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Comparitive Study of Solar PV with Bidirectional C-U-K Converter for BESS

Vimala Devi V
CVR College of Engineering
Hyderabad, India
ORCID: 0009-0002-9428-9679

Udaya Bhasker Manthati
National Institute of Technology
Warangal, India
ORCID: 0000-0002-5919-4482

Abstract— Bidirectional DC-DC converters are pivotal components in hybrid energy storage systems, renewable energy integration, and electric vehicle applications. The effectiveness of these converters' hinges on the choice of control strategy, which governs the power flow between two DC sources. Key characteristics of the bidirectional Cuk converter include its ability to handle non-ideal input sources, low input current ripple, low output current ripple and reduced electromagnetic interference. These features make it more suitable for various power management scenarios, including battery charging and discharging, grid-tied energy systems, and hybrid power sources. This paper presents a comprehensive review of bidirectional Cuk converter for resistive loads, inductive loads and battery energy storage system with DC and solar PV input. Comparative analyses based on key parameters, such as load voltage, load current, input and output inductor currents and the ripple content, provide valuable insights for researchers in selecting the most suitable control strategy for their specific applications. The paper also sheds light on emerging trends and future research directions in bidirectional converter control, contributing to the advancement of power electronics and energy management systems.

Keywords—Bidirectional converters, Battery, Hybrid Energy storage, DC-DC Converter, ripples.

I. INTRODUCTION

Due to the scarcity of resources for energy generation, the usage of renewable power system is increasing. Meanwhile, the power generated by the renewable sources are mainly intermittent thereby inducing stability and regulated power supply issues in power system [1]. of all renewable energy generators, the solar-PV generators are more efficient as the emission rate and fuel consumption in that generators are very low compared to other resources. Also, it has high installation cost and low power generation and maintenance cost [2, 3]. Along with all these advantages the PV power generated is less intermittent than wind based power generator, which make the source more resilient than other sources [4, 5].

To stabilize the power flow with regulated voltage fluctuation [6], the battery is incorporated in DC power transmission [7]. Due to short term fluctuations in PV generators, the stress [8] across the battery increases leads to increased battery sizing [9]. Therefore the hybrid storage units are used such as superconducting magnetic energy storage, fuel cell, super capacitor etc. [10-12]. In case of DC microgrid application, the supercapacitor is much better than other storage device due to low loss [13, 14]. To make power more stable at demand side, the DC converter are used individually. Meanwhile, the individually connected parallel converters add-up the expensive and complex structure of power system hence, the multi-source converters are used. The bidirectional converter allows the power to get switch between storage and demand side, thus the power loss is highly minimized.

The bidirectional power flow is obtained by using full bridge three port converter [15] that make use of fuel cell for energy storage associated with PV system. While to obtain voltage regulation, a dual active bridge-LLC converter [16] was designed to operate on resonant frequency of DC-DC transformer. The power flow direction is controlled by a single-stage dual active bridge converter and main supply is utilized by LLC. The four-port soft switching converter [17] concerning the renewable system was used to have zero voltage switching. The stability was managed by using a battery bank with higher sizing. By reducing the inductance in the circuitry of converter, a bidirectional power converters [18] are designed for hybrid storage system. To obtain soft switching coupled inductors are used in the circuitry. The design was extended to apply in electric vehicle application [19] with model predictive control. As mentioned above number of multiport converter topology are available but the computation burden and reliability makes the system to get extended.

The following references provide dedicated converter settings for merging several sources: [20]–[23]. These articles primarily highlight the works' contributions to the design, investigation, and development of efficient control structures and schemes for power and energy management. On the other hand, the control structure becomes more complex, utilization decreases, costs increase, and efficiency decrease when a separate converter is needed for every source.

