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Design and Optimization of High-Gain DC-DC Converters with Switched Capacitor for Solar Applications

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Abstract: *The growing need for efficient and compact power conversion systems in Photo Voltaic (PV) energy harvesting has driven the investigation into high-gain topologies that can elevate voltage levels. The proposed converter incorporates a Switched Capacitor (SC) mechanism to achieve high conversion efficiency and increased output voltage gain, solving the problem of Solar Panels (SP) low voltage output in an efficient manner. The optimization strategy aims to minimize energy losses, enhance the converter's dynamic performance, and improve its stability under varying load and input conditions. A thorough examination of the converter's operation is provided, along with simulations and comparisons to conventional DC-DC converters, showcasing superior voltage conversion efficiency and system reliability. This paper outlines the design and optimization of high-gain DC to DC converters with a SC mechanism for solar energy applications, presenting a promising approach to enhancing solar power system performance and contributing to more efficient and sustainable energy use in renewable energy applications.*

Keywords: *DC-Dc converters, photovoltaic energy, Power systems, Capacitor.*

1. INTRODUCTION

Switched-mode power converters are widely adopted due to their smaller size and higher efficiency compared to traditional power sources. The advantages of SMPS, such as reduced size and weight, make them essential for space applications. Current space research organizations are focused on developing power supplies that are lighter, more compact, more efficient, cost-effective, and highly reliable [1]. Satellites' electrical power systems incorporate a variety of dc/dc converters. Satellite-based dc/dc converter topologies differ from terrestrial ones in terms of their architectural features [2]. The forward converter is a popular topology for separated output voltage and low-power applications due to its small transformer size, straightforward design, and high efficiency [3]. Nevertheless, there is a chance that these converters could demagnetise. Strategies for resetting the transformer include adding a second reset winding or creating a snubber circuit [4].

This innovative DC to DC converter with a step-up gain that combines a Regenerative Boost (RB) and SC has generated a lot of exploration. By merging the advantages of switching capacitor techniques with a RB setup, this unique converter design addresses the challenges of low-voltage and fluctuating output conditions in Solar PV (SPV) systems. As a result, voltage conversion ratios are significantly improved, facilitating the efficient transfer of energy across capacitors. Additionally, the RB configuration enhances energy efficiency by capturing and reusing energy that would otherwise be wasted.

For renewable energy systems, one of the most effective and intriguing options is the dc-dc converter. Solar and wind energy conversion systems commonly have considerable voltage differences between their output and grid voltages. After the stage of Voltage Source Inverter (VSI), the AC voltage is usually increased by employing a transformer, ensuring the grid synchronization requirements are met. However, the inclusion of a 50 Hz transformer results in increased system volume, higher energy losses, and larger size, ultimately reducing overall efficiency, particularly in challenging environmental conditions. Figures 1(a) and 1(b) show a simplified block diagram of a common grid-connected SPV system.

