An experimental investigation design of a bidirectional DC-DC buck-boost converter for PV battery charger system

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ABSTRACT

The aim of this paper is to present a bidirectional DC-DC buck-boost converter design that is specifically intended for use with storage batteries in a PV system. The primary purpose of the batteries is to mitigate the unpredictable and intermittent nature of renewable energy sources. To achieve this, a DC-DC converter is used in buck mode during daylight hours to charge the batteries with power derived from the PV system. If the photovoltaic energy source is unavailable, the batteries can discharge to power the DC load through the converter in boost mode. Therefore, the bi-directional DC/DC converter, which has a high-power capacity, manages the power storage system. To this end, the paper describes the design and implementation of both the power circuit board and drive circuit board of the buck-boost converter, taking into account the rated current, voltage, and power. Finally, the effectiveness and efficiency of the designed converter are verified through experimental tests carried out in both charge and discharge modes, with results demonstrating the validity and efficiency of the converter.

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1. INTRODUCTION

Among renewable resources, wind and solar energy are the most widely used. According to the 'Renewables Global Status Report (2022) (REN21),' wind energy will be the primary source of new power generation capacity in the United States, Europe, and China in 2023. As of now, 845 GW of wind power capacity has been installed worldwide, as shown in Figure 1. Due to its reliability and advantages, many corporations and private companies are transitioning to this type of power source. Nevertheless, wind potential is limited to specific regions, which is where the photovoltaic system comes in to address this issue [1]. Solar photovoltaic systems have emerged as the primary source of clean energy in markets like Japan, India, China, and the United States. In 2021, the global solar PV capacity increased by about 175 GW, resulting in a total global capacity of 942 GW [1].

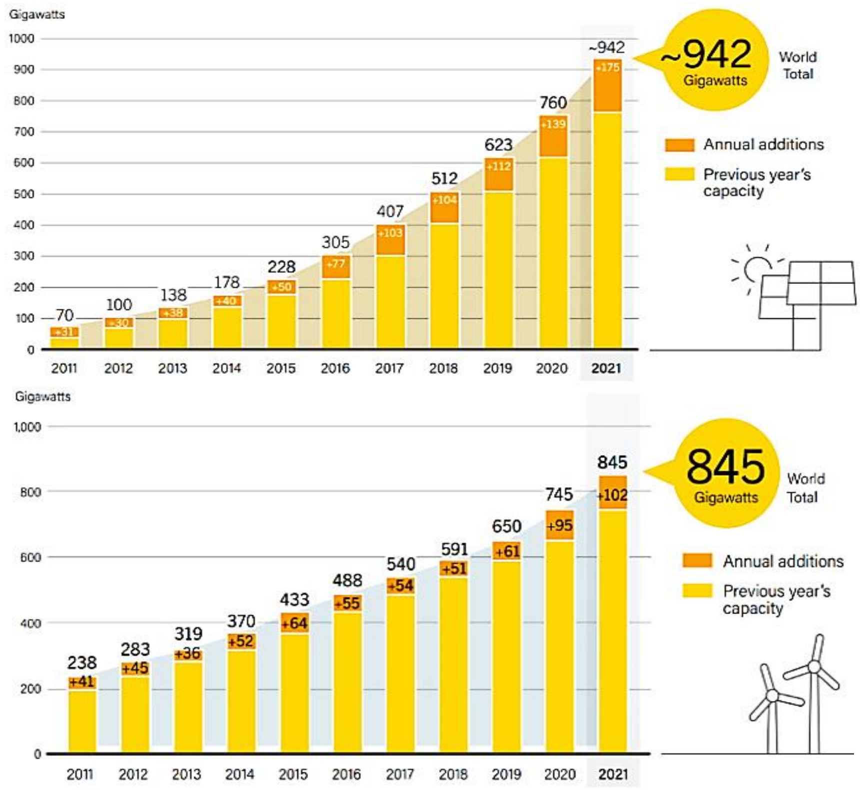


Figure 1. Solar photovoltaics and wind energy annual capacity and globally installed**,** 2011-2021 [1]

The design of energy production systems has shifted towards a smart and microgrid architecture, which necessitates the integration of renewable energy sources. However, the intermittency issue of renewable energy sources requires the use of a storage system. To facilitate the transfer of energy between the storage system and the main microgrid, a bidirectional DC-DC buck-boost converter must be integrated [2], [3]. These converters are highly suitable for use in a variety of applications, such as DC power supply systems, electric vehicle systems, motor drive systems, aerospace power systems, solar power systems, and wind energy systems [4]–[6].

