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Enhanced Sepic Converter with Wide Input Range and Low Voltage Stress for Fuel Cell Application

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***Abstract*—The highly efficient DC-DC converter featuring a broad step-up gain addresses the challenge of voltage compatibility in commercial fuel cell vehicles. This design is based on the traditional SEPIC converter, where the negative terminal of one capacitor is linked to the negative terminal of the power source to enhance energy acquisition. An improved SEPIC DC-DC converter is introduced, which offers a wide voltage conversion range, continuous input current, a common ground, and reduced voltage stress, fulfilling all the specifications required for DC- DC converters in commercial fuel cell vehicles. Results were derived from simulations conducted with MATLAB/SIMULINK. The simulation outcomes indicate that the proposed SEPIC converter minimizes voltage stresses on switching devices and achieves a peak operating efficiency of 81%Ṡubsequently, a hardware prototype was developed with a 2V input, utilizing the TMS320F28335 microcontroller to produce an output. of 10V with a voltage gain of 5.1 is obtained.**

***Index Terms*—SEPIC Buck Boost Converter, Fuel cell vehicles,Gain, Efficiency.**

I. INTRODUCTION

Buck-Boost Converters and SEPIC (Single Ended Primary Inductor Converter) Buck-Boost Converters are both adaptable DC-DC converters utilized for voltage regulation, yet they vary in their design, efficiency, and operational character- istics. The Buck-Boost Converter, which utilizes a single inductor along with switches, is capable of both increasing and decreasing voltage while possibly inverting the output polarity. Its compact and efficient nature makes it suitable for applications that demand simplicity and high performance. Conversely, the SEPIC Buck-Boost Converter employs two inductors (or a coupled inductor) along with a coupling capac- itor to facilitate energy transfer, providing non-inverted output polarity and improved input-output isolation. Nevertheless, this added complexity may result in slightly reduced efficiency and increased electromagnetic interference. Each converter has its unique applications—Buck-Boost Converters excel in compact designs, while SEPIC Converters are favored in scenarios that require stable, same-polarity outputs. To tackle the energy crisis and environmental challenges, the combination of fuel cell vehicles (FCVs) with electric vehicles (EVs) has emerged as a significant trend aimed at minimizing carbon emissions. Due to their distinct energy storage capabili- ties and usage scenarios, EVs are favored in flat terrains, while FCVs are better suited for hilly regions. EVs are proficient in managing light loads and shorter distances, whereas FCVs offer advantages for transporting heavy loads over extended distances. Consequently, commercial FCVs, such as buses, heavy trucks, and trams utilizing hydrogen-electric hybrid systems, have become the leading models. However, the output voltage of fuel cell (FC) stacks often does not align with the vehicle's DC bus voltage.[1] To address this mismatch, a DC-DC converter is essential for voltage regulation and efficient power distribution within the powertrain. Regarding vehicle safety, it is crucial to minimize the electromagnetic interference (EMI) of the powertrain, and the input and output of the buck-boost DC-DC converter should have a common ground to avoid additional EMI caused by high-frequency pulse width modulation (PWM) voltage pulses. [2-3]

A buck-boost converter that features voltage conversion pro- vides an extensive step-down range; however, its step-up range is not as effective when compared to SEPIC converters. Furthermore, the pulsating input current and negative output polarity render it unsuitable for fuel cell vehicles (FCVs).[1]

Another converter design fulfills the criteria for a broad step- up/step-down range, common ground, and continuous input current. Nevertheless, the presence of inductors and capacitors in this converter negatively affects conversion efficiency. While a proposed buck-boost converter offers a positive output along with a wide voltage step-up/step-down range, it is hindered by a pulsating input current. An alternative design accomplishes a wide step-up/step-down range and mitigates input current ripples, yet both its input and output polarities are negative. As a result, current converter topologies encounter difficulties in concurrently satisfying the requirements of a wide step-
up/step-down range, common ground, and continuous input current—essential criteria for commercial FCVs [5-6]

High-gain DC-DC converters that employ impedance networks and coupled inductors are skilled at matching the voltages of low-power fuel cells (FCs). However, the power output of fuel cell stacks designed for commercial vehicles has now risen to as much as 150 kW. As the power output of FCs grows, the output voltage of these stacks also increases, and under certain driving conditions, this voltage can even exceed the vehicle bus voltage. Consequently, high-gain DC-DC converters are unsuitable for commercial fuel cell vehicles (FCVs). To meet the need for voltage alignment, a buck-boost DC-DC converter is required[4].

