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Switched Capacitor-Based Bidirectional Power Converter with Enhanced Voltage Boost and Reduced Switching Strain for Electric Vehicle Applications

G Hari Krishnan[1]*, B V Sai Thrinath[2], G. Karthikeyan[3], V. Ravi[4], and E Parimalasundar[5]

[1,2]Sree Vidyanikethan Engineering College, Mohan Babu University, Tirupati, India; [1]haris_eee@yahoo.com, [2]connectbvst@gmail.com
[3]Department of EEE, Sona College of Technology, Salem, Tamil Nadu, India, karthikeyang@sonatech.ac.in
[4]Department of Electrical and Electronics Engineering, K.S.R. College of Engineering, Tiruchengode, Tamil Nadu, India, ervravi@gmail.com
[5]Sree Vidyanikethan Engineering College, Mohan Babu University, Tirupati, India

***Correspondence:** G Hari Krishnan; haris_eee@yahoo.com

ABSTRACT- This research work presents an improved design of a bidirectional converter for EVs, specifically focusing on its buck and boost operations. The proposed design incorporates a switched capacitor-based double switch converter, which offers enhanced performance compared to conventional converters. The utilization of switched capacitors reduces voltage stress on switches and improves overall efficiency, making it well-suited for electric vehicle applications. Moreover, the inclusion of synchronous rectification enables zero voltage switching, further enhancing the converter's performance. The effectiveness of the design is verified through MATLAB simulations, demonstrating improved voltage gain and reduced switch stress in both voltage increasing and decreasing modes.

Keywords: Bidirectional converter; Switched capacitor; Voltage stress reduction; Efficiency improvement; Synchronous simulations; Electric vehicles; MATLAB.

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1. INTRODUCTION

The increasing depletion of fossil energy sources and the urgent need for sustainable power solutions have propelled the development of renewable energy sources. However, integrating wind and tidal power, into the electrical grid and using them to power electric vehicles (EVs) pose significant challenges. One of the key components required in EVs is a high-performance bidirectional DC-DC converter [1-3]. This converter is responsible for converting the voltage from the battery to a suitable level for the EV's motor and vice versa. The proposed work aims to address the limitations of existing converters and develop an improved bidirectional DC-DC converter for EVs, specifically focusing on buck and boost operations [4-5].

Over the years, various DC-DC converter topologies have been developed and studied. These include double-stage control conversion systems, two-stage non-isolated converters, and integrated inductor converters [6]. However, these converters have their limitations. For example, converters using leakage inductance suffer from non-positive effects, while integrated inductor converters require additional components and increase system complexity. Switched capacitor-based converters have shown potential for achieving high voltage gain with improved efficiency. However, there is still a need for further advancements to overcome the challenges associated with voltage stress and losses in existing converters [7-9].

By employing a double switch arrangement, the converter effectively minimizes voltage stress and losses on the electronic switches. This innovative design not only simplifies the overall structure but also enhances the output voltage gain while reducing the number of switches required. The ultimate aim of this work is to create a high-performance bidirectional power converter that overcomes the limitations of existing designs and offers enhanced voltage gain, efficiency, and reliability specifically tailored for electric vehicle applications.

In the study conducted by [10], the challenges associated with significance of efficient DC-DC converters in EVs are highlighted. The researchers emphasize the necessity of high voltage gain converters to facilitate efficient energy transfer and propose the utilization of switched capacitor converters as a means to enhance overall performance. Another research endeavor, documented in [11], focuses on the exploration of double-stage control conversion systems for bidirectional power flow in EVs. Various converter topologies are compared and evaluated in terms of their efficiency and voltage gain performance.

