$

The calculated components, such as inductors and capacitors, are then used in the simulation to validate the bidirectional converter. The bidirectional converter's output is subsequently verified by the design requirements.

CONTROLLER DESIGN

In bidirectional converter design, this paper implements cascaded PI controllers for current and voltage regulation. The common equation of PI controller is expressed as follows

$$u(t) = K[e(t) + \frac{1}{\tau_i} \int_0^t e(t) dt] \quad (12)$$

Where $u(t)$ is the control signal, K is the gain, $e(t)$ is the error signal, and τ_i is the integral time constant. These controllers are designed to ensure system stability, maintain output current and voltage, compare input and output power for efficiency, and respond dynamically to load changes and irradiation [30][31][32]. For the proposed bidirectional DC-DC converters control, PI controllers are crucial for managing charging and discharging operations on the battery. Each operation has its own set of controls during charging and discharging. The diagram in Figure 2 illustrates the controller aspect of each operation. In Figures 3(a) and (b), the reference voltage is compared to the measured voltage on the DC bus. The result is then processed by the outer loop control to obtain the reference current value. Following this, the reference current is compared with the measured current by the inner loop control to produce PWM connected to the switching devices in the converter.

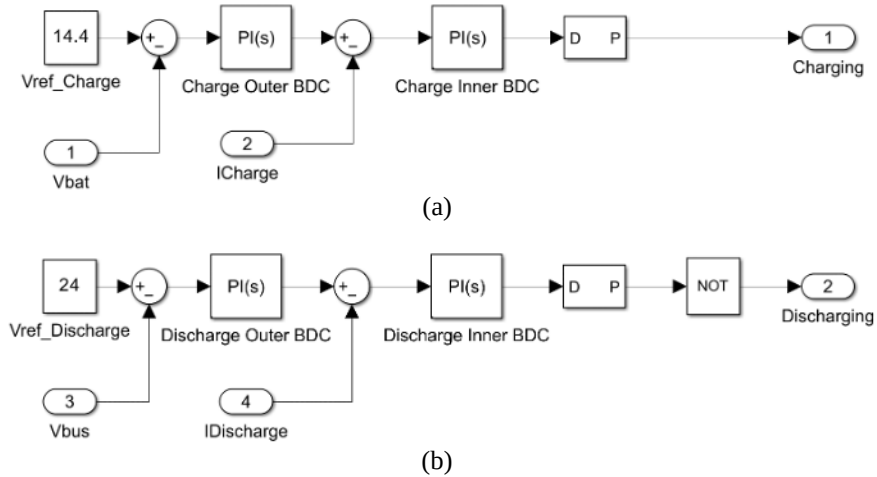


Figure 3. Control diagram of bidirectional converter (a) charging control (b) discharging control

The mode selection for a bidirectional converter starts with a sensor that reads the voltage on the DC bus. If the sensor detects a voltage greater than or equal to 24V, the bidirectional converter switches to buck mode, and the battery is charged. If the sensor detects a voltage less than 24V, the bidirectional converter switches to boost mode, and the battery is discharged. In the simulation, the mode selection for the bidirectional DC-DC converter is determined using a switch in MATLAB/Simulink. The switch has two inputs connected to the charge and discharge control outputs. The block diagram of the mode selection for the bidirectional DC-DC converter is shown in Figure 4.

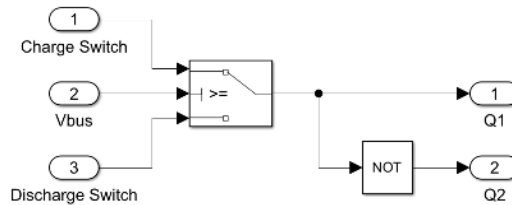


Figure 4. Charging and discharging mode selection control

In Figure 4, if port two reads 24V or higher, port one will allow the output and the battery is charging. If port two reads less than 24V, port three will allow the output and then the battery is discharged.

3. RESULT AND DISCUSSION

Simulations were carried out on MATLAB Simulink to test the performance of a bidirectional converter on a PV charging system. The details of the block diagram are presented in Figure 5.