A high-gain converter topology utilizing a single switch has been analyzed, offering relatively low voltage stresses across the switch and other power components. The circuit incor- porates a voltage multiplier cell with a common ground to enhance the gain, achieving a voltage gain more than twice that of a conventional quadratic boost converter. This design eliminates issues such as leakage current and electromagnetic interference, and its control is simplified due to the use of only one switch.[8] Additionally, the circuit ensures continuous input current with minimal ripple, making it highly suitable for renewable energy applications and reducing the cost of the input filter. It operates across a wide range of duty ratios, avoiding extreme duty cycle conditions and thereby eliminating concerns related to diode reverse recovery time. Through the alteration of the traditional SEPIC converter, an innovative buck-boost topology is introduced. The revised SEPIC converter offers several advantages, including high conversion efficiency, an extensive step-up/step-down range, a broad voltage conversion range, minimal input current rip- ple, a common ground structure, and a reduced number of components, rendering it appropriate for the powertrain of commercial fuel cell vehicles.

To overcome the previously mentioned limitations, a newly enhanced SEPIC DC-DC converter with low voltage stress has been created. This advanced converter reduces voltage stress by integrating a voltage multiplier circuit. Moreover, the output voltage and current ripple are significantly lower compared to other SEPIC DC-DC converters. Consequently, the converter reduces stress on the components while main- taining the voltage gain. Experimental validation performed with a laboratory prototype supports the analytical findings. In summary, the proposed converter design provides a cost- effective, efficient, and scalable solution for high-gain DC–DC conversion, especially in the realm of emerging electric and hydrogen fuel cell vehicles. Furthermore, its design indicates potential for broader applications, such as portable energy systems, renewable energy harvesting, and grid-connected distributed energy resources.

II. METHODOLOGY

The Modified SEPIC DC-DC converter operates in two modes within continuous conduction mode, which is deter- mined by the ON-OFF control actions of the switches. In
mode I, the power switches S_1 & S_2,, are in the ON state, While in the mode II both are in OFF sate. This configura- tion aims to improve voltage gain and minimize component stress while preserving a relatively straightforward design. The specific topology of this converter is depicted in Figure 3.6, which emphasizes the layout and interconnection of all the components involved.

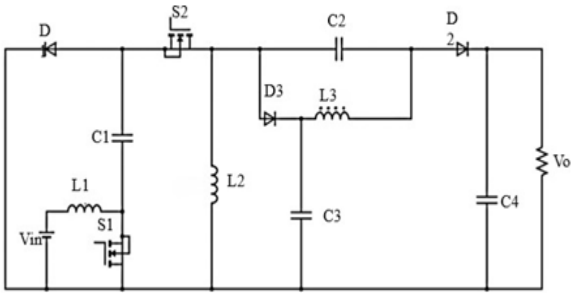

Fig. 1. Enhanced SEPIC DC-DC Converter

A. Modes of Operation

The enhanced SEPIC DC-DC Converter with Wide Step- up Range is shown in Figure 3.5. The topology consists of two synchronously controlled power switches S1 and S2, three inductors L1, L2and L3 four capacitors C1, C2, C3 and C4 three diodes D1, D2 and D3 and load resistor R0. The DC power source is supplied to the inductor L1 and the control signal of the switch S2 is the same as that of the S1.

1) Mode 1: At time t = t0, when switch S is activated and switches S1 and S2 are turned ON, and diodes D1, D2 and D3 are turned off during this time interval. There are four circuit loops in operating mode 1. In this mode the input DC power VIN charges the inductor L1 through switch S1. The capacitor C1 discharges and charges the inductor L2 through switches S1 and S2. The capacitor C1 and C3 discharges and charges the inductor L3 and capacitor C2 through switches S1 and S2. The output capacitor C0 releases energy for the resistive load R. The circuit operation corresponding to Mode 1 is illustrated in Figure ??.