Numerous buck-boost converter topologies have been proposed in the literature [7], including the four-switch non-inverting converter. This type of converter is based on four switches and has both advantages and disadvantages [8]. Ioinovici [9] explained the potential input voltage range of the design is advantageous for battery applications. This topology enables stable mode switching between boost and buck operations. The word [10] employed a four-switch topology for a power system composed of photovoltaic panels capable of discharging and charging up to 20 kW. They achieved 97% efficiency with their 5 kw prototype and concluded that the structure is suitable for a power system.

The result [11], a different topology was introduced that only requires two switches and a single conductor, as shown in Figure 2. The purpose of this topology was to illustrate how it could be used in a PV system that needs to manage battery charging and discharging through an energy management strategy. The researchers used synchronous switching, which resulted in higher conversion efficiency. Another study [12] demonstrated that the same topology could function as a buck converter with non-synchronous switching, by setting Q2 to be blocking and monitoring Q1 in the same way as a basic buck converter [13]. In this case, Q1 is set to conduct in boost mode, even though Q2 is switched based on the way a boost converter is controlled. By incorporating this bidirectional buck-boost converter into a battery charging circuit, a 96% efficiency was achieved. After evaluating various topologies, the researchers chose the bidirectional buck-boost converter with two switches due to its ease of implementation and design.

The main focus of this paper is to provide a comprehensive account of the development and practical implementation of an inexpensive and uncomplicated DC-DC bidirectional buck-boost converter. This converter is particularly suitable for academic institutions and laboratory settings, as it is tailored to the needs of students and researchers. Additionally, numerous experiments have been conducted to showcase the significance of this converter in hybrid energy production systems.

The paper's organization is as follows: i) In section 2, the studied system is described; ii) Section 3 discusses the various operation modes of DC-DC buck-boost converters; iii) Section 4 provides an in-depth explanation of the power and driver circuits' design, along with the software utilized for designing and printing the circuit boards (PCB); iv) The experimental findings of the designed circuits are presented in section 5; and v) Lastly, section 6 summarizes the key points and offers conclusions.

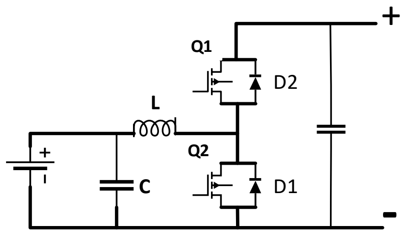


Figure 2. Bidirectional buck-boost converter with two-switch

2. DESCRIPTIONS OF THE STUDIED SYSTEM

Figure 3 illustrates the DC-DC bidirectional converter utilized in the microgrid system under investigation. The system comprises a photovoltaic generator (PVG), which is linked to the DC bus via a DC-DC boost converter Figure 3(a). The converter operates optimally, allowing the GPV to track the maximum power point (MPPT) [13], [14]. Additionally, a storage battery is connected to the DC bus through a bidirectional Buck-Boost converter Figure 3(b). The entire system provides power to a resistive DC load Figure 3(c).

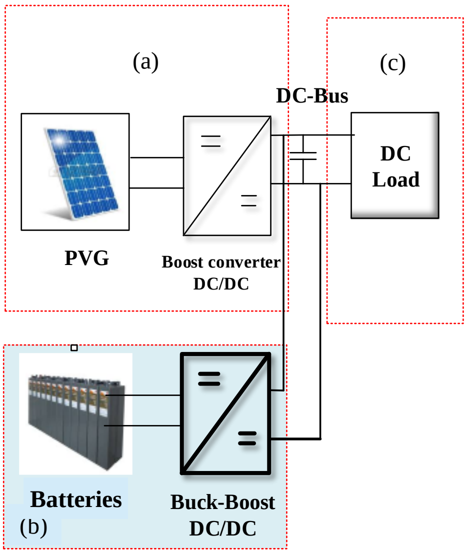


Figure 3. Photovoltaic system with storage batteries, (a) PV-Generator, (b) storage subsystem, and (c) DC-load