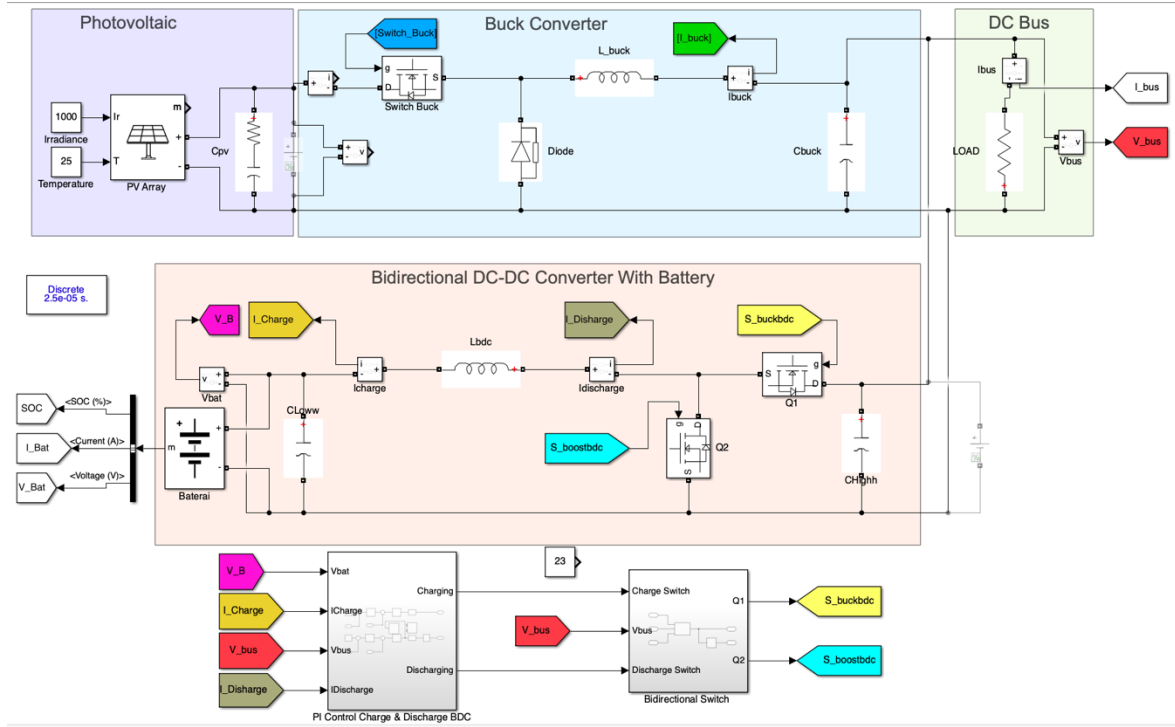


Figure 5. Simulink model of the bidirectional converter model for PV charging system

The tests encompass various conditions, including changes in irradiation and load for charging and discharging states. In the first test, the solar irradiation parameter was gradually reduced from 1000 W/m^2 to 0 W/m^2 . When the solar panel output power exceeds the load demand, the bidirectional converter operates in buck mode with the battery in a charging state. Conversely, when the irradiation decreases, causing the solar panel output power to decrease below the load demand, the bidirectional DC-DC converter operates in boost mode and the battery goes into a discharging state. In the second test, load changes are conducted with constant irradiation, wherein the load demand increases until it surpasses the power generated by the solar panel. In this scenario, the bidirectional DC-DC converter works in boost mode.

In the simulation, the parameters of PI controllers are determined by using Ziegler's Nichols method, and the parameter values of each control are obtained as shown in Table 1.

Table 1. PI controller parameters

Parameters	Charge outer loop	Charge inner loop	Discharge outer loop	Discharge inner loop
P	50.54	0.365	0.1	0.285
I	0.0001	0.00001	300	0.0001

When the power output of the solar panel is greater than the load demand, the bidirectional converter operates in buck mode, charging the battery and increasing the State of Charge (SOC) slowly. Conversely, if the power from the photovoltaic is less than the load demand, the converter operates in boost mode, draining the battery and lowering the SOC slowly. In Figure 6, the results of the varied irradiation test at a fixed load power of 200W are shown. It is observed that with the variations of irradiation at a fixed load of 200W, the bidirectional converter operates in boost mode, meaning the battery is discharged. As irradiation decreases, the voltage and current also decrease. The voltage on the DC bus remains stable between 23.95 and 23.98V with an error of 0.05 to 0.02V, indicating the system is working well. The battery voltage is stable at 12.76-12.86V, while the current increases significantly as the irradiation decreases. These results demonstrate that PV charging systems work optimally even as irradiation levels change.