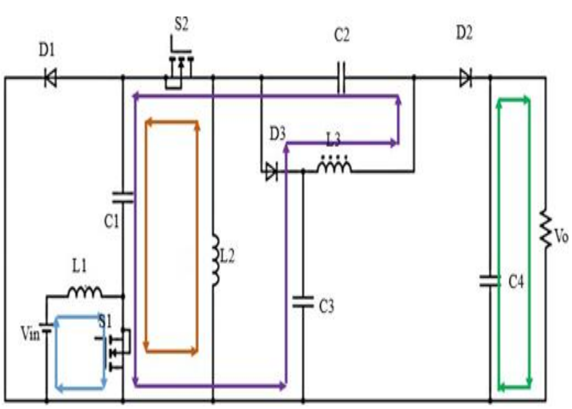

Fig. 2. Operating circuit of of Mode 1

2) Mode 2: At time t = t1, when switch S is turned OFF and switches S1 and S2 are OFF. During this period the diodes D_1, $D_2$and D_3 are turned on . At this moment, the VIN and inductor L1, charges through the D1. And the inductor L2The inductors L is obtained from the following equations.
discharges and supply energy for C3a through diode inductor L2 together with L3 and C3 supply energy for output capacitor C3 and R. The circuit operation corresponding to Mode 2 is illustrated in Figure??.

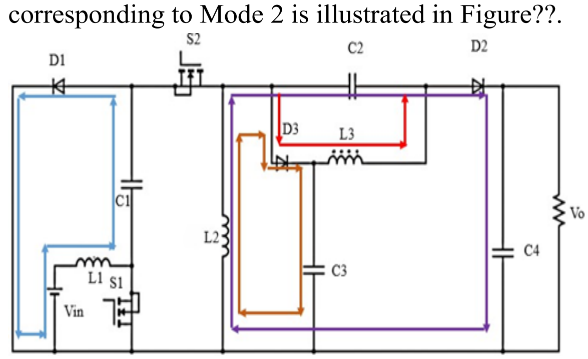

Fig. 3. Operating circuit of of Mode 2

Figure 4 illustrates the theoretical waveforms corresponding to Mode 1 and Mode 2.

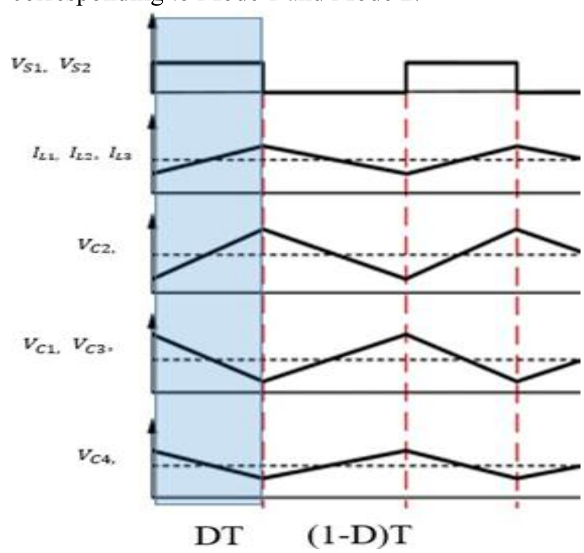

Fig. 4. Theoretical waveform

B. Design of Components

The input voltage is taken as Vin = 40V for boost mode and
Vin = 300V for boost mode. The output voltage is taken as V0
= 200V.The output power is taken as P0 = 200W. The switches are operated with same duty ratio and switching frequency, fs
= 100kHz.
Load resistance can be found by the equation,

Load resistance can be found by the equation,

$$R_o = \frac{V_0^2}{P_0} = \frac{200^2}{200} = 200\Omega \qquad (1)$$

Voltage Gain,

$$M = \frac{V_0}{V\,in} = \frac{2D}{(1-D)^2} = \frac{200}{40}D = 0.55 \qquad (2)$$

The inductors L is obtained from the following equations.

$$I_{L1} = I_{IN} = \frac{2D * I_0}{(1-D)^2} = \frac{0.55 * 1}{(1-0.55^2)} = 5.4A \qquad (3)$$

$$L_1 \geq \frac{(1-D)^4 * R}{\Delta i_{L1} * f_s * D} \geq 114\mu H = 800\mu H \qquad (4)$$

It is approximated to 800 μH.

$$I_{L2} = \frac{I_{L1}(1-D)}{D} = \frac{(1-0.55) * 5.4}{(0.55)} = 4.4A \qquad (5)$$

$$L_2 \geq \frac{(1-D)^2 * R}{\Delta i_{L2} * f_s} \geq 368.25\mu H = 600\mu H \qquad (6)$$