A Valve Regulated Lead-Acid (VRLA) battery, which is frequently used in electric vehicles and UPSs, will be examined in this study. The goal of this work is to compute the coulomb counting and battery discharge characteristic curve for the open circuit voltage method's comparison-based SoC estimation. This study also suggested a more effective method of testing power, in which the spent energy from the test battery's discharge would be utilized to charge a second fake battery or the battery at the output side. To improve test efficiency overall, a dummy battery will be utilized in parallel with the power supply once the test is over to replenish the testing battery. A dual-mode DC-DC converter with versatile conversion capabilities is required for the test system's implementation. Consequently, because bidirectional DC-DC Cuk converters have the same bidirectional characteristics as Buck-Boost converters and can convert in the same ratio, they can output a greater or lower voltage from a constant input. This architecture also has the benefit of having minimal current ripple at both the input and output [24]. When recharging the battery and obtaining a constant current value on the test side, the proportional-integral (PI) approach is utilized in the converter.

II. Mathematical Modeling

A. Mathematical modeling of PV Cell

PV systems directly convert solar energy into electrical energy. They are made up of PV modules, which are made up of solar cells, the smallest unit coupled in series and parallel combinations to generate desired power ratings. Figure 1 represents the one diode equivalent circuit of a photovoltaic cell, where R_s is the series resistance of the cell, which is typically very low value, and R_{sh} is the shunt resistance of the cell, which is typically considered as a very large value. I_D is the diode current, whereas I_{PH} stands for cell photocurrent, which is the direct current produced by the photovoltaic effect. I and I_{SH} are the cell's output current and current through shunt resistance, respectively.

$$I = I_{PH} - I_D - I_{SH} \tag{1}$$

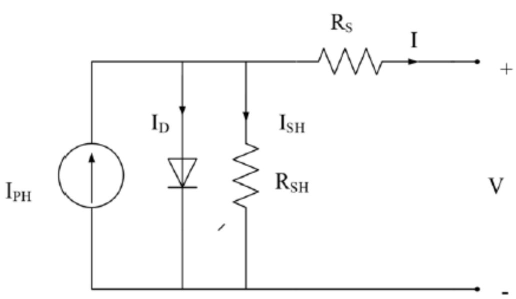

Fig. 1. Equivalent circuit of PV Cell

$$I_D = I_0\left[\exp\left(\frac{V+IR_S}{nV_t}\right) - 1\right] \tag{2}$$

By ohm's law,

$$I_{SH} = \frac{V+IR_S}{R_{SH}} \tag{3}$$

Substituting Equation (2) & (3) in Equation (1)

$$I = I_{PH} - I_0\left[\exp\left(\frac{V+IR_S}{nV_t}\right) - 1\right] - \frac{V+IR_S}{R_{SH}} \tag{4}$$

Where $V_t = \frac{kT}{q}$ and V_t = thermal voltage (0.0259 V at 25°C), k = Boltzmann constant (1.3805 × 10^{-23}J/K), T = absolute temperature (°C), q = elementary charge, n = diode ideality factor (1 for an ideal diode), and I_0 = reverse saturation current(ampere).

The MPPT-controlled DC/DC boost converter is used to maximize the power extracted from the solar resources and so raise the PV system's efficiency. The perturb and observe (P&O) method is a popular maximum power point tracking (MPPT) technique for photovoltaic (PV) systems. It works by varying the duty cycle of a DC/DC boost converter to attain the desired maximum power. Using the P&O approach, the PV system's actual output power (PPV) is calculated after measuring its voltage (VPV) and current (IPV). Next, the working PV voltage is slightly perturbed to track the change in PPV. If power is increased, the operating point of the PV system is shifted in the same direction, otherwise the operating point is shifted in the opposite direction until maximum power point reached ($dP_{PV}/dV_{PV} = 0$).

III. Bidirectional Cuk Converter Design

A Bidirectional Cuk Converter is a modified conventional Cuk converter that can allow the flow of current in two directions and bidirectional operation is obtained by replacing the diode in the conventional circuit with MOSFET. The output of bidirectional Cuk converter is inverted output similar to the output of Buck-boost converter with an added advantage of low current ripple at the input and the output. Because of low input and output ripples Cuk converter is more suitable for the applications related to solar PV and batteries.