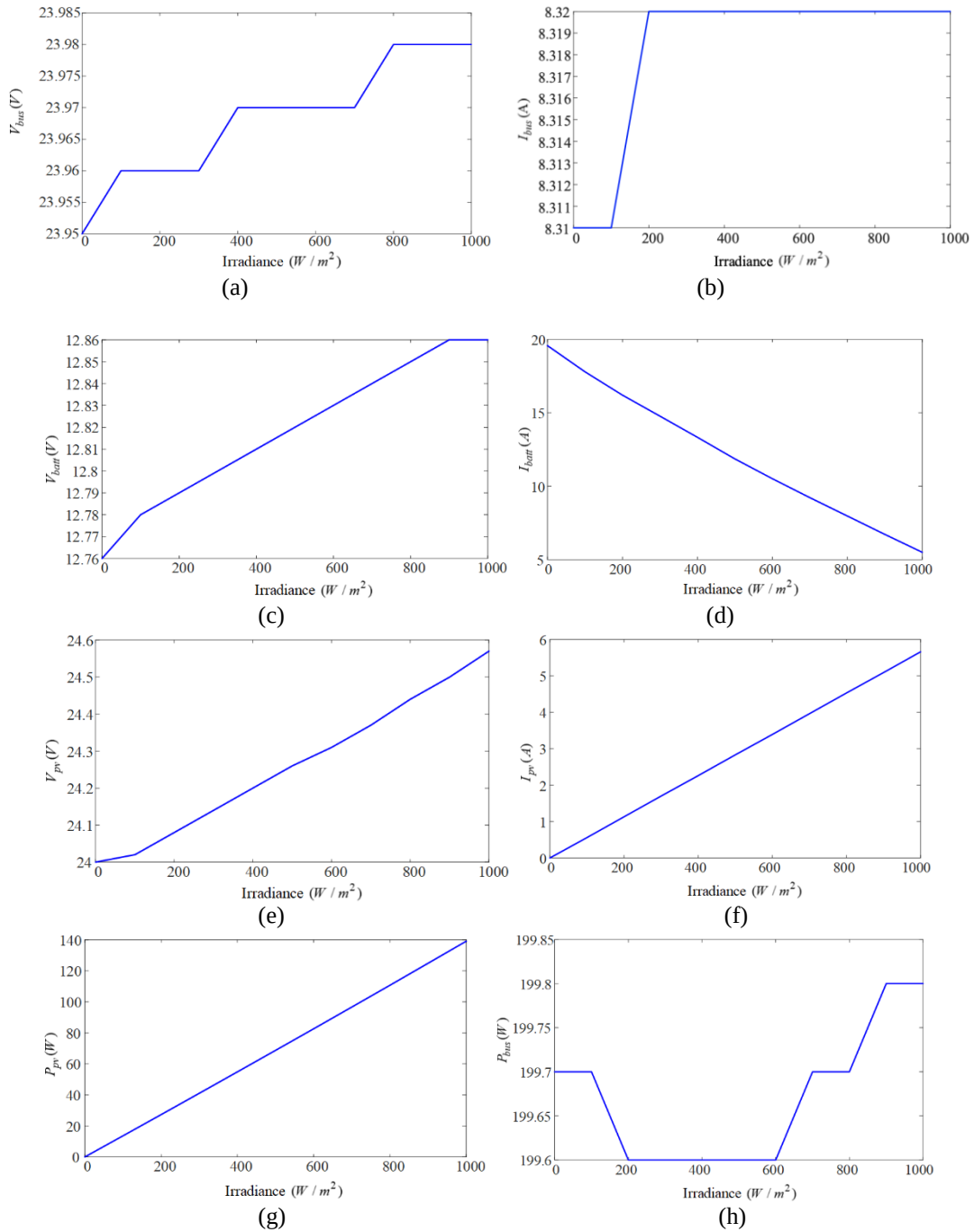


Figure 6. Test results of bidirectional converter under varied irradiation at a fixed load power of 200W

The robust performance of PV charging systems under varying irradiation levels while supporting a consistent 50W load are presented in Table 2. It is evident that the systems effectively stabilize bus voltage and current despite changes in irradiation. Notably, the converter's efficiency experiences a substantial increase at lower irradiance levels, such as from 300 W/m^2 to 0 W/m^2 , signaling its adaptability to challenging conditions. Furthermore, the data illustrates that when the irradiance surpasses 300 W/m^2 , the battery obtains a positive current, indicating effective charging, while irradiance levels below 300 W/m^2 result in battery discharge. This compelling evidence emphasizes the consistent and reliable performance of PV charging systems across varying irradiation conditions.

Table 2. Performance of PV charging systems under varying irradiation levels with a constant 50W load.