3. DC-DC BUCK-BOOST CONVERTER OPERATION MODES

The GPV's converter facilitates the transfer of power in a single direction from sources to the DC bus. However, when it comes to charging and discharging the battery, a reversible converter is required [15], [16]. A bidirectional buck-boost converter, as shown in Figure 4, can achieve power reversibility through its switches which are designed to transfer current efficiently in both directions. This results in two distinct operation modes, as described in references [17], [18].

3.1. Buck mode (charging mode)

While charging the battery, the bidirectional converter functions as a Buck converter. In this mode, switch S1 and diode D1 are turned on, while switch S2 and diode D2 are turned off, as depicted in Figure 4(a). As the cycle progresses, the inductor current diminishes, and the energy stored in inductor L is utilized to charge the battery, as explained in reference [19], [10]. Moreover, whenever there is a surplus of renewable energy production, the bidirectional converter transfers the extra power from the DC bus to the battery.

3.2. Boost (discharging) mode

During battery discharge, the bidirectional converter operates as a boost converter. This means that switch S2 and diode D2 are turned on, while switch S1 and diode D1 are both turned off, as shown in Figure 4(b). The converter's role in this mode is to transfer energy from the battery to the DC bus. However, in situations where the renewable energy production falls short, the bidirectional converter regulates the power flow and maintains the DC bus voltage in both charge and discharge modes [4], [20], [21].

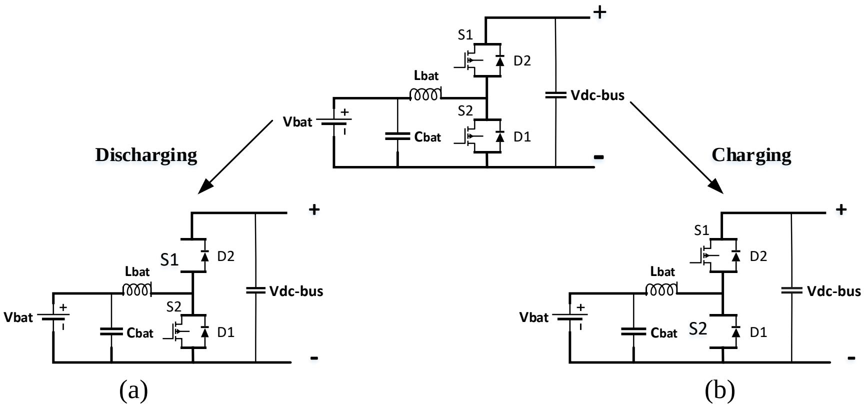


Figure 4. Describes the configuration of a bidirectional DC/DC converter in two modes: (a) discharging mode and (b) charging mode

4. DC-DC BUCK-BOOST CONVERTER CIRCUIT DESIGN

Zed two separate circuit boards, each serving a specific purpose. One circuit board was dedicated to the power circuit, responsible for handling the electrical power conversion and distribution. The power circuit board was designed to efficiently manage the input power, regulate voltage levels, and ensure proper current flow. The second circuit board was specifically designed for the drive circuit. This board focused on controlling the switching operations and managing the overall functionality of the converter. It incorporated components and circuitry to enable precise control of the power flow, timing of switching transitions, and protection mechanisms. Now, let's delve into the specifications of each circuit board to provide a more detailed understanding of their capabilities and features.

4.1. A driver circuit board

The driver circuit board depicted in Figure 5 is designed around the IR211 driver, which receives control signals from the microcontroller's outputs, such as Pic or Arduino. These control signals are analog and have voltage levels ranging from 0 to 5 volts, with sufficient current levels to power the MOSFETs. However, it is important to note that the low voltage of the gate must be isolated from the high voltage applied to the collector, which requires a signal conditioning mechanism [21], [22].