Switched capacitor converters are the primary subject of investigation in [12]. The paper thoroughly discusses the operational principles and advantages associated with switched capacitor converters, including the reduction in component count and improved efficiency. The integration of inductor converters for bidirectional power flow in EVs is examined in [13-14]. The collective insights garnered from these studies significantly contribute to the existing literature on bidirectional power converters, switched capacitor converters, and high voltage gain converters [15-16]. They provide valuable knowledge pertaining to the challenges encountered in the pursuit of efficient power conversion in EVs, propose novel converter topologies, and validate their performance through experimental and simulation data. The findings from these studies serve as vital references for the proposed work, which seeks to develop an improved bidirectional DC-DC converter for EVs, characterized by enhanced voltage gain, reduced voltage stress, and increased overall efficiency.

2. MATERIALS AND METHODS

The proposed topology consists of two inductors (L), two capacitors (C), and three power switches (S_1, S_2, and S_3) along with a load (R). This converter operates in dual modes, allowing for efficient power transfer in different scenarios. In step-up operation, the excess power generated from the source is transferred to the load. By switching on S_1 and turning off S_2 and S_3, the voltage stress is minimized.

The voltage gain, which represents the increase in output voltage compared to the input voltage, can be calculated using the formula.

$$\frac{V_{high}}{V_{low}} = \frac{[1 - d_{Boost}]}{d_{Boost}} \qquad (1)$$

In step-down mode, when there is an excess of power generated from the load, it is efficiently transferred back to the source. This is achieved by activating switch S_3 and deactivating switches S_1 and S_2, resulting in a reduction of the voltage. Thus, the converter dynamically adapts its operation to efficiently handle power flow in both step-up and step-down scenarios, ensuring effective energy transfer between the source and the load. The voltage gain, which represents the decrease in output voltage compared to the input voltage, can be calculated using the formula.

$$\frac{V_{low}}{V_{high}} = \frac{[1 - d_{Buck}]}{d_{Buck}} \qquad (2)$$

Built-in isolated two-port DC-DC battery system converter used in this work as shown in *figure 1* comprises an inductor L_1 and L_2, controls S_1, S_2, and S_3, and capacitor C_s. When the supply is given in the input, the supply passes from the source to the load, which is from the C low to C high. In the voltage increasing approach, when the excess drive is created over the source to load, the current passes from the U_{low} to U_{high} by turning on and off between the switches S_1, S_2, and S_3. In this system, current permits from source to load, and the action of the switches is controlled to achieve the desired voltage gain. The figure also shows the equations used to calculate the current stress of S_1 and S_2 switches.

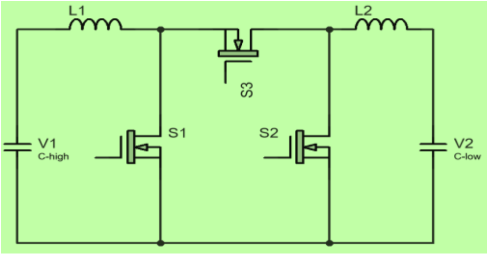

Figure 1: Built-in isolated two-port dc–dc battery system converters

When operating in the step-up mode, where the voltage is increased, the voltage stress on switch S_1 and capacitors C_1 and C_2 can be estimated at approximately half of the high-side voltage, as indicated by equation (1). This reduction in voltage stress plays a crucial role in ensuring the safe operation of the switches while also minimizing losses and enhancing the converter's overall efficiency. It safeguards the components from excessive strain, allowing them to operate optimally and prolonging their lifespan. Moreover, the reduced voltage stress contributes to enhanced system reliability, making the converter a robust solution for various applications requiring efficient voltage conversion. By keeping the voltage stress at a lower level, the proposed converter demonstrates improved performance and increased reliability in various applications, including electric vehicles.

$$V_{stress\_s1} = V_{stress\_c1} = V_{stress\_c2} \approx \frac{V_{high}}{2} \qquad (3)$$

$$V_{stress\_s2} = V_{stress\_s3} = V_{stress\_c1} = V_{stress\_c2} \approx \frac{V_{high}}{2} \qquad (4)$$

