SIMULATION OF A NOVEL CLOSED LOOP CONTROL SCHEME FOR A SINGLE-SWITCH BUCK-BOOST CONVERTER

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ABSTRACT

Simulation of a novel closed-loop control scheme for a single -switch buck - boost DC - DC converter , demonstrating superior voltage gain compared to buck-boost , SEPIC(Single Ended Primary Inductor Converter), ZETA converters . By employing a suitable duty cycle , high - voltage outputs can be achieved. The closed - loop control system enhances output voltage efficiency and stability, while minimizing energy losses through the use of a low-resistance power switch. The converter's simple structure facilitates straight forward control and reduces overall system complexity. A detailed explanation of the converter's operating principle and mathematical analysis is provided, with results confirming the converter's feasibility and effectiveness.

Keywords : *Power Switch, Buck-Boost Converter, Closed-loop, dc-dc converter, voltage gain, voltage stress, closed-loop control, PID controller.*

1. INTRODUCTION

As the world faces increasing environmental challenges, particularly those related to global warming and climate change, the demand for clean, sustainable energy sources has never been more urgent. These environmental issues, primarily driven by rising carbon dioxide emissions, are prompting a global shift toward low-emission and renewable energy solutions. In this context, fuel cell systems are gaining significant attention as a promising alternative for environmentally conscious energy generation. Fuel cells produce electricity through electrochemical reactions and are widely recognized for their clean operation, high energy conversion efficiency, and low emissions. They serve as a perfect substitute for fossil fuel-based energy sources in various applications, such as emergency backup systems and electric vehicles. Users can benefit from their ability to generate energy continuously, provided a renewable fuel supply, making fuel cells a compelling solution for the future of sustainable power. Despite these benefits, fuel cells face certain limitations. A primary concern is that the output voltage from a single fuel cell unit is both low and variable, which restricts its direct use in most electronic loads. This creates the need for a power conversion stage that can reliably regulate and step up the voltage. To address this, buck–boost DC–DC converters are commonly employed, as they can both increase and stabilize the voltage to meet load requirements. However, traditional buck–boost converters struggle to deliver high efficiency due to various power losses associated with switches, diodes, and the equivalent series resistance (ESR) of inductors and capacitors. These losses are especially critical in systems that rely on clean energy sources like fuel cells, where efficiency and compactness are paramount. To overcome these limitations, this paper proposes a novel single-switch, transformer-less buck–boost DC–DC converter. The proposed converter offers high step-up voltage gain and operates with low voltage stress on its power switch, significantly reducing conduction losses. Its simple and compact topology not only enhances efficiency but also simplifies the overall control architecture, making it highly suitable for practical implementation in low-power systems. Moreover, to further improve performance, a closed-loop control scheme is implemented. This control system employs a voltage feedback mechanism, where the output voltage is continuously monitored and compared with a reference voltage. A Proportional-Integral (PI) controller processes the resulting error signal to adjust the duty cycle of the PWM control signal, thereby stabilizing the output under varying load and input conditions. The closed-loop design ensures precise voltage regulation, fast transient response, minimal voltage ripple, and improved reliability. These characteristics make the proposed converter highly adaptable for modern applications such as fuel-cell-powered devices, electric vehicle components, LED drivers, and portable electronic gadgets. With its efficient operation, simplified structure, and strong voltage regulation capability, the proposed system addresses key challenges in fuel cell integration and sets the stage for broader adoption of clean energy technologies.

