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International Journal for Modern Trends in Science and Technology
Volume 11, Issue 08, pages 45-51.
ISSN: 2455-3778 online
Available online at: http://www.ijmtst.com/vol11issue08.html
DOI: https://doi.org/10.5281/zenodo.16890705

Design and Analysis of a High-Efficiency Single-Input Multiple-Output DC–DC Converter

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To Cite this Article
M.D.N. Rajesh & Dr. Ch.V.N. Raja (2025). Design and Analysis of a High-Efficiency Single-Input Multiple-Output DC–DC Converter. International Journal for Modern Trends in Science and Technology, 11(08), 45-51. https://doi.org/10.5281/zenodo.16890705

Article Info
Received: 23 July 2025; Accepted: 14 August 2025.; Published: 17 August 2025.

KEYWORDS

Single-Input Multiple-Output (SIMO), DC-DC Converter, Soft Switching, High Efficiency, Fuel Cell (FC), High Voltage Gain, switching Losses.

ABSTRACT

The growing demand for clean energy sources, such as fuel cells (FCs), necessitates the development of highly efficient and cost-effective power conversion systems. These energy sources often require multiple DC voltage levels to power auxiliary components, but conventional solutions using multiple single-input single-output (SISO) converters suffer from high complexity, increased cost, and poor efficiency due to hard-switching losses. This paper addresses these limitations by proposing a novel single-input multiple-output (SIMO) DC-DC converter. The proposed topology integrates a soft-switching technique to minimize power losses and utilizes a reduced number of switches to simplify the circuit and its control. A detailed analysis of the converter's operating principles is presented, and its performance is validated through a simulation model based on the FLYBACK converter. The results demonstrate that the proposed SIMO converter achieves high efficiency and high voltage gain, offering a superior, cost-effective, and less complex alternative for clean energy applications.

1. INTRODUCTION

In Order to protect the natural environment on the earth, the development of clean energy without pollution has the major representative role in the last decade. By dealing with the issue of global warming, clean energies, such as fuel cell (FC), photovoltaic, and wind energy, etc., have been rapidly promoted. Due to the electric characteristics of clean energy, the generated power is critically affected by the climate or has slow transient responses, and the output voltage is easily influenced by load variations. Besides, other auxiliary components, e.g., storage elements, control boards, etc., are usually required to ensure the proper operation of clean energy[1-4]. For example, an FC-generation system is one of the most efficient and effective solutions to the environmental pollution problem. In addition to the FC stack itself, some other auxiliary components, such as the balance of plant (BOP) including an electronic control board, an air compressor, and a cooling fan, are required for the normal work of an FC generation system. In other words, the generated power of the FC stack also should satisfy the power demand for the BOP.

Thus, various voltage levels should be required in the power converter of an FC generation system. In general, various single-input single-output dc–dc converters with different voltage gains are combined to satisfy the requirement of various voltage levels, so that its system control is more complicated and the corresponding cost is more expensive. The motivation of this study is to design a single-input multiple-output (SIMO) converter for increasing the conversion efficiency and voltage gain, reducing the control complexity, and saving the manufacturing cost. In this paper presented a SIMO dc–dc converter capable of generating buck, boost, and inverted outputs simultaneously. However, over three switches for one output were required. This scheme is only suitable for the low output voltage and power application, and its power conversion is degenerated due to the operation of hard switching[3-8].

Proposed a new dc–dc multi-output boost converter, which can share its total output between different series of output voltages for low- and high-power applications Unfortunately, over two switches for one output were required, and its control scheme was complicated. Besides, the corresponding output power cannot supply for individual loads independently. Investigated a multiple-output dc–dc converter with shared zero-current switching (ZCS) lagging leg. Although this converter with the soft-switching property can reduce the switching losses, this combination scheme with three full-bridge converters is more complicated, so that the objective of high-efficiency power conversion is difficult to achieve, and its cost is inevitably increased.