The proposed converter topology incorporates an analysis of the current stress on the switches using the ampere-second balance principle. In the step-up mode, the current stress on switch S1 is evaluated by considering the ampere-second balance among capacitors C_1, C_2, and the high-side current (I_{high}), as depicted in equation (3). Moreover, the duty cycle of the boost converter, referred to as d_{Boost}, is taken into account to accurately assess the current stress. Similarly, in the step-down mode, the current stress on switch S1 is calculated utilizing the ampere-second balance principle, taking into consideration the duty cycle of the buck converter (d_{Buck}). By applying this meticulous analysis, the current stress imposed on the switches is substantially minimized, thereby augmenting the reliability and longevity of the converter while upholding efficient power flow. This comprehensive approach ensures the optimal performance and robustness of the converter design.

$$I_{stress\_s1} \approx \left[\frac{I_{high}}{2}\right] \times [1 - d_{Boost}] \qquad (5)$$

$$I_{stress\_s1} \approx \left[\frac{I_{high}}{2}\right] \times [1 - d_{Buck}] \qquad (6)$$

The ampere-second balance principle, with reduced stress compared to conventional converters. These characteristics provide valuable insights into the converter's performance, reliability, and efficiency, making it a promising solution for bidirectional power flow in various applications, including electric vehicles.

The *table 1* encompasses crucial details such as the input voltage (U_{low}), output voltage (U_{high}), switching frequency (Fs), inductance (L), capacitance (C), and resistance (R) values of the components utilized in the simulation. This comprehensive overview of the parameters ensures a detailed understanding of the converter's behavior and performance under various operating conditions. By analyzing these parameters, researchers can gain valuable insights into the converter's efficiency, voltage gain, and overall performance. The simulation circuit includes both the aggregate (Boost converter) and declining (Buck converter) modes, utilizing components selected from the MATLAB Simulink library for accurate representation.

Table 1: Specifications of Simulation parameters

Parameters	Standards
Power Ps	300W
Capacitors Clow and C high	200 µF
Switched Capacitors C_1	200 µF
Load side U_{high}	100 µH

Table 1 also presents essential details such as the duty cycle values (d_{Boost} and d_{Buck}) and the voltage stress on the switches (Vstress_S_1, Vstress_S_2, and Vstress_S_3). These parameters play a vital role in evaluating the efficiency, voltage gain, and current stress of the switches within the proposed converter. By utilizing these simulation factors, a thorough assessment of the converter's performance can be conducted.

3. RESULTS AND DISCUSSION

The simulation setup in MATLAB Simulink employed components sourced from the MATLAB/Simulink library to construct a comprehensive simulation rig. *Figure 2* illustrates Simulink model of proposed converter. The simulation parameters used in the analysis are summarized in *table 1*. Specifically, in the increasing mode, the simulation results demonstrated a gradual increase in the output voltage (U_{low}) from 0V to 40V within the initial 2 seconds, facilitated by the soft start circuitry. Subsequently, the output voltage continued to rise steadily, reaching a value of 300V. Correspondingly, the input voltage (U_{low}) also experienced a rise from approximately 0V to 40V. *Figure 3* illustrates the capacitor voltages (UC_1 and UC_2) corresponding to the power voltage levels of U_{high} = 300V and U_{low} = 40V. Furthermore, *figure 4* depicts the voltage waveforms of the developed converter in the increasing mode, providing an in-depth visual representation of the voltage behavior during operation.