2. Literature Review

Over the years, various DC–DC converter topologies have been developed to interface low-voltage fuel cell outputs with practical electronic loads. Conventional buck–boost converters, while simple, exhibit poor efficiency due to switching losses, diode drops, and ESR effects in inductors and capacitors [6]. To address the need for high voltage gain, several high step-up DC–DC converter configurations have been proposed. A notable approach includes the flyback converter, which achieves high gain by increasing the transformer's turns ratio. However, this comes at the cost of voltage spikes across the switches and reduced efficiency due to leakage inductance and reverse-recovery issues [9]–[11]. Coupled inductor based converters have also been introduced to enhance gain [12], [13]. Nonetheless, leakage inductance remains problematic, causing high voltage stress. In [14], a switched capacitor method is used for voltage boosting, while in [15] and [16], bidirectional high step-up converters are presented with low voltage stress. Yet, these designs are often complex, involving multiple power switches, leading to higher conduction losses and system cost. Other notable works include: An interleaved transformer-less step-down converter [17], which uses two switches but suffers from abrupt charging. Transformer-less high step-up converters [18], [19], which improve gain but may lack robustness. A KY-based buck–boost converter [20] and a CUK-based converter [21], both of which achieve voltage gain roughly double that of traditional buck–boost converters.Multi-output converters [22] and two-stage topologies [23], [24], which enhance functionality but often involve higher component counts. Despite these advancements, many converters either compromise on simplicity, suffer from high voltage stress, or demand complex control mechanisms. In light of these limitations, this paper proposes a new single-switch transformer-less buck–boost converter. The proposed topology surpasses conventional designs like buck–boost, SEPIC, CUK, and ZETA in terms of voltage gain while maintaining a compact and simple structure. It employs only one power switch, experiences reduced voltage stress on active and passive components, and achieves minimal conduction losses, thereby enhancing overall efficiency. To further improve system performance, a closed-loop control strategy is implemented. This strategy compares the output voltage with a reference value, generating an error signal that is processed through a PI controller. The resulting control signal modulates the PWM duty cycle, ensuring precise voltage regulation even under dynamic conditions. This closed-loop approach offers improved transient response, reduced voltage ripple, and increased reliability. Such a configuration makes the converter highly suitable for modern low-power, low-voltage applications, particularly where clean and efficient power delivery is essential—such as in fuel cell-based devices, electric vehicles, mobile gadgets, and LED lighting systems.

3. Operation Principle of proposed converter

The converter in Fig - 1(a) is the proposed converter. The converter has one power switch S, three diodes D1, D2, and D3, three inductors L1, L2, and L3, five capacitors C1, C2, C3, C4, and Co and load R.

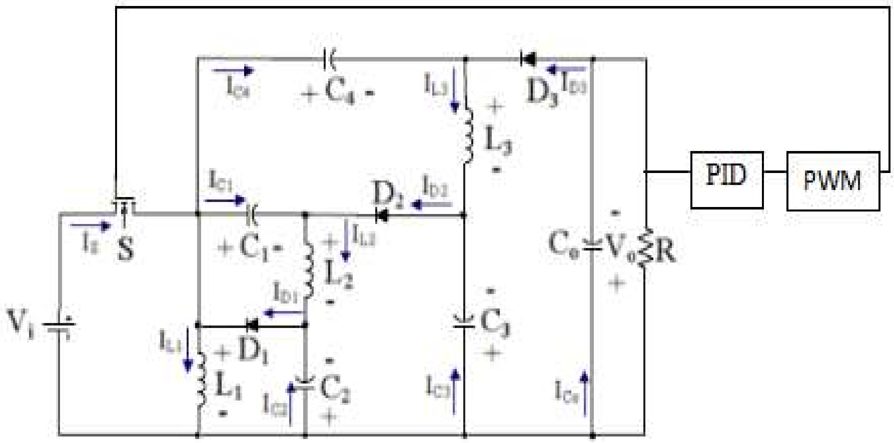


Fig - 1(a) : Equivalent Circuit of the proposed converter

For ease of analysis of the operating principles, the following assumptions are made :-

1) The capacitors of the proposed converter are sufficient, therefore the voltage across capacitors is taken as constant.

2) The main switch of the proposed converter is considered ideal and the parasitic capacitor of the main switch is not considered.

The proposed converter can operate in both the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM). The CCM can further be classified as two operation modes. The derivation of the described converter in a single switching cycle under CCM is discussed step by step in detail as follows:

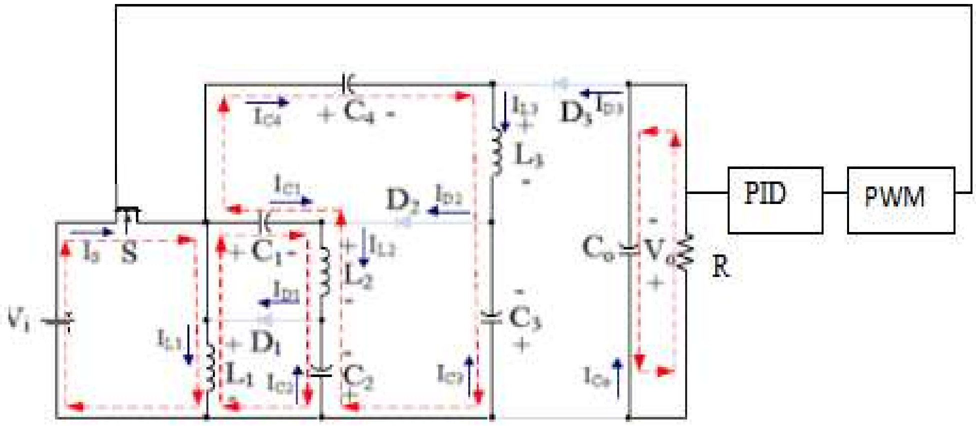


Fig - 1(b) : Equivalent Circuit of the proposed converter when Switch ON Mode

1) First mode [$0 \leq t \leq DTs$]: In this interval of time as indicated in Fig. - 1(b), the switch S is ON and the diodes D1, D2, and D3 are OFF. The inductors L1, L2, and L3 are magnetized linearly. The capacitors C1 and C4 are charged by the capacitors C2 and C3. Therefore, the related equations can be described as follows:

$$VL1 = Vi \qquad (1)$$

$$VL2 = VC\,2 - VC\,1 + Vi \qquad (2)$$

$$VL3 = VC\,3 - VC\,4 + Vi \qquad (3)$$

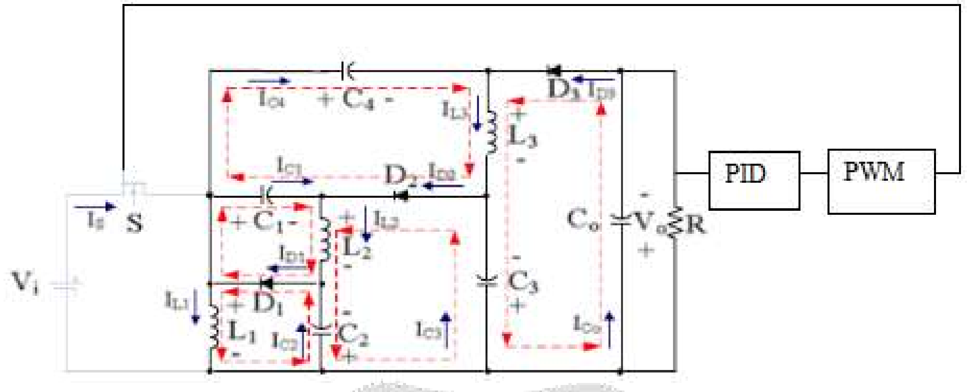


Fig - 1(c) : Equivalent Circuit of the proposed converter when Switch OFF Mode

2) Second mode [DTs ≤ t ≤ Ts]: The equivalent circuit is displayed in Fig. - 1(c). At this time interval, the switch S is shut off and the diodes D1, D2, and D3 are shut on. Inductors L1, L2, and L3 are demagnetized linearly. The capacitor C2 is charged from the inductor L1 and the capacitor C3 is charged from the inductors L1 and L2 and capacitors C1 and C4 are discharged. The relevant equations can be given as below:

$$V_{L1} = -V_{C2} \quad (4)$$
$$V_{L2} = -V_{C1} = V_{C2} - V_{C3} \quad (5)$$
$$V_{L3} = V_{C1} - V_{C4} = V_{C3} - V_o \quad (6)$$

4. STEADY STATE ANALYSIS OF THE PROPOSED CONVERTER

The voltage gain curves for the proposed converter, conventional boost, buck—boost, and CUK converters, proposed converter III in [18] and proposed converter in [19] are shown in Chart - 1(a). It is seen that the proposed converter is buck–boost and the voltage transfer gain of the converter is higher than that of the other converters.