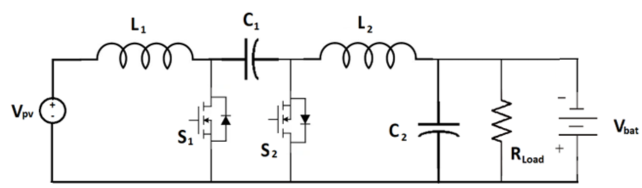

Fig. 2. Bidirectional Cuk Converter with battery load

A. Mode 1:

Initially when Switch S_1 is ON and Switch S_2 is OFF, inductor L_1 charges and no current flows through the load and battery as shown in figure 3, hence output voltage is zero.

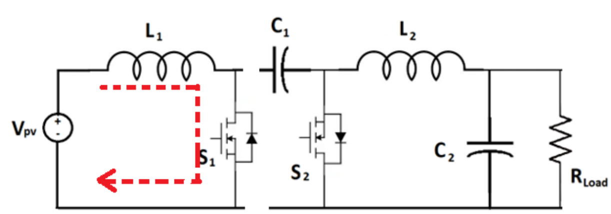

Fig. 3. Mode 1 circuit operation with S_1 ON and S_2 OFF

And the inductor current is given by

$$I_{L1} = \frac{P_s}{V_s} \tag{5}$$

B. Mode 2:

when Switch S_1 is OFF and Switch S_2 is ON, inductor L_1 starts discharging through S_2 and it charges the capacitor C_1 to

V_s+V_0.. In this mode, there is no current flow through the load and battery as shown in figure 4, hence output voltage is zero.

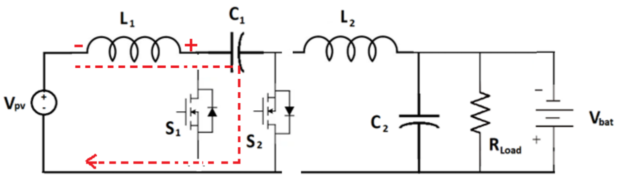

Fig. 4. Mode 2 circuit operation with S_1 OFF and S_2 ON

C. *Mode 3:*

When Switch S_1 is ON and Switch S_2 is OFF again, inductor L_1 charges, capacitor C_1 starts discharging through S_1 and current flows through the load and battery which charges the inductor L_2 as shown in figure 5.

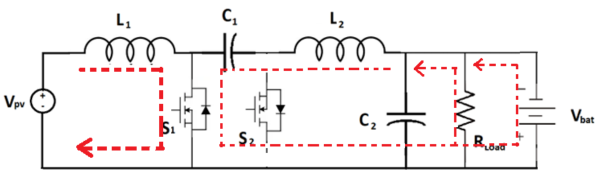

Fig. 5. Mode 3 circuit operation with S_1 ON and S_2 OFF

The value of inductor current is given by,

$$I_{L2} = \frac{P_0}{-V_0} \tag{6}$$

D. *Mode 4:*

when Switch S_1 is OFF and Switch S_2 is ON again, inductor L_1 starts discharging through S_2 and it charges the capacitor C_1 and inductor L_2 discharges through S2 as shown in figure 6.