It is approximated to 600 μ H.

$$I_{L3} = \frac{I_{L2}(1-D)}{2D} = \frac{(1-0.23) * 3.6}{(2 * 0.23)} = 6.02A \qquad (7)$$

$$L_3 \geq \frac{(1-D)^4 * R}{\Delta i_{L3} * f_s} \geq \frac{(1-0.23)^4 * 200}{1.5 * 100000} \geq 342\mu H = 600\mu H \qquad (8)$$

It is approximated to 600 μ H

The values of the capacitors are determined using the following equations.

$$C_1 \geq \frac{D^2}{\Delta V_{C1} * (1-D)^2 * R * f_s} \qquad (9)$$

C_1 is taken as 100 μF

$$C_2, C_3 \geq \frac{2D^2}{\Delta V_{C2} * (1-D)^2 R * f_s} \qquad (10)$$

C_2 and C_3 is taken as 100 μF

$$C_4 \geq \frac{D}{\Delta V_{C4} * R * f_s} \qquad (11)$$

C_4 is taken as 220 μF

III. SIMULATIONS AND RESULTS

The modified SEPIC DC-DC converter is simulated in MAT- LAB/SIMULINK by choosing the parameters listed and the Simulink model,waveforms are obtained.The waveform ob- tained from a modified SEPIC DC-DC converter in MATLAB typically demonstrates a regulated output voltage with minimal ripple, showcasing its ability to provide both step-up and step- down conversion efficiently. The output waveform, shaped by the interaction between inductors and capacitors, illustrates the continuous conduction mode, ensuring stable operation across varying input conditions.This simulation helps visualize the converter's behavior, highlighting key characteristics such as voltage regulation, transient response, and efficiency. In the simulation, a DC input voltage of 40 V was applied to the converter, and it successfully produced an output voltage of 200 V while supplying an output power of 200 W. The waveforms for the input voltage and current are shown in Figure 5, and the output voltage and current waveforms are

presented in Figure 6.

Table I Simulation Parameters Of Modified Sepic Dc-Dc Converter

Parameters	Value
Input voltage, V_{in}	40 V-300V
Output voltage, V_O	200 V
Duty Ratio	55% (boost)
Output load, R	200 Ω,200W
Switching frequency, f_s	100 kHz
Inductance,L_1	800 μH, 6A
Inductance L_2, L_3	600μH,4A
Capacitance C_1, C_2, C_3	100 μf,100V
Capacitance C_4	220μF,250V

Based on the input and output voltages, the voltage gain of the converter is calculated as:

$$\text{Voltage Gain} = \frac{V_{out}}{V_{in}} = \frac{200}{40} \approx 5 \qquad (12)$$

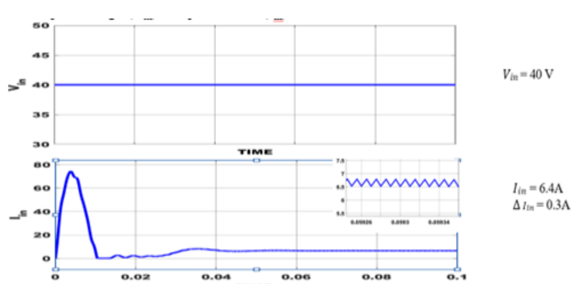

Fig. 5. (a) Input Voltage (V_{in}) and (b) Input Current (I_{in})

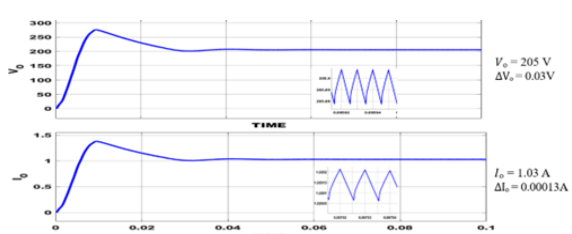

Fig. 6. (a) Output Voltage (V_0) and (b) Output Current (I_0)

Figures 7 and 8 illustrate the gate drive signals and the voltage stresses experienced by the switches in the converter circuit. The measured voltage stress across switch S1 is approximately 55V, while switch S2 experiences a slightly higher stress of around 48V.
The voltages across the capacitors are measured as VC1 = 86.7 V, VC2 = 103 V, VC3 = 103 V, andVC4 = 205 V asillustrated in Fig. 8. Fig. 9 presents the current through the inductor showing that the filter inductance current iL