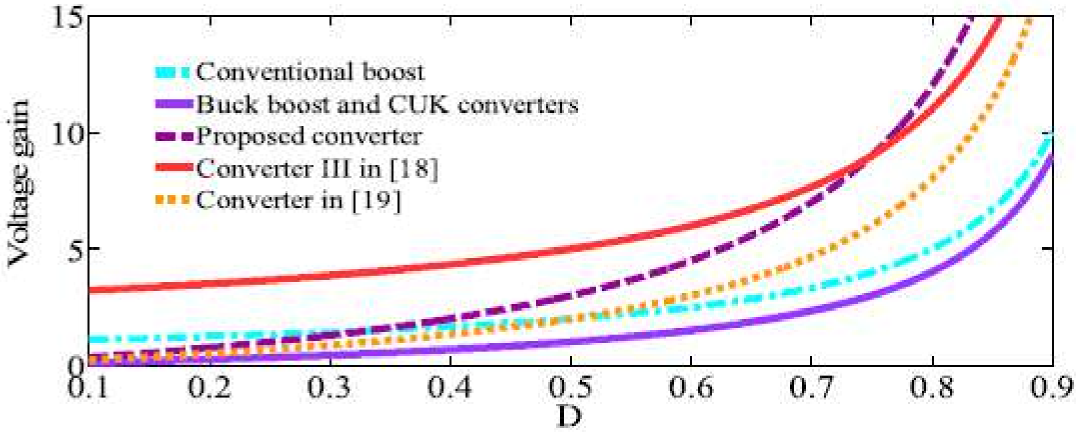


Chart - 1(a) : Curves of voltage gain comparison of proposed converter and other converters at CCM

The operation modes in DCM can be divided into three modes. The first mode in DCM is the same as the initial mode in CCM. In the next mode, the diodes currents are decreasing and in the third mode the diodes D1 , D2 , and D3 currents will be zero and the diodes and switch will turn OFF. The equivalent circuit and the typical waveform in third mode are shown in Fig - 1(d). In this mode, the inductors L1 , L2 , and L3 currents will be constant; therefore, the voltage of the inductors L1 , L2 , and L3 will be zero.

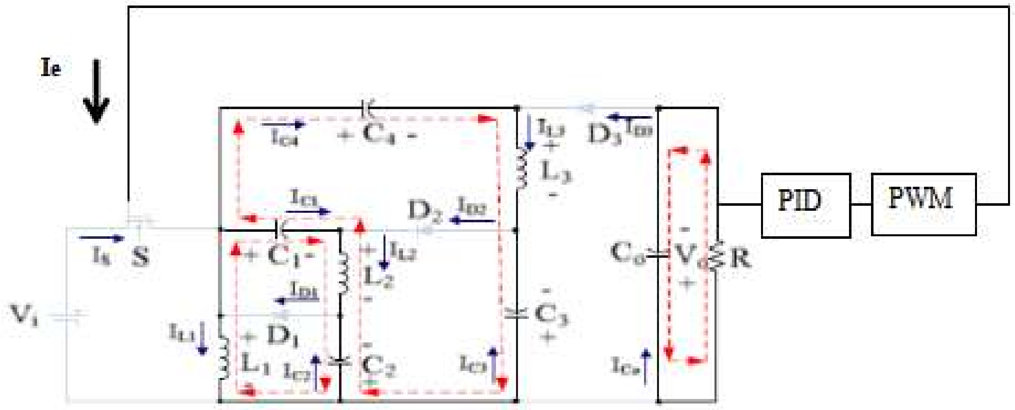


Fig - 1(d) : Proposed converter third mode at DCM operation

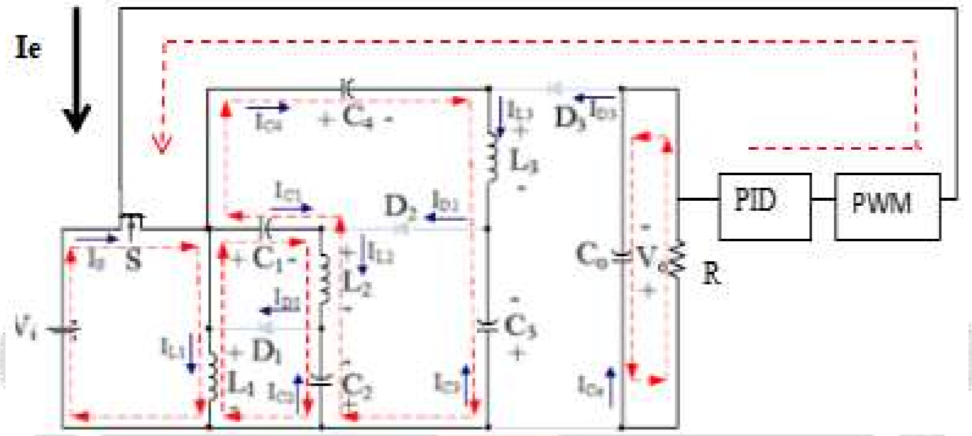


Fig - 1(e) : Error correction mode in proposed converter

3) After second mode the circuit displayed the error voltage between output voltage and reference voltage in the Fig - 1(e). That error is comes from summing point and it goes to PID Controller (This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking).