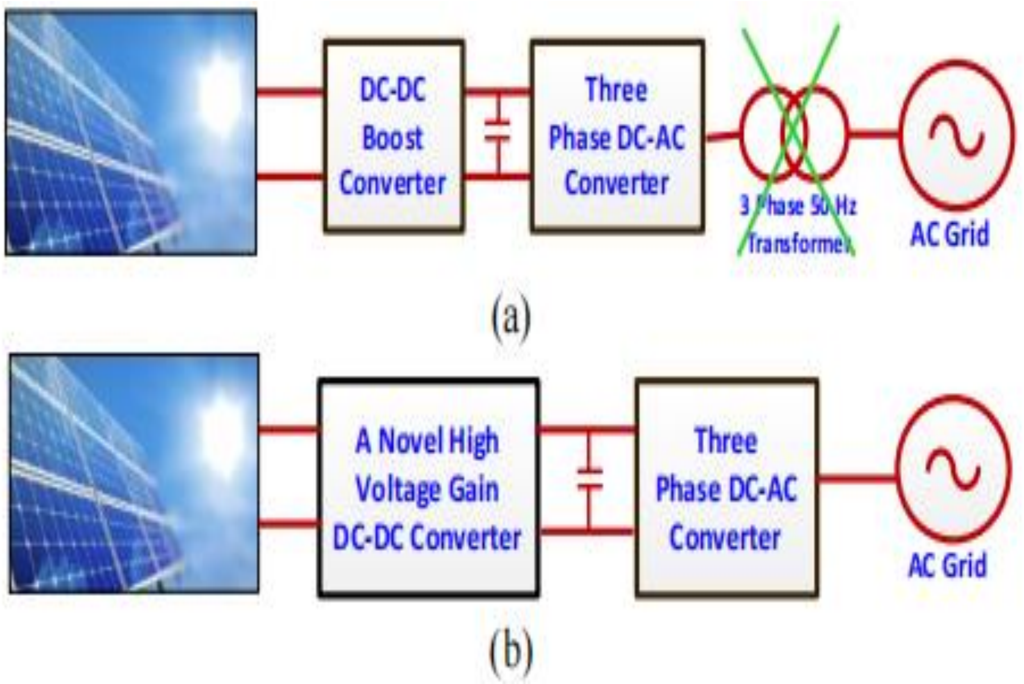

FIGURE 1. Block diagram of the conventional grid-connected SPV system

Higher DC voltage gain was achieved by adapting classic boost-type converters into derived topologies. Performance under transient conditions is hampered by the need to run at a lower duty cycle in order to accommodate a greater conversion ratio. A harmonic enhanced resonance converter was suggested as a way to increase DC voltage gain; however, the resonant nature necessary for the improved functioning makes its design complicated. Several reconfigurable converters based on dual coupled inductors and single inductors have been reported, which can operate efficiently under transient conditions. However, these converters generate Electro Magnetic Interference (EMI), require more devices, and need additional snubber circuits to mitigate energy stored in leakage inductance.

The proposed ultra-high gain converter with minimum voltage stress does not deliver a DC voltage gain sufficient to satisfy the DC link voltage requirements. The market has seen the introduction of galvanically isolated DC to DC converters in order to attain the necessary conversion ratio. However, there are drawbacks to these converters, such as increased size and volume, EMI issues, and high voltages on the main switches.

The foundation for analysing the key features and advantages of the proposed converter design is set in this introduction, which underscores its potential to improve the effectiveness and efficiency of solar photovoltaic technology [5]. Advanced DC-DC converters are seen as essential for unlocking solar power's full potential, aiding in the transition to a cleaner, more sustainable energy future as renewable energy solutions gain global traction. Among these converters, SC converters are widely recognized as the most common method for achieving unlimited gain. Significant improvements in DC voltage gain are achieved when integrated with traditional boost-type converters. However, an increase in the reactive components of the converter is necessary to obtain higher DC voltage gain. For a comprehensive comparison of SC-based converters, it is crucial to consider factors like the number of reactive elements, device stress, and DC voltage gain to provide meaningful insights for researchers.

2. LITERATURE REVIEW

Rao and Kumar have conducted a detailed analysis of previous research on high step-up gain DC to DC converters that use switching capacitors and RB methods for improved SPV applications. They highlight the crucial role of SPV systems in renewable energy integration and stress the increasing need for efficient energy conversion solutions. Their analysis underscores the importance of DC-DC converters in optimizing solar energy extraction. The study points out that conventional converters face challenges such as energy inefficiencies, fluctuating output conditions, and limited voltage conversion effectiveness. The authors go on to discuss the advantages of RB setups as well as the SC techniques in power electronics: its theoretical foundations and practical applications. Along with discussing performance enhancements, design difficulties, and practical ramifications, they also look at numerous research and real-world applications of these strategies in high step-up converters for SPV systems [6].

Zhu et al. have proposed that distinct features characterize different DC-DC converter topologies, each presenting unique strengths and limitations. They argue that selecting an appropriate converter topology requires a holistic evaluation, emphasizing the importance of power conversion efficiency. According to their findings, prioritizing efficiency minimizes energy losses and enhances the overall performance of Electric Vehicle (EV) systems. Furthermore, cost-effectiveness and size constraints are deemed essential, ensuring the converter's practical compatibility with EV requirements. The authors also stress the significance of reliability, particularly for EV applications, where stability and durability are critical [7].

Kumar and Balakrishna., have observed that employed to increase the voltage of PV sources, high step-up DC-DC converters are, facilitating maximum power point tracking. Used often for this purpose, conventional boost converters are, they note, but experience on both the diode and the switch, voltage stress, equivalent to the output voltage. Such stress, they argue, renders them unsuitable for high voltage gain scenarios, as excessive duty cycles lead to increased conduction and switching losses. Furthermore, causes significant reverse recovery issues, the brief conduction time of the output diode does [8].

A boost converter with a dynamic switching inductor design has been developed by Sadaf et al., who note its advantages, which include steady input current, reduced voltage ratings for passive components, and less voltage stress across the diode. The authors ascribed the differences between practical and theoretical results to the parasitic resistivity of different components, which reduces efficiency, with a gain of 4/(1-D) [9].