IV. PERFORMANCE ANALYSIS

The efficiency of power equipment at any given load is defined as the ratio of output power to input power. In this

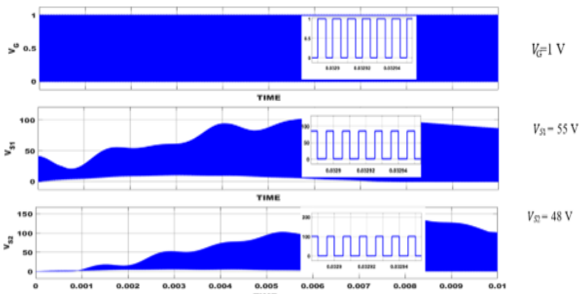

Fig. 7. Gate Pulse (Vgs1) and Voltage Stress (Vs1) of switch S1

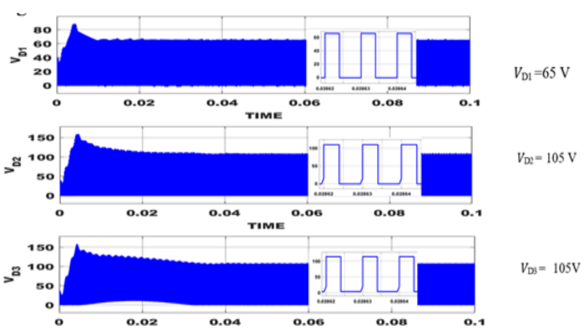

Fig. 8. Voltage across diode (V_{D1}) and Voltage Stress (V_{D2}) of switch S2

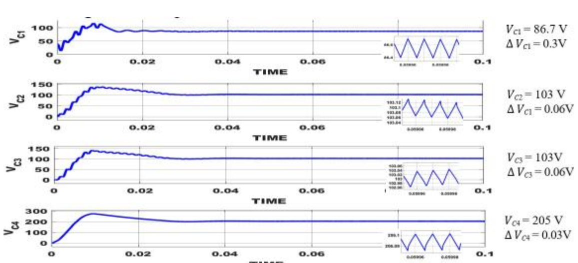

Fig. 9. Voltage across Capacitor (a)VC1, (b)VC2, (c)VC3, (d)VC4

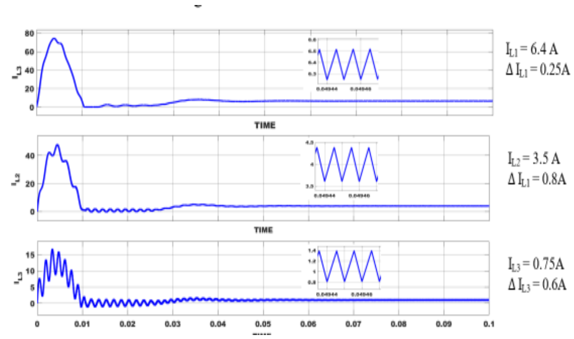

Fig. 10. Current across Inductance (a)iL1, (b)iL2, (c)iL3

study, the relationship between efficiency and output power for a Modified SEPIC DC-DC Converter was analyzed under both resistive (R) and resistive-inductive (RL) loading conditions, as illustrated in Fig. 11. The converter achieved peak efficiencies of 91% for the R load and 90% for the RL load. The efficiency variation across output power levels is moderate, particularly around 200 W. These results indicate that the Modified Dual- Switch Boost Converter is well-suited for medium-power applications.

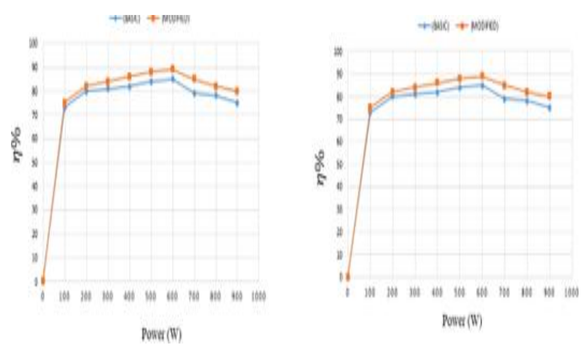

Fig. 11. Efficiency Vs Output Power for (a) R load (b) RL load

Figure 12 illustrates the gain of the Modified SEPIC DC-DC Converter plotted against the duty ratio. It can be observed that the gain rises with an increase in the duty ratio.