In general, various single-input single-output dc–dc converters with different voltage gains are combined to satisfy the requirement of various voltage levels, so that its system control is more complicated and the corresponding cost is more expensive. This scheme is only suitable for the low output voltage and power application, and its power conversion is degenerated due to the operation of hard switching. There are three existing methods for building the simulation models: the state-space averaging technique and linearization, linear circuit technique and nonlinear design technique. In a flyback switching converter, the transfer functions of some blocks are highly nonlinear, because of the optical parts and pulse width modulated (PWM) integrated circuits (ICs), etc.

The accuracy of simulation by the first two methods relies heavily on the modeling process of the optical parts and PWM ICs. To increase the simulation accuracy, the third method was employed. However, it is also of high complexity. In general, various single-input single-output dc–dc converters with different voltage gains are combined to satisfy the requirement of various voltage levels, so that its system control is more complicated and the corresponding cost is more expensive. This scheme is only suitable for the low output voltage and power application, and its power conversion is degenerated due to the operation of hard switching.

2. LITERATURE SURVEY

The integration of distributed and renewable energy resources into modern power systems heavily relies on advanced power electronic converters to ensure efficient and reliable operation. This survey synthesizes key research focusing on converter topologies, control strategies, and system integration for sources like fuel cells, solar photovoltaics, and wind energy. A significant body of work focuses on developing specialized interfaces for various energy sources. For fuel cell (FC) systems, which are recognized as a clean energy conversion technology [7], research has explored DSP-controlled power electronic interfaces for distributed generation [1] and real-time emulation models for hardware-in-the-loop applications [9]. The practical application of FCs has been demonstrated in systems like hybrid electric scooters [8]. Similarly, for photovoltaic (PV) systems, concepts such as the DC-building-module for Building-Integrated Photovoltaic (BIPV) systems have been proposed to enhance integration [2]. In the context of wind energy, sensorless control of Permanent Magnet Synchronous Generators (PMSG) using adaptive network-based fuzzy inference systems has been developed to handle nonlinear loads effectively [3].

To meet the diverse demands of renewable energy systems, researchers have developed various advanced converter topologies.

- Multi-Function Converters: There is a strong trend towards creating integrated converters that serve multiple functions. This includes multi-output DC-DC converters, which are crucial for systems requiring several DC voltage levels. Different approaches have been explored, such as single-inductor multiple-output switchers [10], topologies based on diode-clamped configurations [11], and designs with a shared zero-current-switching (ZCS) lagging leg for improved efficiency [12]. Furthermore, three-port half-bridge converters have been developed to seamlessly manage power flow between a renewable source, an energy storage unit, and a load in a single package [6].
- High Voltage-Gain Converters: Many renewable sources, like PV and fuel cells, produce a low DC voltage. Therefore, high step-up converters are essential. Novel integrated DC/AC converters with high voltage gain capabilities have been designed specifically for distributed energy systems [4]. The use of coupled inductors is a well-established technique to achieve high step-up ratios in DC-DC converters [13].
- Energy Storage and Bidirectional Flow: Integrating energy storage is critical for mitigating the intermittency of renewables. A direct integration scheme using a diode-clamped three-level inverter has been proposed for combining batteries and supercapacitors [5]. For applications requiring both charging and discharging, such as battery bank interfaces, bidirectional converters are necessary. The design of high-efficiency, integrated Zero-Voltage-Transition (ZVT) PWM bidirectional converters has been analyzed to minimize switching losses and improve performance [15].

The principles underlying the design and application of these converters are well-documented in foundational texts like Mohan, Undeland, and Robbins [14], which provide a comprehensive basis for the field. In summary, the literature highlights a clear progression towards creating more efficient, compact, and multi-functional power electronic converters tailored to the specific needs of modern distributed energy systems.