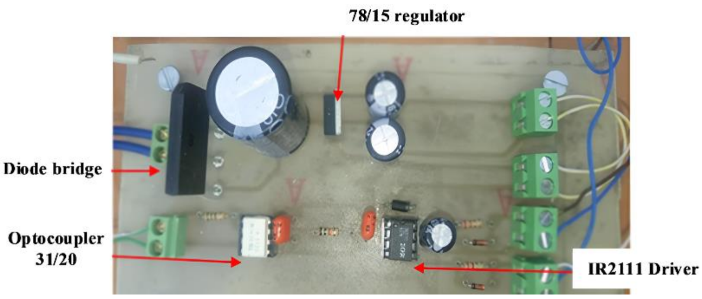


Figure 5. Converter driver card typically, the signal conditioning circuit consists of two stages

4.1.1. HCPL-3120 optocoupler

The initial step towards achieving galvanic isolation between the driver circuit board's two sides (the microcontroller and power circuit board), is illustrated in Figure 6. The HCPL-3120 comprises a GaAsP LED that is optically linked to a power output stage integrated circuit, making it beneficial for motor drive applications that involve driving MOSFETs and IGBTs. The output stage's broad functional voltage range offers the necessary drive voltages for the gate-controlled devices. With the optocoupler's current and voltage output, IGBTs rated up to 1200 V/100 A can be directly driven. If the IGBTs have higher ratings, the HCPL-3120 can be used to supply a separate power stage that controls the IGBT gate [4], [23].

4.1.2. IR2111 driver

In the second stage, depicted in Figure 7, an IR2111 driver is utilized, which possesses high voltage and high frequency for the power supply, making it suitable for driving power MOSFETs and IGBTs. The reference dependency between the high and low side output channels is taken into account in the half-bridge design. The use of HVIC technology proprietary to the device and a CMOS latch allows for a robust monolithic structure. The logic input operates with standard CMOS outputs, while output drivers employ a high pulse current buffer stage to minimize conductive cross-conduction. Internal dead time is set to prevent output Half-Bridge from switching. The floating channel has the ability to supply power to a high-side configuration N-MOSFET or power IGBT channel that operates up to 600 volts.

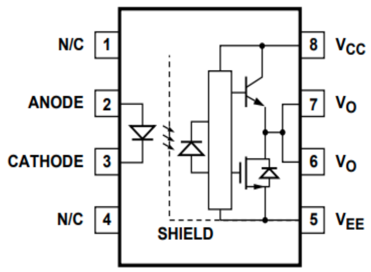


Figure 6. Functional diagram of HCPL 3120 optocoupler

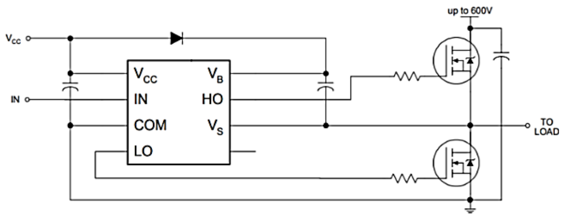


Figure 7. IR2111 driver

4.2. Converter power circuit board design

As shown in Figure 8, the power circuit portion of the Buck-Boost converter has been implemented. The key components are listed: i) a MOSFET transistor, ii) an input and output capacitors, iii) an inductor, iv) a heat sink and v) connection cables. The main components of the power circuit board were selected according to the following procedures.

4.3. Inductance choice

When designing a DC/DC converter, it is crucial to take into account the inductor design because it is often tailored to meet specific requirements based on frequency, voltage, and current [8], [16]. To select an appropriate inductor with a desired inductance L for a back mode converter (1) or boost mode converter (2), the following equations can be utilized.

$$L > \frac{V_{out}.(V_{inmax} - V_{out})}{K_{ind}.F_{sw}.V_{inmax}.I_{out}} \quad (1)$$

$$L > \frac{{V_{inmin}}^2.(V_{out} - V_{inmin})}{K_{ind}.F_{sw}.I_{out}.{V_{out}}^2} \quad (2)$$

Where V_{out} is the voltage at the output, V_{inmax} is the maximum voltage at the input, I_{out} is the rated current at the output, K_{ind} is the maximum current ripple and F_{sw} is the switching frequency. The inductance with the highest value was chosen.