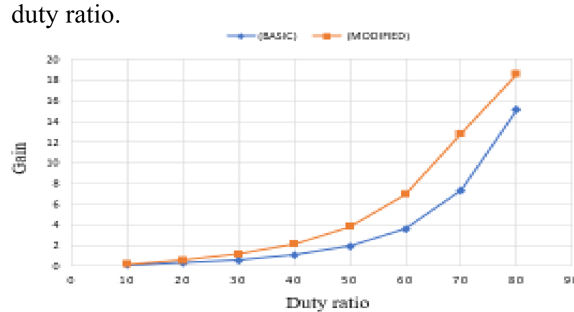

Fig. 12. Voltage gain VS Duty ratio

The plot of output voltage ripple as a function of duty Ratio for Modified SEPIC DC-DC Converter is shown in figure 13.

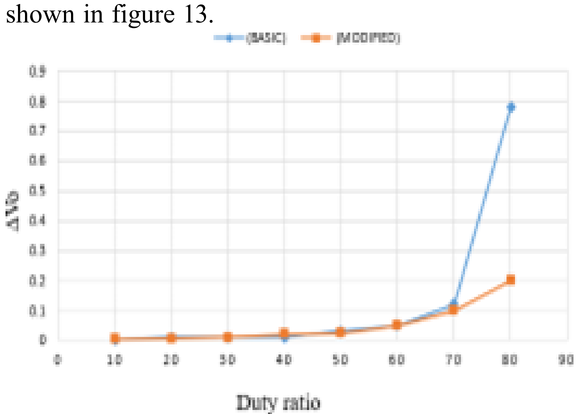

Fig. 13. Output Voltage Ripple VS Duty Ratio

Figure 14 illustrates the output voltage ripple behavior of the modified SEPIC converter with respect to varying switching frequencies. It is observed that the output voltage ripple diminishes as the switching frequency increases.

V. COMPARITIVE STUDY

A comparative analysis between the conventional Modi- fied SEPIC DC-DC Converter and the proposed enhanced version both operating under identical conditions with an input voltage of 40V and a switching frequency of 50kHz—is presented in Table 2. The results indicate that, with the duty ratio held constant, the voltage gain improves significantly from 4.17 to 8.34 in the proposed topology. However, this improvement comes at the cost of increased output voltage and current ripple, which is a trade-off to consider in practical

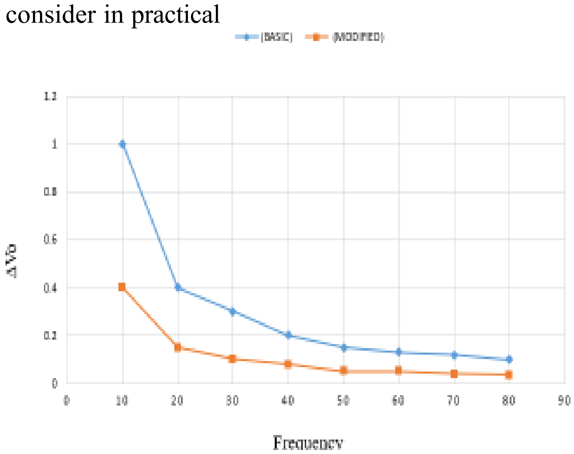

Fig. 14. Output voltage ripple VS frequency

Table II Comparison between SEPIC DC-DC Converter& Proposed Modified SEPIC DC-DC Converter

Parameters	SEPIC Buck Boost Converter	Modified SEPIC Buck Boost Converter
No. of Switches	2	2
No. of Inductors	2	3
No. of Capacitors	2	4
Duty ratio	65%	55%
Output Current (I^O)	1.02 A	1.03 A
Input Current (Iin)	6.4 A	6.4 A
Efficiency (η)	81 %	83 %
Voltage Gain	5.1	5.12
Voltage stress across switches	V_{s1}= 205 V V_{s2}= 115V	V_{s1}= 48V V_{s2}= 55V
Input Current ripple	0.3A	0.3A
Output Voltage ripple	0.1V	0.003V
Output Current ripple	0.004A	0.00013A

applications. Table 3 provides a detailed comparison of the components used in the proposed Modified SEPIC DC-DC Converter against those in other converter designs.