Then it goes to PWM generator (It is DC-DC PWM generator). It creates spikes and passes to MOSFET for improving efficiency and stability of the circuit.

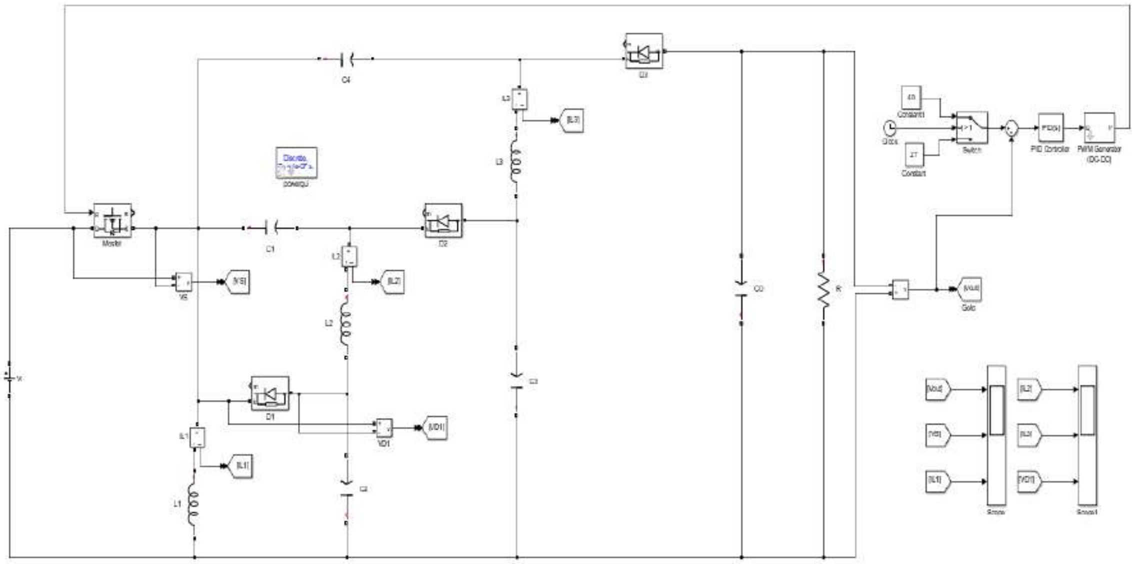
Here V_r = Reference Voltage
V_o = Output Voltage
V_e = Error Voltage
I_e = Error Current
$V_r - V_o = V_e$ (7)

The waveform of the proposed converter is shown in scopes and they are show the efficiency and stability of the converter. According to , the voltage gain of the proposed converter is higher than that of the conventional boost, buck–boost, CUK, SEPIC, and ZETA converters and is thrice as large as the voltage gain of the conventional buck–boost converter.

5. Results and Analysis

Simulations were conducted using MATLAB Simulink:

5.1 MATLAB/SIMULINK Model of Proposed Converter



5.2 Voltage Stress of the Switch

In this converter, the voltage stress across the active components, such as switch and diodes, is lesser than output voltage. The voltage stress on power switch (Vs) can be achieved as follows:

$$V_S = \frac{V_i}{1-D}.$$

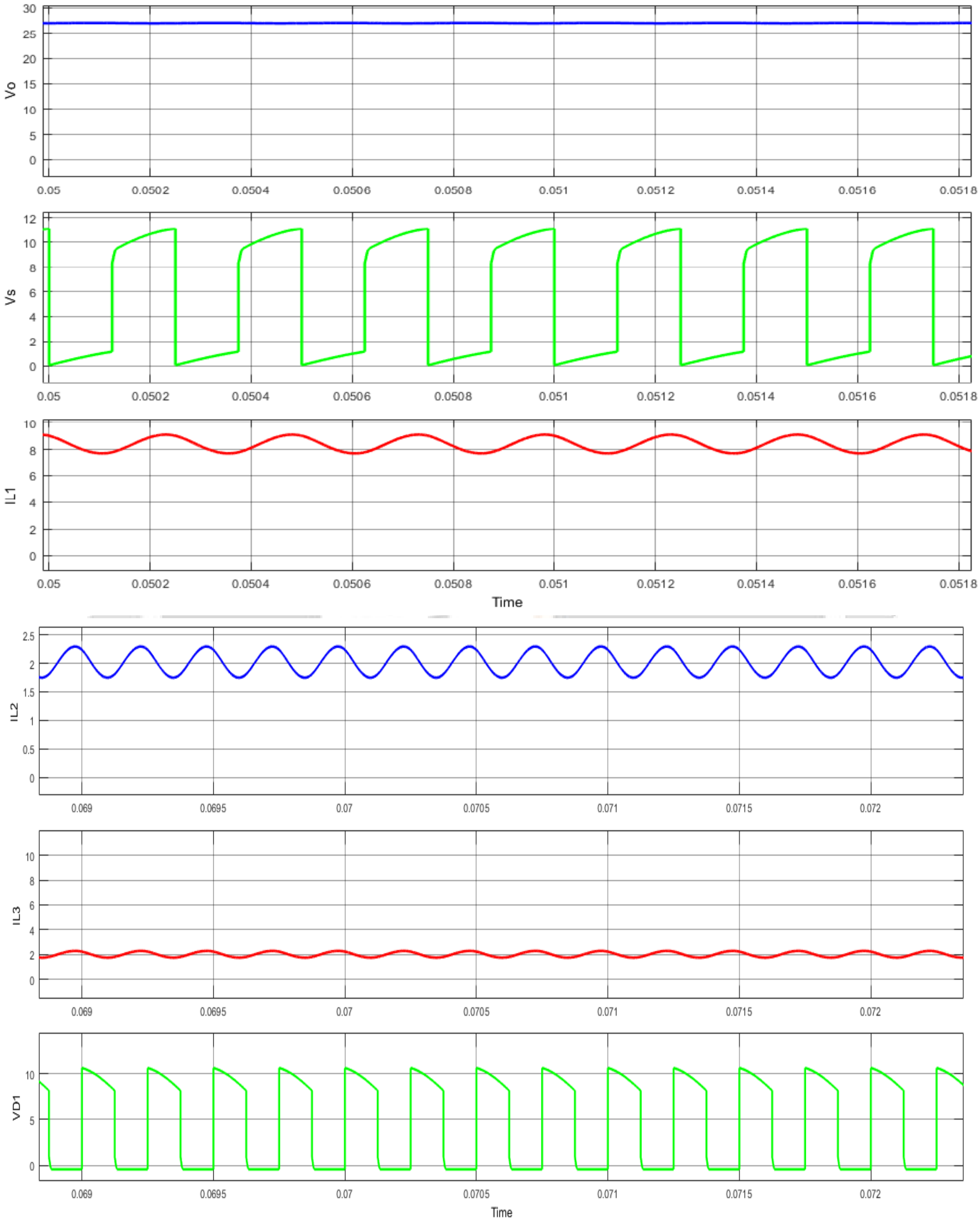
The relationship between the normalized voltage stress across power switch of the proposed converter and other converters is depicted. The normalized voltage stress of the switch in the proposed converter is lesser than that in other converters.

To demonstrate the performance of the presented converter, experimental results are provided. The proposed converter components specifications are as follows:

1) input voltage: 11 V;
2) switching frequency (buck): 37 kHz;
3) switching frequency (boost): 33 kHz;
4) switch: IRFP460A;
5) diodes D1 , D2 , and D3 : MUR860;
6) inductor L1 (buck): 1 mH;
7) inductors L2 and L3 (buck): 580 μH;
8) inductor L1 (boost): 100 μH;
9) inductors L2 and L3 (boost): 260 μH;
10) capacitors C1 ,C2 , C3 and C4 : 100 μF;
11) capacitor Co : 470 μF.

The proposed converter is tested in the buck and boost states operation. The proposed converter is operated in CCM operation mode. In the buck state operation, the output voltage waveform is shown in Chart - 2(a). The output voltage is equal to 27 V. The inductors L1 , L2 , and L3 currents waveforms are shown in Chart - 2(c), 2(d), and 2(e), respectively. The average values of inductors L1 , L2 , and L3 currents , which closely agree with the experimental results. The voltages of diodes D2 and D3 waveforms are not shown since the diodes waveforms are similar to diode

D1 voltage waveform.The voltage of diode D1 waveform is shown in Chart - 2(f). The voltage of the switch S is shown in Chart - 2(b). In the boost state operation, the output voltage is shown in Chart - 2(a). The output voltage is equal to 42 V and the output power is equal to 135W.The maximum efficiency is appropriately 98.9%. The full-load efficiency is around 97.2%.