3. PROPOSED SIMO CONVERTER

This study presents a newly designed SIMO converter with a coupled inductor. The proposed converter uses one power switch to achieve the objectives of high-efficiency power conversion, high step-up ratio, and different output voltage levels. In the proposed SIMO converter, the techniques of soft switching and voltage clamping are adopted to reduce the switching and conduction losses via the utilization of a low-voltage-rated power switch with a small RDS(on). Because the slew rate of the current change in the coupled inductor can be restricted by the leakage inductor, the current transition time enables the power switch to turn ON with the ZCS property easily, and the effect of the leakage inductor can alleviate the losses caused by the reverse-recovery current. Additionally, the problems of the stray inductance energy and reverse-recovery currents within diodes in the conventional boost converter also can be solved, so that the high-efficiency power conversion can be achieved. The voltages of middle-voltage output terminals can be appropriately adjusted by the design of auxiliary inductors; the output voltage of the high-voltage dc bus can be stably controlled by a simple proportional-integral (PI) control.

The proposed SIMO converter as shown in Figure 1 can boost the voltage of a low-voltage input power source to a controllable high-voltage dc bus and middle-voltage output terminals we can use that low voltage to charging circuit of the main circuit and high voltage can be used for high voltage application like motor drives, etc,. The proposed converter uses one power switch to achieve the objectives of high-efficiency power conversion, high step-up ratio, and different output voltage levels. In the proposed SIMO converter, the techniques of soft switching and voltage clamping are adopted to reduce the switching and conduction losses via the utilization of a low-voltage-rated power switch with a small R_{DS}(on). Use of the coupled inductor and capacitors we will achieve that both low and high voltages.

The proposed technique is distinguished by several advantages that enhance both performance and design simplicity. A primary benefit is the substantial reduction in power dissipation; the use of soft switching minimizes switching losses, and the topology is inherently designed for reduced conduction loss. This combined reduction in losses is the principal reason for the converter's high efficiency. Furthermore, the system delivers a high voltage gain using just one power switch, which streamlines the design and improves reliability. The relavant waveforms of the proposed converter is given in Figure 2.