Table III Comparison between Modified SEPIC DC-DC Converter& Other converters

Converter	DC-DC Converter [3]	Buck Boost converter [4]	SEPIC converter [1]	Enhanced SEPIC DC DC Converter
No. of Switches	2	1	2	2
No. of Diodes	2	3	2	3
No. of Inductors	2	2	2	3
No. of Capacitors	2	2	2	4

VI. EXPERIMENTAL SETUP WITH RESULT

To facilitate the implementation of hardware, the input voltage is lowered to 2V, and switching pulses are produced using the TMS320F28335 processor. The switch employed is the MOSFET IRF3205. A driver circuit is constructed utilizing the TLP250H, which serves as an optocoupler to isolate and safeguard the microcontroller from potential damage, while also supplying the necessary gating to activate the switches.

The experimental configuration of the Modified

SEPIC DC- DC Converter is illustrated in Fig. 15. A 2V DC supply is provided from a DC source. The switching pulses are sourced

from the TMS320F28335 microcontroller to the driver circuit. Consequently, an output voltage of 9.7V is achieved from the power circuit, as depicted in Fig. 16. The output voltage of the converter is measured using a DSO oscilloscope.

for fuel cell vehicles and suggest its potential for future implementation. This high-performance digital controller guar- antees precise duty cycle modulation, rapid dynamic response, and stable voltage regulation under varying load conditions. With its combination of high voltage gain, compact design, low component stress, and integration of digital control, the proposed converter topology emerges as an exceptional power interface solution for fuel cell vehicles, photovoltaic energy systems, and distributed energy resources that necessitate high step-up DC conversion.

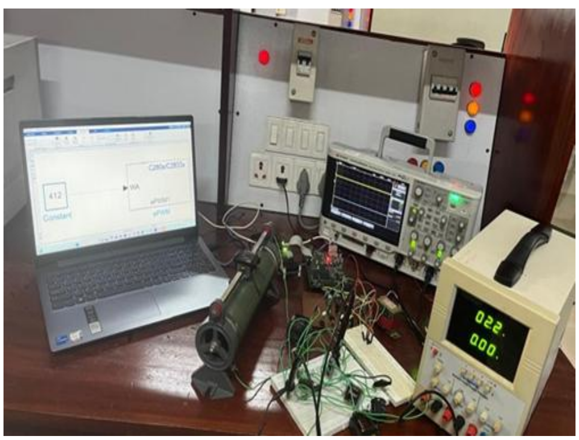

Fig. 15. Experimental Setup

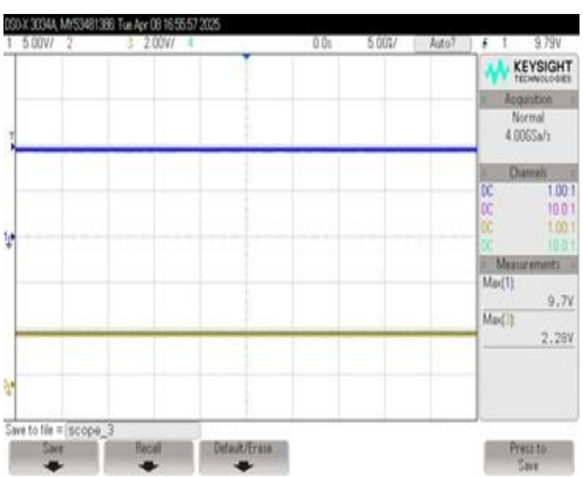

Fig. 16. Output Voltage of Proposed Converter

VII. CONCLUSION

A novel topology for a SEPIC DC-DC converter that minimizes voltage stress on the switches has been proposed and successfully implemented. The design incorporates a voltage multiplier concept. In comparison to other topologies, the enhanced SEPIC converter demonstrates reduced voltage stress on the switching devices and a decrease in output ripple content. Comprehensive simulation and analysis of the enhanced SEPIC converter have been conducted. The results indicate that the converter achieves an efficiency of 80% for an output power of 200W. Furthermore, the analysis reveals that the modified converter reaches a peak efficiency of 81% at the same output power of 200W. A hardware prototype was developed with an input voltage of 2V, utilizing the TMS320F28335 microcontroller, resulting in an output voltage of 10V and a voltage gain of 5.1. The proposed topology also presents several advantages, including the absence of transient current, a wide operational range concerning duty ratio, and a common ground configuration. Consequently, these character- istics render the proposed topology an outstanding interface

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