Pourfarzad., have described a transformer-less boost-based DC-DC converter, emphasizing that by incorporating additional interleaving stages, significantly reduced can be the peak voltage stress on components [10]. Chandrasekar et al. have analysed the DC-DC buck-boost converter, noting that elevated switching losses contribute to the numerous switches [11]. Ahmad et al. have presented a non-inverting DC-DC converter, designed to achieve higher voltage gain while imposing minimal stress on switches. A voltage gain expressed as (3+D)/(1-D) is offered by this symmetrical configuration, simplifying component selection [12].

3. RESEARCH METHODOLOGY

The research methodology centers on exploring high-gain DC-DC converters and the implementation of switched capacitors in solar energy systems. Following a comprehensive review, a novel converter topology has been introduced, incorporating switched capacitors to achieve enhanced voltage gain. The design process includes selecting suitable components such as inductors, capacitors, and switches, along with developing a control circuit. A prototype of the proposed converter is built and evaluated using a solar panel emulator to mimic real-world solar input conditions. Key performance parameters, including efficiency, voltage regulation, and dynamic response, are assessed. The findings are analyzed and compared with conventional DC-DC converters, highlighting notable performance improvements. Experimental results validate the effectiveness of the proposed design. Conclusions are drawn from the results, and potential areas for future advancements are identified.

Proposed High-Gain DC-DC Converter with SCRB

As mentioned previously, enhancing DC voltage gain is significantly impacted by SC-based networks. Regenerating the boosted voltage is the fundamental approach of this study, achieved through the combined use of switched capacitors and inductors during the switches' on-state. During the off-state, stored energy in the reactive elements is released in a cascaded manner. This operation enables the converter proposed to achieve a higher DC voltage gain significantly.
Depicted in Fig. 2 is the circuit diagram of the proposed high-gain DC-DC converter. Two active switches, S1 and S2, are incorporated into the design. For the boost operation, inductor L1 and capacitor C1 are employed. According to the proposed topology, the voltage is regenerated and boosted, stored subsequently in inductor L2 and capacitor C2. By switches S1 and S2, the energy stored in these components is regulated.

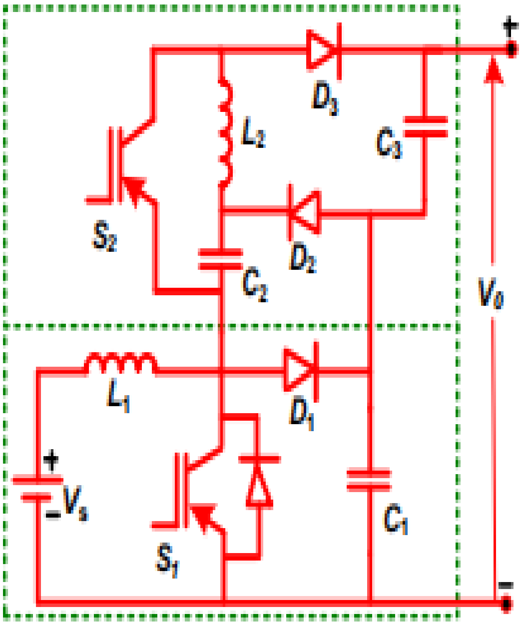

FIGURE 2. Single-stage transformer less dc-dc converter

A high step-up DC to DC converter architecture with switching capacitors and regenerated boost is developed for SPV applications in order to achieve the desired output voltage.

To start the converter function, the switches are initialised at a low-duty cycle. Initial configuration parameters include control gain values, current restrictions, and voltage references. When the output voltage is measured in relation to the reference voltage target, a Proportional-Integral (PI) controller uses the voltage deviation to produce an error signal.

The converter, which is made up of five diodes, two switches, capacitors, and inductors, raise the output voltage. Upon applying a DC supply, diodes 1, 2, 3, and 4 remain forward-biased, allowing current to flow. Energy is stored by the inductors, and the capacitors charge to raise the voltage level. A discharge path for the capacitor is provided by a diode, The C2 capacitor provides a voltage that is ripple-free along the resistive load.

Switched Capacitor Circuit: The voltage step-up process relies on the SC circuit. Multiple capacitors are switched in a predetermined sequence, facilitating energy transfer to the output stage and effectively boosting the voltage.

Regenerative Boost Circuit: This circuit recovers energy that would otherwise be wasted as heat during switching, considerably increasing the converter's overall efficiency.