3.1 Equivalent Circuit and Characteristics wave form of SIMO converter

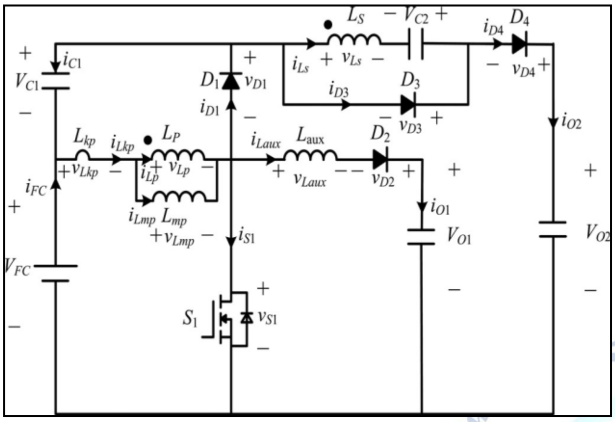

Figure 1: EQUIVALENT CIRCUIT OF SIMO CONVERTER

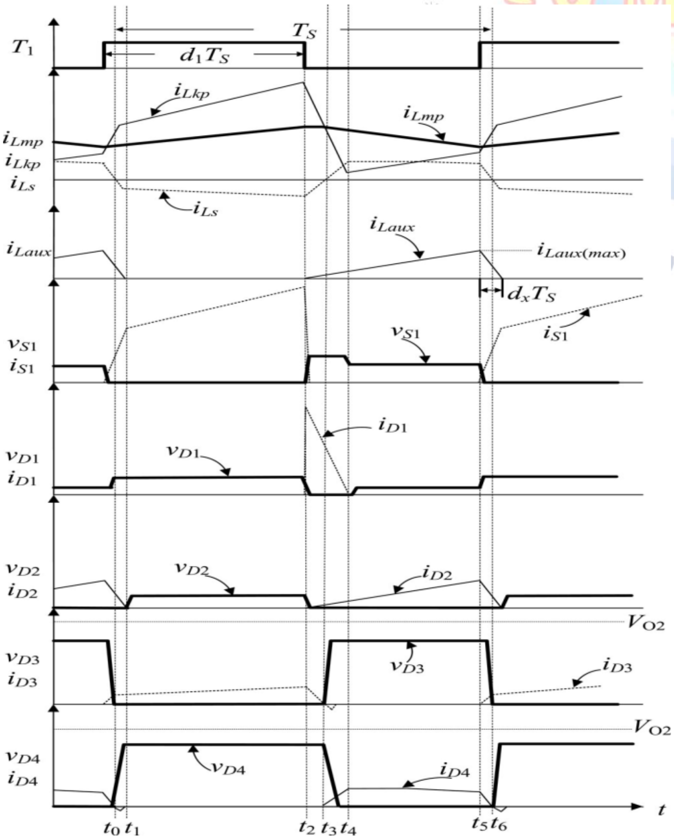

Figure 2: WAVEFORMS OF SIMO CONVERTER

3.2 Operating Modes

MODE 1 (t0-t1)

In this mode, the main switch S1 was turned ON for a span, and the diode D4 turned OFF. Because the polarity of the windings of the coupled inductor Tr is positive, the diode D3 turns ON. The secondary current iLs reverses and charges to the middle voltage capacitor C2. When the auxiliary inductor Laux releases its stored energy completely, and the diode D2 turns OFF, this mode ends as depicted in Figure 3.

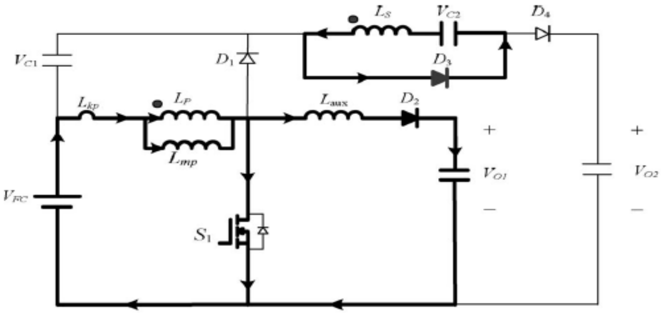

Figure 3: operating mode (t0-t1)

MODE 2 (t1-t2)

At time t = t1, the main switch S1 is persistently turned ON. Because the primary inductor LP is charged by the input power source, the magnetizing current iLmp increases gradually in an approximately linear way. At the same time, the secondary voltage vLs charges the middle-voltage capacitorC2 through the diode D3. Although the voltage vLmp is equal to the input voltage VFC both at modes 1 and 2, the ascendant slope of the leakage current of the coupled inductor (diL kp /dt) at modes 1 and 2 is different due to the path of the auxiliary circuit. Because the auxiliary inductor Laux releases its stored energy completely, and the diode D2 turns OFF at the end of mode 1, it results in the reduction of diLkp /dt at mode2 as shown in Figure 4.

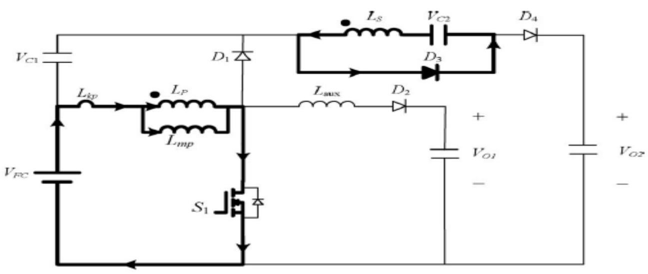

Figure 4: operating mode (t1-t2)

MODE 3 (t2-t3)

At time t = t2, the main switch S1 is turned OFF. When the leakage energy still released from the secondary side of the coupled inductor, the diode D3 persistently conducts and releases the leakage energy to the middle-voltage capacitor C2. When the voltage across the main switch VS 1 is higher than the voltage across the clamped capacitor VC1, the diode D1 conducts to transmit the energy of the primary-side leakage inductor Lkp into the clamped capacitor C1. At the same time, partial energy of the primary-side leakage inductor Lkp is transmitted to the auxiliary inductor Laux, and the diode D2 conducts. Thus, the current iLaux passes through the diode D2 to supply the power for the output load in the auxiliary circuit. When the secondary side of the coupled inductor releases its leakage energy completely, and the diode D3 turns OFF, this mode ends as given in Figure 4.