$$L > 0.6944mH$$

4.4. Capacitor output selection

A low equivalent series resistance (ESR) capacitor is the best practice to reduce the output voltage ripple [11]. As a result, the peak-to-peak resistance of the ripple voltage $V_n = 0.05\ V$ and $(I_2 - I_1) = 0.2\ A$, so the need for ESR is (13).

$$R_0 = \frac{V_{rr}}{dI} = \frac{V_{rr}}{(I_2 - I_1)} = 0.25\Omega \quad (3)$$

Using the typical ESR capacitor value relationship.

$$R_0C_0 = 20 * 10^{-6}, \text{ it can be } C_0 = 50 * \frac{10^{-6}}{R_0} = 200\mu F \quad (4)$$

4.5. Power switch selection

The converter's maximum input voltage is 48 V. As a result, The IRFP260N can function as the primary circuit-switching device [24], [25]. The threshold voltage is 200 V, whereas, the threshold current is 50 A. The resistance is 4 mΩ, which is extremely short.

4.6. PCB design

The PCB design was created using EASYEDA software. Figure 9 illustrates the specific segments of the footprints and traces that make up the essential bidirectional DC/DC converter's components. Consequently, the power circuit PCB board and the driver PCB board were created using EASYEDA software, as depicted in Figures 10 and 11 respectively. The illustration presented Figure 12 shows the complete design of the DC-DC bidirectional buck-boost, comprising both the driver and power circuit boards, which are divided into two parts.