Inductors: Energy is stored and released by inductors during switching cycles, contributing to voltage boosting and maintaining regulation of the output voltage. Prior to creating a high step-up DC to DC converter employing a RB design and switching capacitor, first define the system requirements in MATLAB, including input as well as output voltage specifications. Use of suitable parts like shifts, capacitors, and inductive devices is necessary to guarantee compatibility with MATLAB's built-in models or, if necessary to construct custom models. It is necessary to create a control method for switching operations using Simulink blocks or MATLAB code.

The designated parts and control logic ought to be configured in a MATLAB or Simulink framework. Accurate voltage regulation requires feedback loops, and system parameter optimisation can increase efficiency. For the purpose of simulating actual operational conditions, the converter model ought to be connected with a SPV system. For more complex electrical simulations, MATLAB and SPICE can be connected optionally. To enhance performance, the control method and component settings must be adjusted and the simulation results verified. Lastly, a thorough report outlining the implementation procedures and important discoveries should be supplied, together with documentation of the model.

4. RESULT AND DISCUSSION

In order to address the increasing need for renewable energy integration into the power grid, this study investigates a simpler approach that focusses on power grid integration using hysteresis Pulse Width Modulation (PWM). Figures 3 and 4 illustrate the switch currents and output voltage.

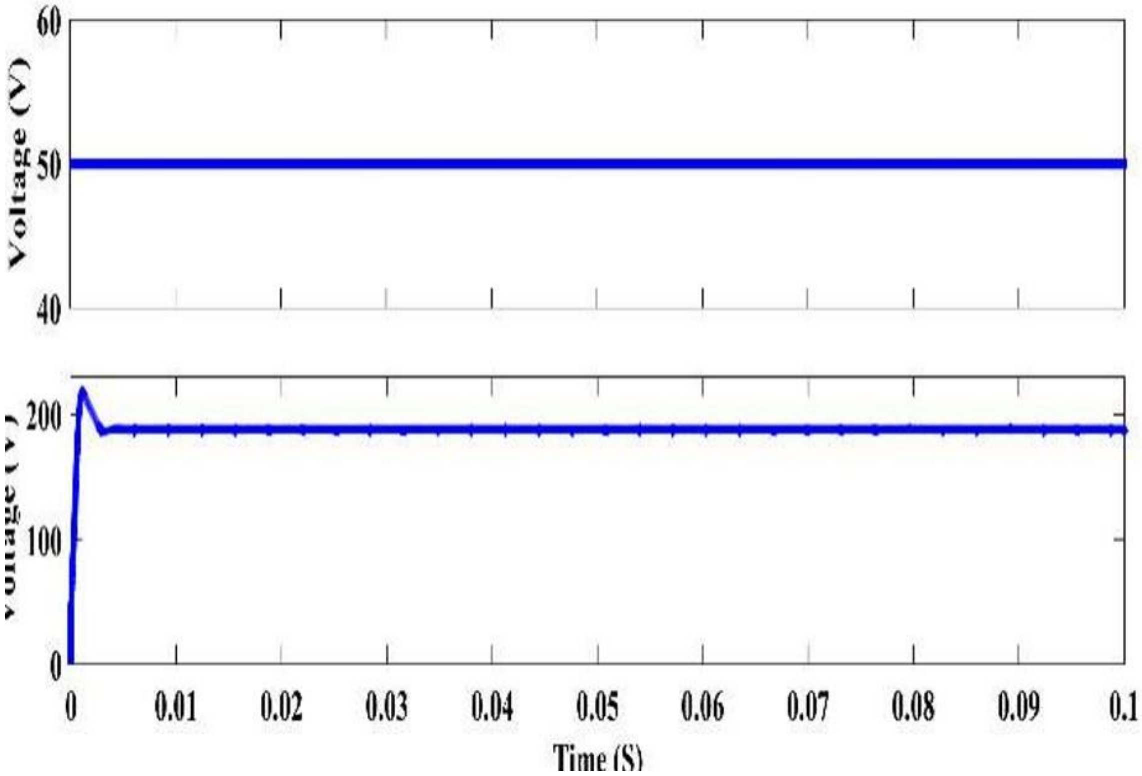

FIGURE 3. Output Voltage

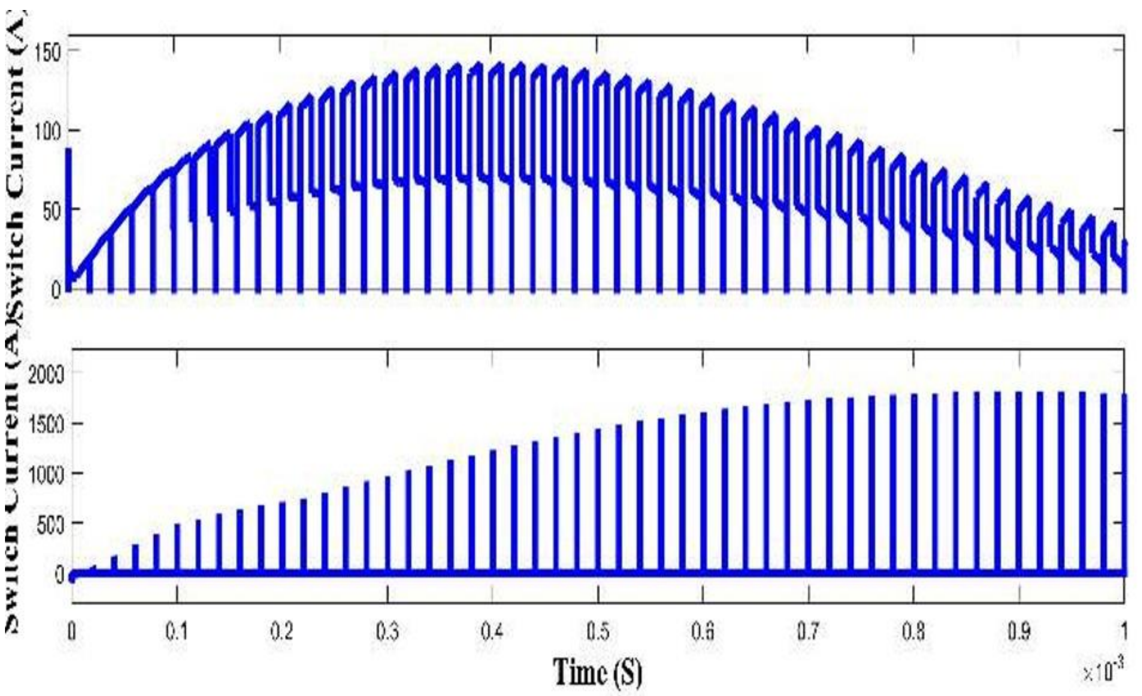

FIGURE 4. Switch Currents

The proposed DC-DC converter integrates a range of innovative design features to tackle the specific challenges associated with SPV applications. By incorporating SC and RB configurations, the converter achieves substantially higher efficiency, ensuring optimal utilization of the energy generated by SP. This enhancement minimizes energy losses and significantly elevates overall system performance. Additionally, the advanced construction guarantees excellent voltage regulation, providing a steady and reliable output voltage even in the face of changing load fluctuations or variable input conditions, which is essential for reliable operation in dynamic scenarios.