Experimental results,**Chart - 2(a)** : output voltage, Chart - **2(b)** : switch S voltage, Chart - **2(c)** : inductor L1 current, Chart - **2(d)** : inductor L2 current, Chart - **2(e)** : inductor L3 current, Chart - **2(f)** : diode D1 voltage.

We take the **technical and performance-based differences** between traditional DC-DC converters and the **novel single-switch buck–boost converter** proposed in this work.

Table - 1 : Comparison Table: Traditional vs Proposed Converter

Parameter	**Traditional Buck-Boost / SEPIC / ZETA Converters**	**Proposed Single-Switch Buck-Boost Converter**
Topology	Complex (multiple switches and passive elements)	Simple (single switch and fewer passive elements)
Voltage Gain	Limited, especially at moderate duty cycles	High gain even at moderate duty cycles
Component Count	Higher, which increases size and cost	Reduced – only one main switch used
Voltage Stress on Switch	High – affects efficiency and switch lifespan	Low voltage stress → Improved efficiency
Control Simplicity	Moderate (especially with complex topologies)	Simple control structure due to single switch
Efficiency	Lower due to switching losses and ESR effects	Higher due to low-resistance switch and better layout
Dynamic Load Handling	Poor without external regulation	Excellent when combined with closed-loop control
Application Suitability	Limited to fixed load scenarios	Ideal for renewable energy, EVs, LED drivers

Table - 2 : Open-Loop (Existing) vs Closed-Loop Control (Proposed Converters)

In many previous designs, **open-loop control** was employed, where no feedback from the output was used to regulate the converter. This often led to poor voltage regulation under dynamic conditions. The proposed converter utilizes a **closed-loop control** system to address this.

Aspect	**Open-Loop Control(Existing)**	**Closed-Loop Control (Proposed)**
Feedback Mechanism	❌ No feedback – output is not self-corrected	✅ Feedback from output is used to adjust operation
Voltage Regulation	Poor – cannot correct for variations	Precise and stable under varying load/input
Transient Response	Slow and unstable during input/load changes	Quick adjustment to dynamic conditions
Duty Cycle Control	Fixed or manually adjusted	Automatically regulated via PI controller
Output Voltage Accuracy	Low – prone to drift and noise	High accuracy and reliability
System Stability	Can be unstable without tuning	Stable due to feedback and PID tuning
Real-Time Adaptability	Cannot respond to sudden disturbances	Adapts instantly to system changes
Efficiency under Dynamic Load	Degrades under varying conditions	Optimized efficiency at all times

6. Discussions

We take the key points of the proposed closed-loop system

1. The output voltage (V_o) is continuously monitored.
2. This value is fed back and compared with a reference voltage at a summing point.
3. The error signal is passed through a PI (or PID) controller.
4. PWM generator adjusts the duty cycle of the main switch based on this control signal.
5. Result: Stable, efficient, and high-performance voltage regulation in real time.

Table - 3 : Real-World Applications and Benefits

Application Area	**How the Proposed System Helps**
Fuel Cell Systems	Maintains constant output despite varying input voltage
Electric Vehicle Components	Reliable power delivery for dynamic load changes
LED Drivers	Reduced flicker and better brightness control
Mobile & Portable Devices	Compact, efficient power with battery integration
Telecom Backup Systems	High voltage gain and reliability in low-power scenarios

7. CONCLUSION

In this paper, a novel single-switch buck–boost converter with an effective closed-loop control strategy has been introduced. The small and transformer-less structure not only reduces the hardware complexity but also minimizes conduction loss and switch stress, leading to higher efficiency. As opposed to open-loop systems, which are sensitive to variations in input and load, the closed-loop system provides higher voltage regulation, quicker dynamic response, and higher system stability. The proposed converter provides a higher voltage gain than conventional topologies like boost, buck–boost, CUK, SEPIC, and ZETA. All these benefits make the converter a viable candidate for applications in contemporary low-power systems like portable equipment, automotive electronics, and LED drivers. Its simplicity and reliability attest to its practical usability in real applications.

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