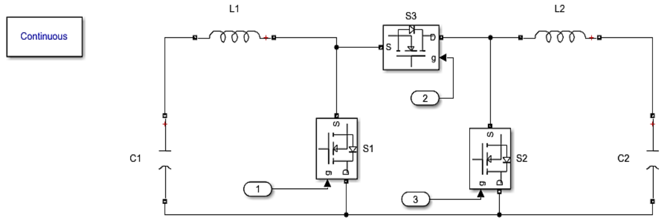

Figure 2: Simulink model of proposed converter

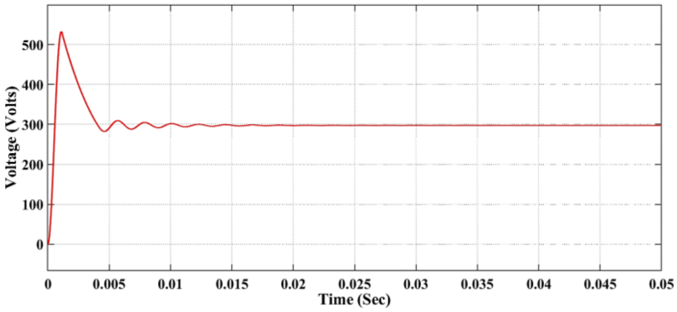

Figure 3: Input voltages from switched capacitor in increasing mode

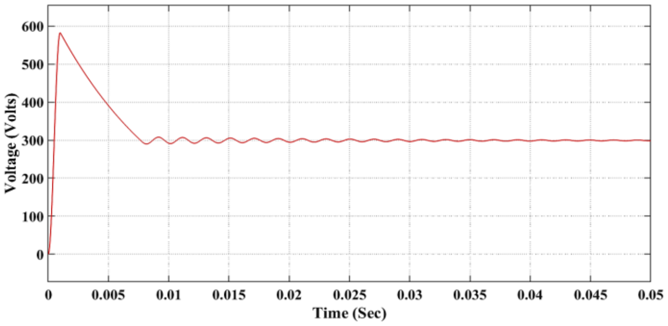

Figure 4: Output voltages in developed converter

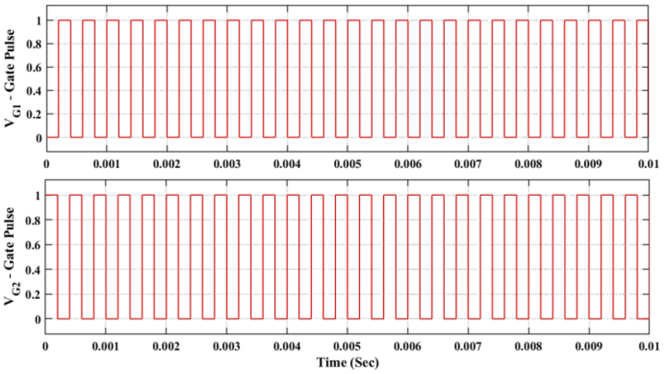

Figure 5: (a) V_{S1} – Pulse and (b) V_{S2} - Pulse

The operation of the buck converter with U_{low} = 40V and U_{high} = 300V, d_{Boost} = 0.26, and capacitor C_2 experienced a voltage stress. *Figure 5 (a) and (b)* illustrate the S_1 and S_2 pulse generation of proposed DC converter. In the decreasing mode of the proposed converter, it was found that the stress on the switches and capacitors is approximately half of the high-side voltage (U_{high}), which amounts to 150V in this case.

This observation indicates that the stress experienced by the switches and capacitors is effectively limited to half of the high-side voltage. The corresponding output voltage waveform in the decreasing mode can be seen in *figure 5*, while the input voltage waveform is presented in *figure 7*. Moreover, the capacitor voltages (V_{c1} and V_{c2}) during the decreasing mode are depicted in *figure 8(a)* and *figure 8(b)*, respectively, providing a visual representation of their behavior throughout the operation. *Table 2* illustrates the simulation design parameters of boost converter.

Table 2: Simulation design parameters of boost converter

Specifications	Standards
Duty cycle	92%
ON-OFF Frequency	4500 Hz
Output power	1.52 kW
Input voltage	100 Volts
Ripple in capacitor voltage	30%
Ripple in inductor current	5%