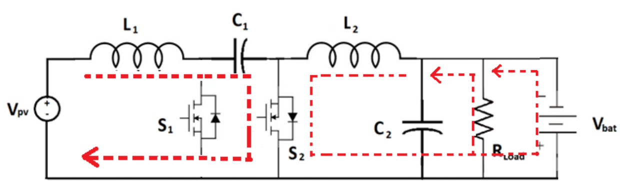

Fig. 6. Mode 4 circuit operation with S_1 OFF and S_2 ON

E. *Calculation of Design parameters*

The suitable values of Inductor L_1, L_2, Capacitor C_1 and C_2 can be calculated by considering the percentage ripple and switching frequency as,

Ripple current magnitude of L_1 and L_2 are calculated as,

$$\Delta I_{L1} = (\%\ Ripple) * I_{L1} \tag{7}$$

$$\Delta I_{L2} = (\%\ Ripple) * I_{L2} \tag{8}$$

The value of Inductor L_1 and L_2 can be calculated as,

$$L_1 = \frac{V_S D}{\Delta I_{L1} f_{sw}} \tag{9}$$

$$L_2 = \frac{V_S D}{\Delta I_{L2} f_{sw}} \tag{10}$$

The values of C_1 and C_2 can be calculated as,

$$C_1 = \frac{V_S D}{R f_{sw} \Delta V_{C1}} \tag{11}$$

$$C_2 = \frac{1-D}{8L_2\left(\frac{\Delta V_0}{V_0}\right) f_{sw}{}^2} \tag{12}$$

F. *Perturb and Observe Algorithm*

Perturb and Observe method is used for tracing maximum power from solar PV

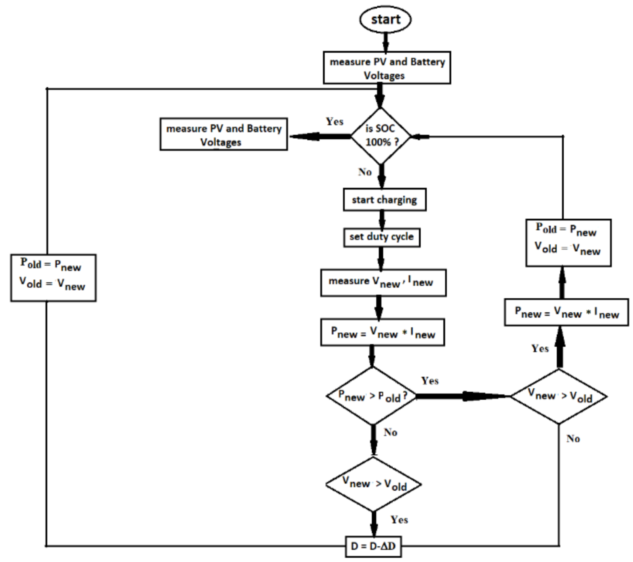

Fig. 7. Flowchart of P&O Algorithm

IV. MATLAB IMPLEMENTATION AND HARDWARE SETUP

The Proposed bidirectional Cuk converter is implemented using MATLAB Simulink with fixed DC and with Solar PV inputs. Figure 8 shows the simulation of bidirectional Cuk converter with DC input and Battery load and figure 9 shows the simulation of bidirectional Cuk converter with solar PV input and Battery load.

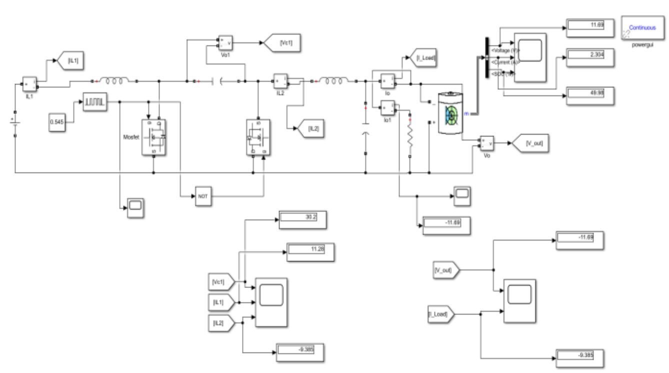

Fig. 8. Simulation of Bidirectional Cuk Converter with DC Input

Closed loop control is implemented for bidirectional Cuk converter with solar PV input. Switching pulses for switches S_1 and S_2 are generated using P&O algorithm along with MPPT tracking from PV panel. The same is verified with experimental setup as shown in figure 10.