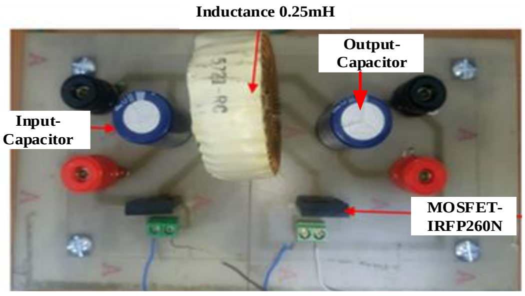


Figure 8. Converter power circuit board

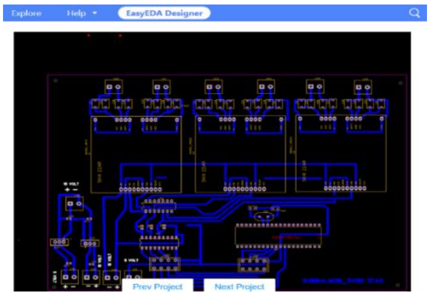


Figure 9. Easy EDA PCB designer software

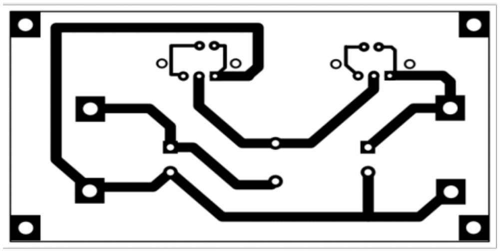


Figure 10. Power circuit board PCB

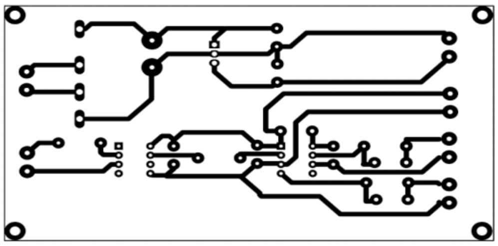


Figure 11. Driver circuit board PCB

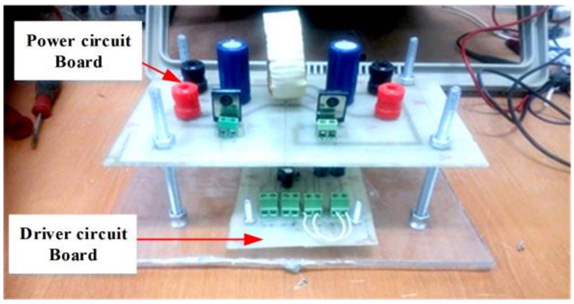


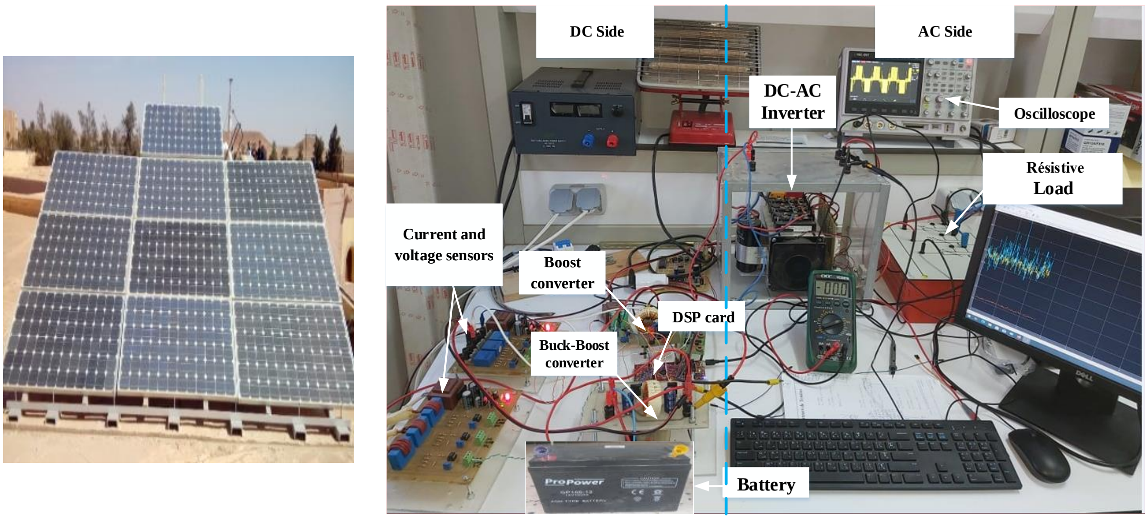
Figure 12. Bidirectional DC-DC buck-boost converter

5. RESULTS AND DISCUSSION

5.1. Experimental test bench exhibition

The photovoltaic conversion chain experimental setup illustrated in Figure 13 was divided into two parts. The first part, a continuous DC current section, includes a DC-DC Boost converter, which efficiently harvests power from the photovoltaic generator. The storage component comprises a bidirectional DC-DC Buck-Boost converter and a gel battery to regulate the DC bus voltage and ensure power balance between the source and load sides. The second part is the alternative current (AC) section, which features a 1.5 KVA

inverter based on IGBT modules controlled by the PWM technique. Real-time regulation loops are implemented using the DSP cards TMS320F28377S and TMS320F28335. This complete conversion chain is suitable for various photovoltaic applications, such as water pumping, charging solar batteries, and supplying electricity to three-phase engines in remote locations, as demonstrated in the experimental test bench of the photovoltaic conversion system shown in Figure 13.
Note: The PV system examined in this study consisted of several components, namely the PV panel, Boost, buck-Boost battery, and DC load.



(a) (b)

Figure 13. Buck boost converter test bench: (a) PV array-l'URAER-ghardaïa and (b) experimental test bench of the photovoltaic conversion system

5.2. Experiment results and discussion

Initially, the bidirectional DC-DC buck-boost converter is tested to verify the regulation of the DC bus voltage. This test involves assessing the performance of the converter at different voltage set points. Subsequently, the converter is employed to administer the storage system, allowing the batteries to be charged or discharged depending on the amount of photovoltaic power available and the load requirements. Figures 14, 15, and 16 display the results that were obtained.

- The waveform of the control signals generated by the control board is presented in Figure 14. The signals generated for both IGBTs are complementary to prevent any potential short circuits.
- In Figure 15, the waveform of the DC bus voltage during the transition phase is illustrated. It is evident that the measured voltage tracks the reference voltage accurately and rapidly when the reference voltage changes. This demonstrates the effectiveness of the regulation system developed and emphasizes the significance of the transformer's buck-boost operation.