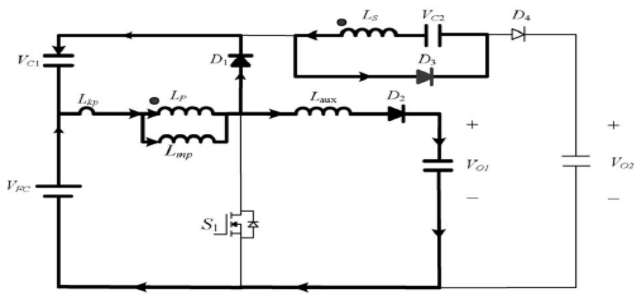

Figure 5: operating mode (t2-t3)

MODE 4 (t3-t4)

At time t = t3, the main switch S1 is persistently turned OFF as presented in Figure 6.

When the leakage energy has released from the primary side of the coupled inductor, the secondary current iLS is induced in reverse from the energy of the magnetizing inductor Lmp through the ideal transformer, and flows through the diode D4 to the HVSC. At the same time, partial energy of the primary side leakage inductor Lkp is still persistently transmitted to the auxiliary inductor Laux, and the diode D2 keeps conducting. Moreover, the current iL aux passes through the diode D2 to supply the power for the output load in the auxiliary circuit.

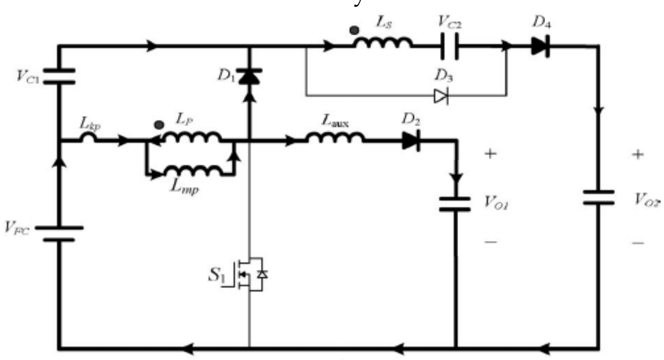

Figure 6: operating mode (t3-t4)

MODE 5 (t4-t5)

At time t = t4, the main switch S1 is persistently turned OFF, and the clamped diode D1 turns OFF because the primary leakage current iLkp equals to the auxiliary inductor current iLaux. In this mode, the input power source, the primary winding of the coupled inductor Tr, and the auxiliary inductor Laux connect in series to supply the power for the output load in the auxiliary circuit through the diode D2. At the same time, the input power source, the secondary winding of the coupled inductor Tr, the clamped capacitor C1, and the middle voltage capacitor (C2) connect in series to release the energy into the HVSC through the diode D4 as depicted in Figure 7.

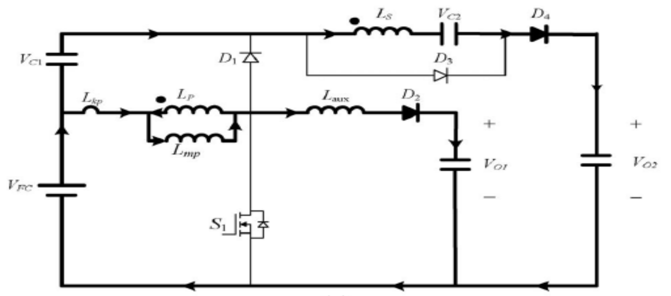

Figure 7: operating mode (t4-t5)

MODE 6 (t5-t6)

At time t=t5, this mode begins when the main switch S1 is triggered as shown in Figure 8.

The auxiliary inductor current iL aux needs time to decay to zero, the diode D2 persistently conducts. In this mode, the input power source, the clamped capacitor C1 , the secondary winding of the coupled inductor Tr, and the middle-voltage capacitor C2 still connect in series to release the energy into the HVSC through the diodeD4. Since the clamped diodeD1 can be selected as a low-voltage Schottky diode, it will be cut off promptly without a reverse-recovery current. Moreover, the rising rate of the primary current iLkp is limited by the primary-side leakage inductor Lkp. Thus, one cannot derive any currents from the paths of the HVSC, the middle-voltage circuit, the auxiliary circuit, and the clamped circuit. As a result, the main switch S1 is turned ON under the condition of ZCS and this soft-switching property is helpful for alleviating the switching loss.