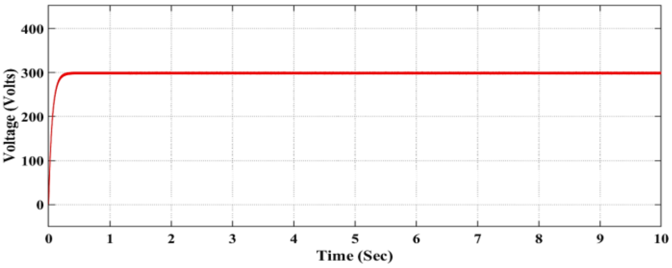

Figure 6: Output voltage in the decreasing mode

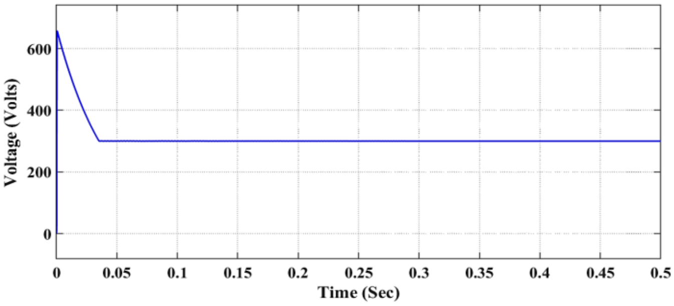

Figure 7: Input voltage in the decreasing mode

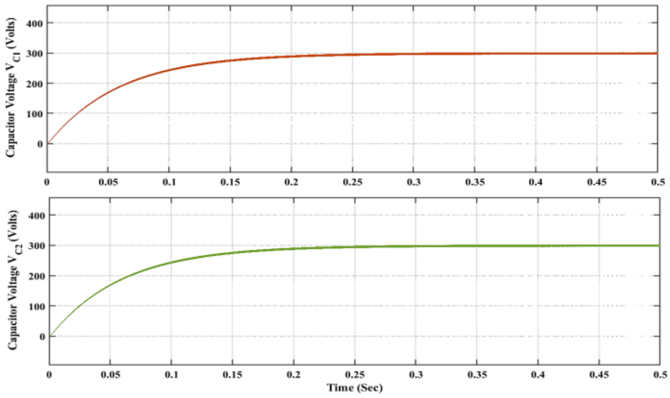

Figure 8: (a) Capacitor voltage V_{C1} in decreasing mode and (b) Capacitor voltages V_{C2}

The simulation provides valuable insights into the performance and voltage behavior of the converter, supporting its potential application in various systems requiring bidirectional power flow.

Table 3: Summary of Simulation Results

Parameter	Output
Output Voltage (U_{low})	Starts at 0V, reaches 40V in 2s, peaks at 300V
Input Voltage (U_{low})	Rises from 0V to 40V
High-side Voltage (U_{high})	300V
d_{Boost} Value	0.26

The key results obtained from our simulation work were summarized in *table 3*. It shows how the output voltage (U_{low}) starts at 0V, gradually increases to 40V within the initial 2 seconds, and eventually reaches 300V. The input voltage (U_{low}) also rises from 0V to 40V, with Capacitor C2 experiencing voltage stress, and a d_{Boost} value of 0.26 used in the simulation. The simulation results indicate that the developed converter topology shows promise in achieving higher performance compared to conventional converters. It focuses on reducing stress on switches, which can lead to longer component lifespan. The bidirectional capability of the converter makes it versatile and suitable for various application scenarios, ensuring continuous operation in different modes. The simulations suggest increased efficiency while subjecting components to less voltage stress, which can enhance their durability and lifespan. To further enhance efficiency, future extention of this work could involve optimization and the integration of advanced control algorithms into the converter design.

4. CONCLUSION

The results of the simulation support the recently developed converter topology's higher performance in comparison with conventional converters, with a focus on switch stress reduction. This device is adaptive for a number of application scenarios thanks to its bidirectional capability, which guarantees continuous functioning in different modes. The simulations further indicate that the proposed converter achieves increased efficiency while subjecting components to less voltage stress, hence increasing their ability to last. In order to uncover even bigger efficiency advantages, the future scope entails more optimization and the integration of advanced control algorithms. In result, the proposed converter design represents an extremely promising approach to high-performance and efficient DC-DC power conversion, offering improved overall performance and efficiency with a fascinating future for future improvements.

Conflicts of Interest: The authors declare no conflict of interest.

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