Irradiance (W/m^2)	P_{Load} (W)	$V_{bus}(V)$	$I_{bus}(A)$	P_{bus} (W)	$V_{pv}(V)$	$I_{pv}(A)$	P_{pv} (W)	$V_{batt}(V)$	$I_{batt}(A)$	P_{batt} (W)
1000	50	24	2.08	50	24.57	5.66	139.1	12.95	-6.17	-79.9
900	50	24	2.08	50	24.52	5.09	124.9	12.94	-5.18	-67.03
800	50	24	2.08	50	24.45	4.53	110.8	12.93	-4.20	-54.31
700	50	24	2.08	50	24.39	3.96	96.7	12.93	-3.20	-41.38
600	50	24	2.08	50	24.33	3.39	82.70	12.92	-2.22	-28.68
500	50	24	2.08	50	24.30	2.83	68.83	12.91	-0.76	-9.81
400	50	24	2.08	50	24.22	2.26	54.90	12.90	-0.14	-1.81
300	50	23.99	2.08	49.99	24.16	1.70	41.08	12.90	0.94	12.13
200	50	23.99	2.08	49.99	24.10	1.12	27.32	12.89	2.06	26.55
100	50	23.99	2.08	49.99	24.05	0.56	13.63	12.88	3.19	41.09
0	50	23.99	2.08	49.99	24.03	0	0	12.87	4.36	56.11

When the power generated by the solar panels exceeds the power on the DC bus, the bidirectional converter operates in buck mode to charge the battery. Test results in Figure 7 display the impact of changing load power at a constant irradiation of $1000 W/m^2$. The bus voltage remains stable, with a slight decrease observed at the highest load, while the current increases linearly with the load. The battery voltage remains steady at around 12.9V and the battery current changes from negative (charging) to positive (discharging). The data indicates that the battery is charging within a load range of 75-125W, and discharging within a load range of 150W-200W. The proposed PV charging systems perform well under varying irradiation, input voltage, and load power demand. Both buck converters and bidirectional DC-DC converters effectively maintain stable voltages and currents, with PI control being utilized to optimize the control of bidirectional converters.

Figure 8 illustrates the efficiency of the bidirectional converter as the irradiation changes at a fixed 200W load power. During the test, the power supplied to the load remains steady at 199.6 W to 199.8 W despite the varying irradiation. The power produced by the PV drops from 139.1 W to 0 W at 0 W/m^2 irradiation. To offset the decrease in power from the PV, the power provided by the battery rises from 70.73 W to 249.71 W. The system's efficiency ranges from 95.22% at high irradiation to 79.97% at zero irradiation, demonstrating an increased reliance on the battery as the irradiation decreases. Bidirectional DC-DC converters exhibit good efficiency, maintaining a consistent performance as irradiation changes from $1000 W/m^2$ to 0 W/m^2 with a fixed load of 200W.

In Figure 9, the efficiency of the PV charging system is depicted at various load powers, while the power generated by the PV remains constant at 139.1 W. As the load power increases, the battery switches from charging to discharging, indicating that at low load power, the battery receives power from the PV, and at high load power, the battery provides additional power. The system's efficiency increases from 90.65% to a peak of 96.50% at a load power of 175 W, then slightly decreases to 95.08% at a load power of 200 W. These findings demonstrate that the PV charging system can maintain a constant load power with the assistance of a battery while maintaining high efficiency under various load conditions.

4. CONCLUSIONS

The bidirectional DC-DC converter with cascaded PI control for a photovoltaic energy storage system was successfully simulated in MATLAB/Simulink. The converter can operate in two modes: buck and boost. In buck mode, when the power from the photovoltaic system exceeds the load requirement, the converter charges the battery, leading to a negative battery current and an increase in state of charge (SOC). In boost mode, when the power from the photovoltaic system is less than the load requirement, the converter draws power from the battery, resulting in a positive battery current and a decrease in SOC. The PI control effectively maintains system stability, with the largest error value of 0.1V in a 200W load power, where the actual output was 23.9V instead of the expected 24V. Based on this result, the bidirectional converter is highly reliable and suitable for various applications in the PV system industry.