When the secondary current iLS decays to zero, this mode ends. After that, it begins the next switching cycle and repeats the operation in mode 1.

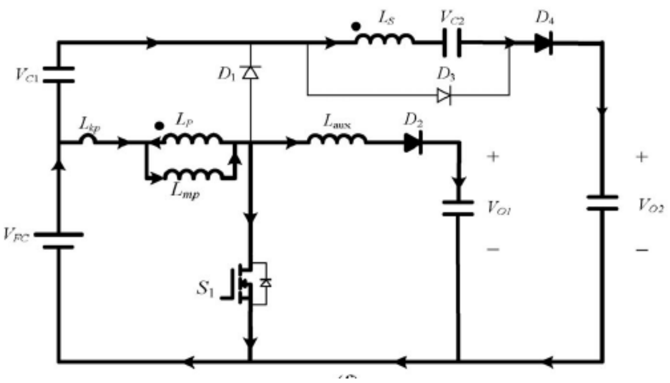

Figure 8: OPERATING MODE (t5-t6)

4. SIMULATION RESULTS

A simulation design open loop system as shown in Figure 9 is implemented in MATLAB SIMULINK with the help of coupled inductor, voltage clamping circuit and switched capacitor we get desired output voltage level (Figure 10,11) low voltage output and high voltage waveforms.

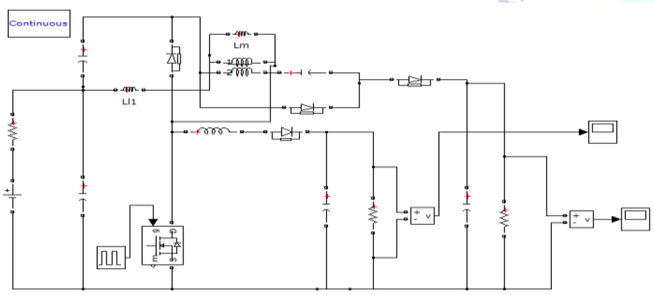

FIGURE 9: OPEN LOOP SYSTEM OF SIMO CONVERTER

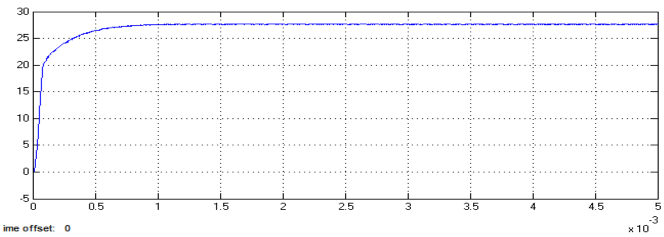

FIGURE 10: LOW VOLTAGE OUTPUT (28V DC)

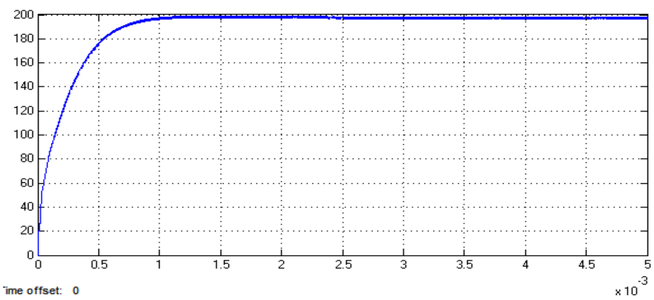

FIGURE 11: HIGH VOLTAGE OUTPUT (200V DC)

4.4 Simulation Design closed loop

A simulation design closed loop system as shown in Figure 12 is implemented in MATLAB SIMULINK with the help of coupled inductor, voltage clamping circuit and switched capacitor and PI controllers we get desired output voltage level (Figure 13, 14) low voltage output and high voltage waveforms.