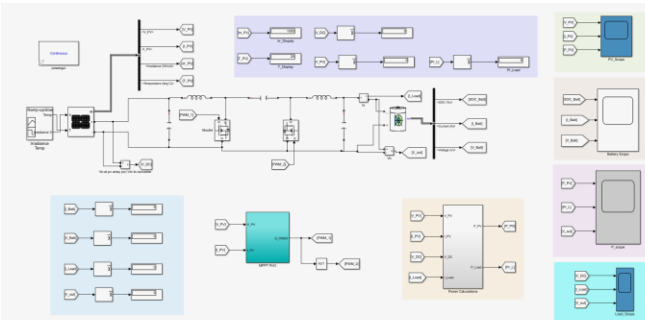

Fig. 9. Simulation of Bidirectional Cuk Converter with solar PV Input

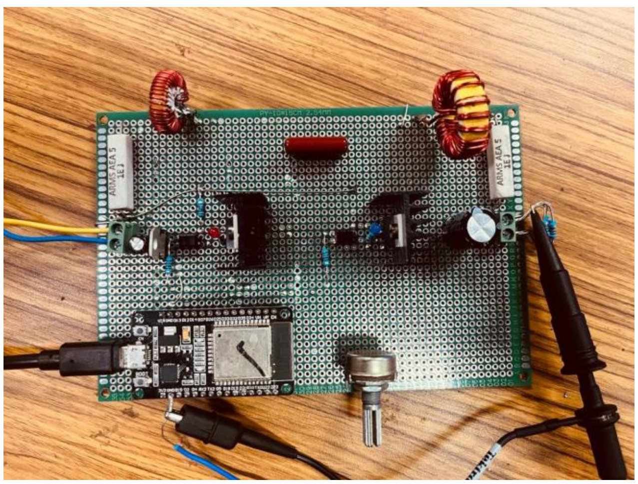

Fig. 10. Experimental setup of Bidirectional Cuk Converter with solar PV Input

V. RESULTS AND DISCUSSION

Simulation results of bidirectional Cuk converter with DC input for Inductor current, capacitor voltage, load voltage , battery parameters and load currents are as shown in figure 11, 12 and 13.

Fig. 11. Capacitor Voltage, Inductor L_1 current and L_2 Current

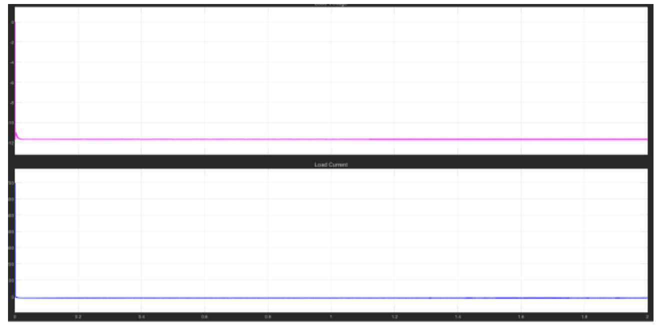

Fig. 12. Output voltage and Output current

Fig. 13. Battery voltage, Battery current and SOC

Simulation results of bidirectional Cuk converter with solar PV input with changes in irradiance conditions are shown in figure 14, 15 and 16. For 0 to 0.5 sec Irradiance is maintained as 100%, from 0.5 to 1.2 sec Irradiance is maintained as 50% and from 1.2sec to 2 sec Irrandiance is taken as 80% with constant temperature of 25 degree celsius.