One of the standout features of the converter is its compact and lightweight design, achieved through cutting-edge circuit topologies. This aspect is particularly advantageous for SPV systems, where weight and space restrictions are frequently encountered, making the design highly practical for real-world applications. In order to successfully enhance the low-voltage generated by SP to levels appropriate for a variety of applications without causing major energy losses, the converter can reach higher step-up voltage ratios. This functionality is crucial for extending the applicability of SPV systems while maintaining exceptional performance.

To validate these enhancements, the converter's design can undergo rigorous testing through simulations with tools like This can be achieved through the use of the SPICE or by conducting physical laboratory tests. Such validation processes confirm that the proposed design aligns with established benchmarks for efficiency, reliability, and performance. In conclusion, this DC-DC converter signifies a major advancement in addressing the specialized needs of SPV applications, delivering significant gains in energy efficiency, operational dependability, and overall system performance, thereby advancing the field of renewable energy technologies.

5. CONCLUSION

The SC-RB architecture of the improved the step-up gain DC to DC converter, which was created and used for SPV applications, has demonstrated a great deal of potential. This design significantly improves system efficiency and energy output, addressing the need for more compact, cost-effective SPV systems by eliminating the need for transformers. A comprehensive evaluation that compares performance metrics including DC voltage gain and stress on the active elements, as well as stable state wave (CCM) and Discontinuous Conduction Mode (DCM) operations, shows how much better the suggested converter is than existing designs. High efficiency is ensured by minimising energy losses through the reduction of duty cycle operations and decreased on-state resistance. Experimental validation confirms the theoretical predictions, establishing the feasibility and reliability of the design. This work advances the field of high-efficiency DC-DC converters, providing a foundation for future innovations that will further optimize SPV systems, enhancing their practicality and performance in real-world applications.

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