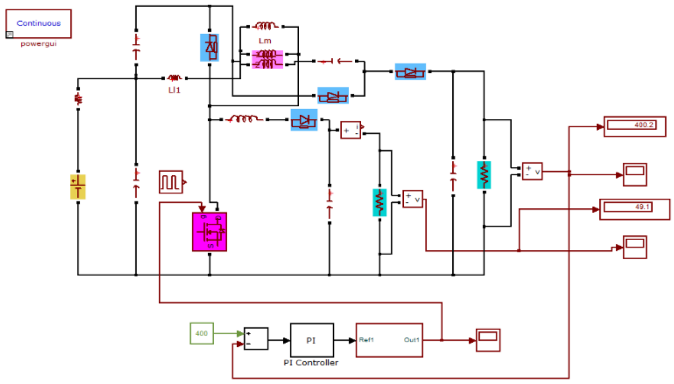

FIGURE 12: CLOSED LOOP CIRCUIT OF SIMO CONVERTER

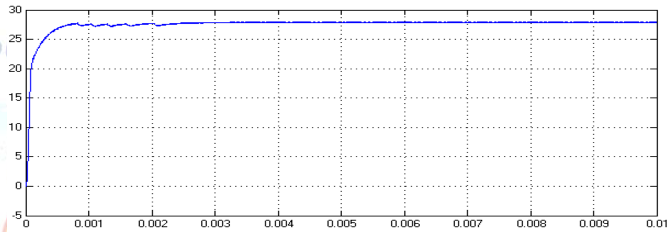

FIGURE 13: LOW VOLTAGE OUTPUT (28V)

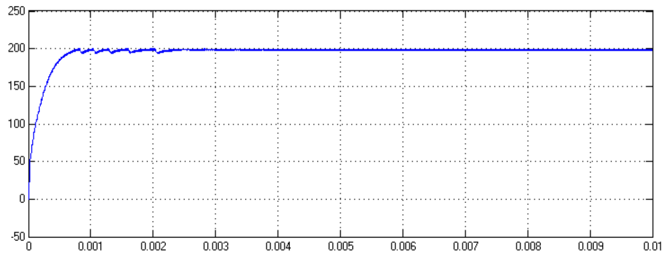

Figure 14: HIGH VOLTAGE (200V)

Here the Input given to the circuit is 12V DC and the output got is 28V DC (low voltage) and 200V DC (high voltage) for modification circuit given input is 24V DC and got output is 54V DC (low voltage) and 400V DC (high voltage). The proposed technique offers significant advantages, primarily its high operational efficiency and simplified design. By employing a soft-switching method, switching losses are greatly minimized. This benefit, combined with reduced conduction loss, directly results in the system's overall high efficiency. Additionally, the use of just one power switch streamlines the circuit design, reducing complexity and potential cost. The proposed converter is highly versatile, demonstrating robust performance in both low-power and high-power applications. Its efficient design makes it particularly suitable for integration into advanced power systems, including Switched-Mode Power Supplies (SMPS) and Uninterruptible Power Supplies (UPS), where reliable and multi-level voltage regulation is essential.

5. CONCLUSION

This paper has presented the design and analysis of a novel single-input multiple-output (SIMO) DC-DC converter to overcome the challenges associated with powering auxiliary systems in clean energy applications. By successfully integrating a soft-switching mechanism and a minimal component topology, the proposed converter effectively addresses the high switching losses and circuit complexity found in conventional multi-converter systems and prior SIMO designs. The simulation results have validated the converter's ability to achieve high power-conversion efficiency and significant voltage gain. The key advantages of this design—namely its reduced cost, simplified control, and superior efficiency—make it an excellent candidate for fuel cell systems and other renewable energy applications requiring multiple DC outputs from a single, low-voltage source. Future work will focus on the development of a hardware prototype to experimentally verify the simulated performance and further explore its dynamic response under various load conditions. This research can be extended in several promising directions. A primary avenue for future work is to expand the system's architecture to accommodate a wider voltage range or an increased number of output levels. Such an expansion could potentially enhance the converter's overall voltage gain and efficiency. Furthermore, the system's functionality can be broadened by incorporating an inverter stage. This would enable the conversion of the DC outputs to power AC loads, significantly increasing the converter's range of practical applications.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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