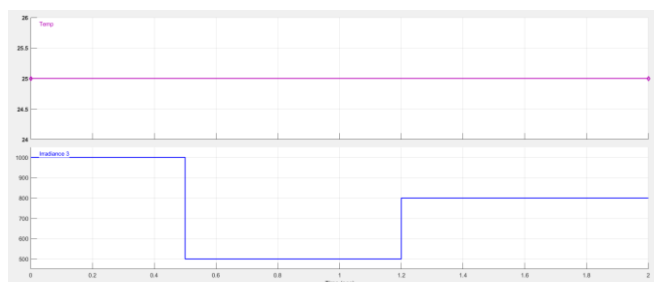

Fig. 14. Temperature and irradiance levels of Solar PV

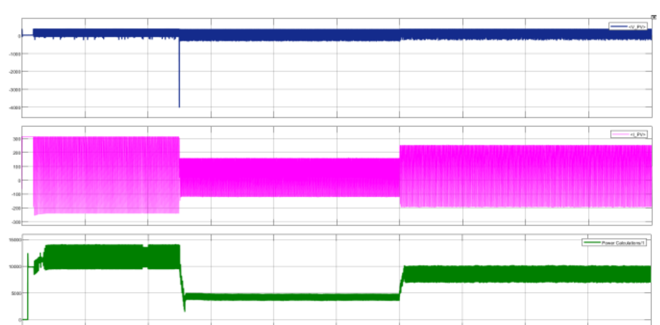

Fig. 15. Voltage, current and Power of Solar PV Panel

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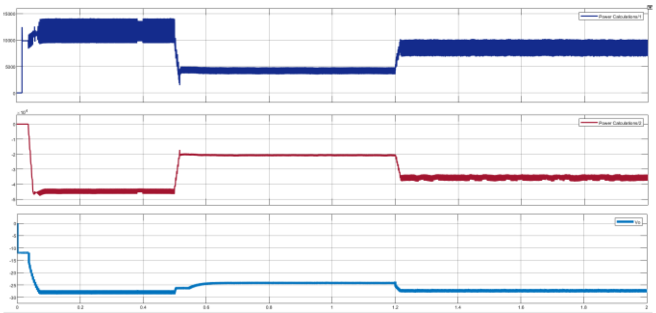

Fig. 16. PV power, Load power and load Voltage of Solar PV Panel

Initial state of charge of battery is considereed as 50%.

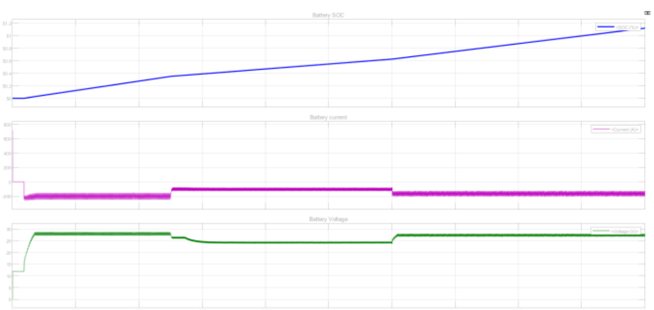

Fig. 17. Battery SOC, Bttery Current and Battery Voltage

TABLE I. SPECIFICATIONS OF HARDWARE SETUP

Parameters	Values
DC input	25V
Inductance L_1	820μH
Inductance L_2	680μH
Capacitance C_1	8μF
Capacitance C_2	3.33μF
MPP Voltage	24V
Battery Voltage	24V
Battery capacity	14Ah

VI. CONCLUSION

This article describes the development and testing of a proposed bidirectional Cuk converter configuration and control framework for the PV and batteries under various operating conditions. Only when the battery's state of charge (SoC) is between 20% and 80% does energy storage provide the necessary power. Energy storage only started to draw power when the battery's state of charge was below 20%. Additionally, the suggested system complies with the desired guidelines for renewable energy sources and ESU, including operating at the maximum power point and utilizing a battery that can meet the average power consumption.

The system performed satisfactorily through variations in PV and load. The primary benefit of the suggested approach is low input and output ripple content combined with a simpler control stage. proposed bidirectional converter configuration, will be considered as future work for integrating hybrid energy storage systems with various control techniques for optimal performance of converter with proper power balance between ESUs.

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