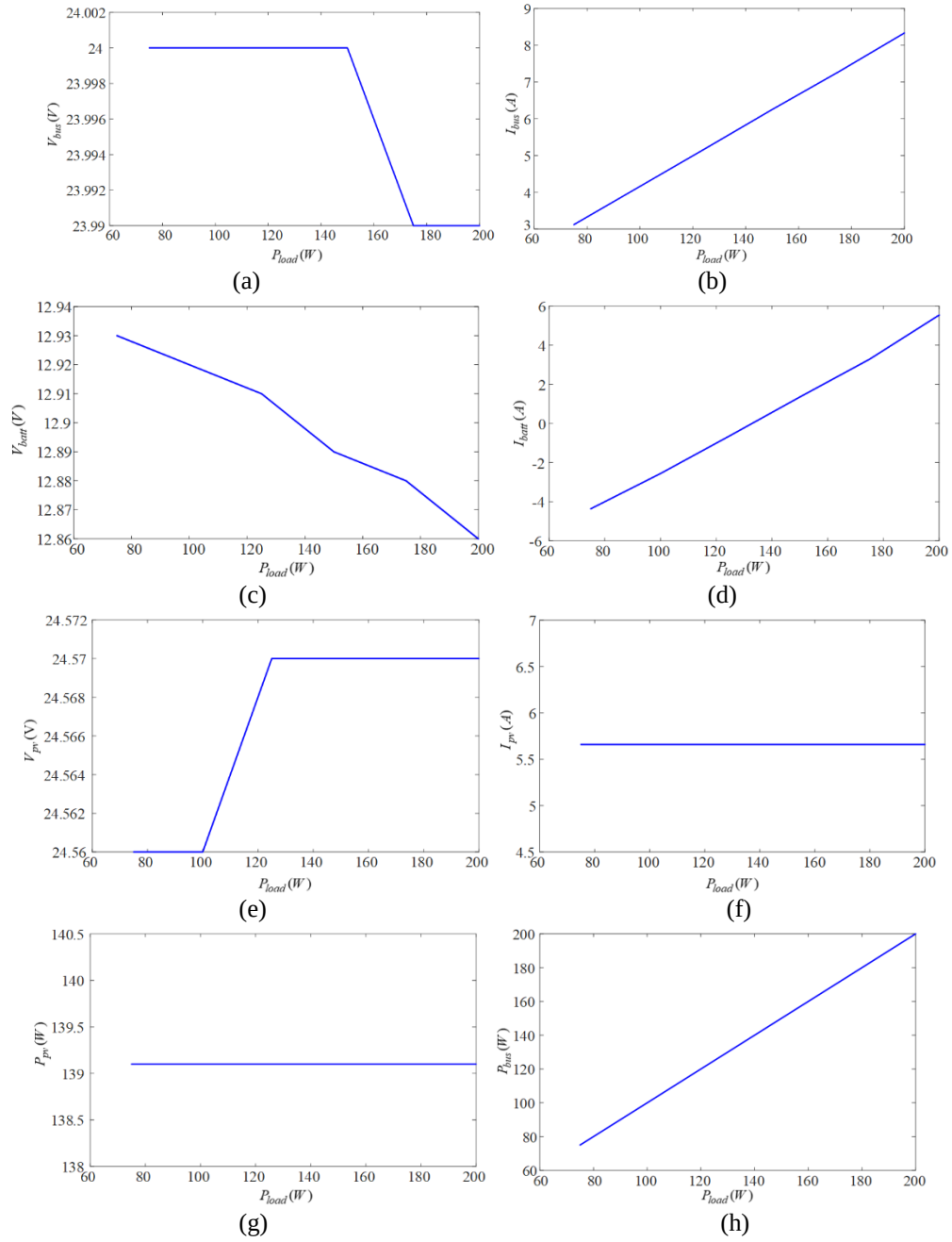


Figure 7. Test results of bidirectional converter under varied load power at a fixed solar panel irradiations of 1000 W/m^2

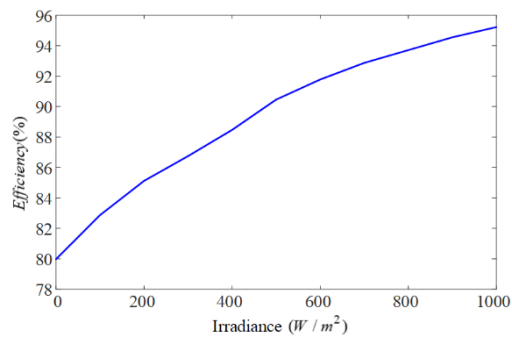


Figure 8. The efficiency of the bidirectional converter under varied irradiation at a fixed 200W load power.

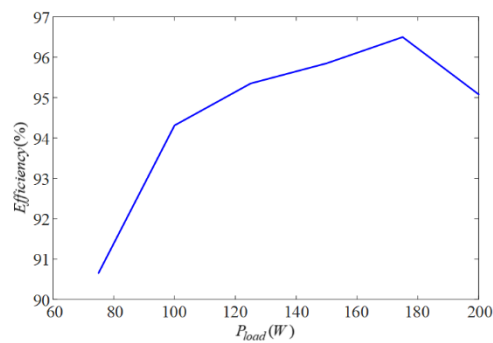


Figure 9. The efficiency of the bidirectional converter under various load power at a fixed solar panel irradiation

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