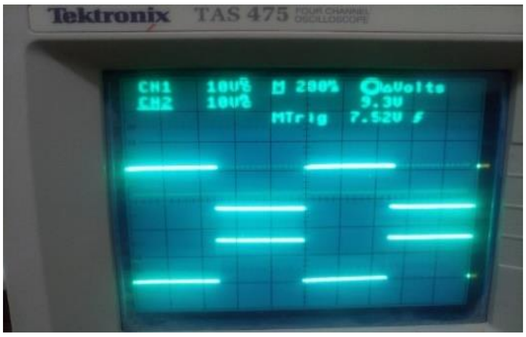


Figure 14. The shape of the control signals

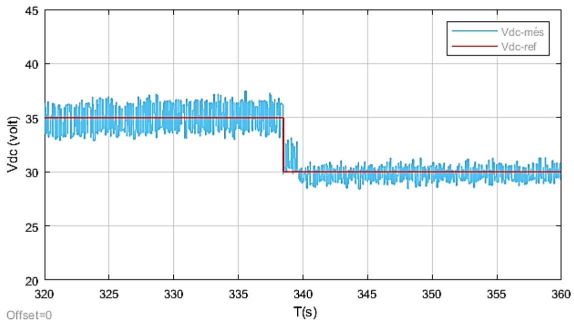


Figure 15. DC bus voltage regulation

Figure 16 illustrates the waveforms of PV's power, current and voltage, DC link voltage and battery current while operating in the charging and discharging modes. The plot demonstrates that the required power exceeds the generated power during the time interval of [19.5-28.7s]. As a result, the battery discharges to compensate for the power deficit, which is made possible by the boost operation mode of the implemented buck-boost converter.

During the time intervals of t[15-19.5s] and [28.7-33], the power produced by the PV generator is greater than the power needed by the load. As a result, the buck-boost converter functions in a buck mode, which enables it to store the excess power in the battery. The successful implementation of the system indicates that the control is valid and efficient. It ensures that the power demand for charging and discharging is met even when there are fluctuations in weather conditions, while also following the battery charging procedure. This demonstrates that the system is able to provide sufficient power and maintain consistency.

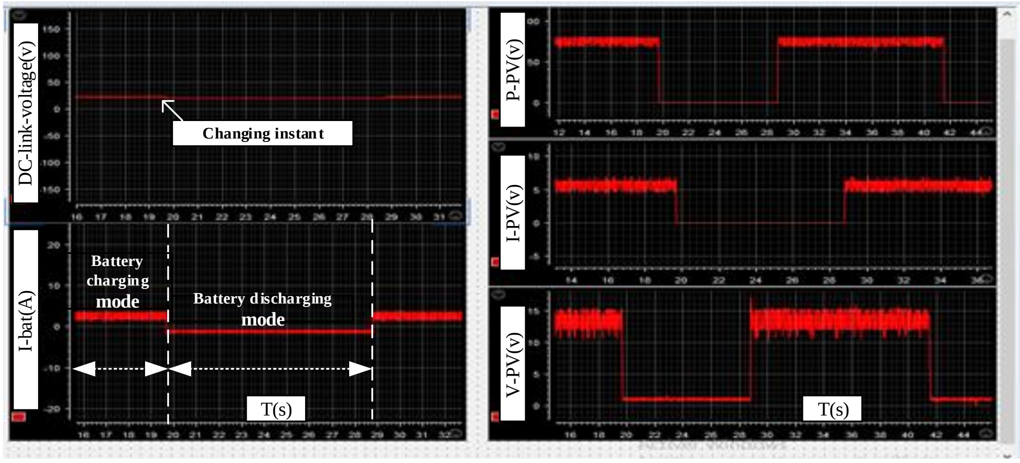


Figure 16. Battery current while charging and discharging

6. CONCLUSION

To address the unpredictable and intermittent nature of renewable energy sources, energy storage technology is crucial. Therefore, a buck-boost bidirectional converter has been designed and implemented in a dual battery application to facilitate the energy storage process. The driver and power converter boards have been designed to handle current and voltage stress on both sides, and the appropriate software has been utilized to create these boards. To evaluate the converter's capabilities in a microgrid, an experimental test was conducted. The buck-boost converter was used to regulate the DC bus voltage and charge/discharge the battery using dual control. The experimental results demonstrate that the converter design is capable of bidirectional energy transfer.

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