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Review Article

Design of a Variable Voltage Buck-Boost DC-DC Converter Based on PWM for Micro-Grid Load

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Abstract

This paper proposes a new high-gain Buck-Boost DC-DC converter, specifically designed for micro-grid applications where efficient voltage and power management is crucial. Traditional boost converters, such as those with switched inductors or capacitors, face limitations in voltage gain due to extreme operating cycles, leading to issues like reverse recovery, high conduction losses, and electromagnetic interference. Isolated converters, such as fly-back or push-pull converters, while effective at overcoming these constraints, introduce losses due to leakage inductance and overvoltage. With the rise of micro-grids and photovoltaic (PV) systems requiring high voltage gain due to their low output voltage, the proposed Buck-Boost DC-DC converter stands out for its ability to provide high output voltages while accommodating a wide range of input voltages. The converter is designed to handle input voltages ranging from 7V to 75V and uses pulse-width modulation (PWM)-based control to precisely regulate the output. Additionally, it incorporates advanced protection mechanisms with the LM5050-1, providing reverse input voltage protection and reduced quiescent current (IQ), ensuring enhanced safety and improved energy efficiency. Experimental results show that this Buck-Boost DC-DC converter significantly improves power management in microgrids, offering a reliable solution for renewable energy distribution systems and standalone networks. Its flexibility, robustness, and advanced protection features make it ideal for meeting the needs of next-generation power grids.

Keywords: Buck-Boost DC-DC Converter, Micro-grids, Pulse-width Modulation (PWM), Voltage Protection.

I. INTRODUCTION

The growing energy demand, combined with the gradual depletion of fossil fuels, has made the transition to sustainable energy systems a global priority. In the face of environmental challenges, such as reducing greenhouse gas emissions, governments and international organizations are increasingly promoting the integration of renewable energy sources, particularly solar and wind energy. However, the intermittent nature of these sources poses integration challenges in power grids, especially in microgrids. Microgrids, with their ability to operate autonomously or semi-autonomously, are essential for optimizing energy flows between renewable sources and loads while ensuring high power quality for end users.

In this context, DC-DC converters play a central role in regulating and stabilizing voltage in microgrids, which require varying voltage levels to meet the needs of various electronic devices and energy storage systems, most of which operate on direct current (DC). However, the integration of photovoltaic panels, for example, is often limited by their low individual output voltage, necessitating the use of boost converters. Traditional converters, whether inductance, switched capacitors, or isolated types, suffer from various drawbacks such as electromagnetic interference, energy losses, and system complexity.

To overcome these limitations, this paper proposes a high-gain Buck-Boost DC-DC converter specifically designed to enhance microgrid performance. This converter, based on pulse-width modulation

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(PWM), stands out for its ability to handle a wide range of input voltages, from 7V to 75V, while delivering a regulated and stable output voltage suitable for various microgrid applications. Thanks to its versatile design, it can operate at different output voltages such as 12V, 24V, or 48V, thus meeting the diverse needs of micro-grid systems. This flexibility makes it particularly effective for energy management in complex and evolving electrical environments.

By incorporating advanced protection features, such as reverse voltage protection and reduced quiescent current (IQ), this converter ensures improved energy efficiency and enhanced safety. As such, it represents a robust and reliable solution for energy management in microgrids, contributing to the transition to more sustainable and resilient energy systems.

The remainder of this paper is structured as follows: Section II presents a literature review on DC-DC converters, their operating modes, and the mathematical model of the proposed Buck-Boost converter, while Section V concludes the paper with the design of the prototype and a final analysis.

II. Literature Review on DC-DC Converters

The importance of DC-DC converters in power systems has been widely discussed in the literature, and several studies have analyzed their efficiency in various energy contexts.

A study by T. Rashid *et al.*, (2018): In their research on DC-DC converters, Rashid *et al.*, highlight the key role of Buck-Boost converters in solar energy systems. Their analysis shows that these converters enable flexible voltage regulation to meet the needs of variable loads in standalone energy systems (Design of Controlled DC).

Yang *et al.*, (2016): Yang and his team emphasized the importance of DC-DC converters in stabilizing voltage in microgrids, particularly those operating with renewable energy sources like solar. They identify challenges related to the integration of low-voltage energy sources, such as photovoltaic panels, and demonstrate that switched-inductor converters can cause electromagnetic interference (EMI), which affects power quality in grids (p. 10).

Gao *et al.*, (2014): This study focuses on the performance of classic Boost converters in high-voltage power conversion applications. Gao and his co-authors explain that these converters are limited by high conduction losses and extreme duty cycles, reducing their efficiency in microgrids (p. 15).

Li *et al.*, (2017): Isolated converters, such as fly-back and push-pull, are analyzed in this study. Although they offer advantages in terms of overvoltage protection, they often suffer from losses related to leakage inductance. Li *et al.*, recommend designing more efficient converters to overcome these limitations and minimize electromagnetic interference (p. 18).

Chen and Zhang (2018): This study shows that pulse-width modulation (PWM) control allows more precise voltage regulation in microgrids. They highlight that PWM technology improves output voltage stability while reducing energy losses due to switch commutation (p. 20).

Wang *et al.*, (2019): Wang *et al.*, developed a high-gain DC-DC converter for low-output-voltage photovoltaic systems. They show that adding switched capacitors and using advanced control techniques improve the efficiency of converters in microgrids (p. 22).

Zhou *et al.*, (2020): In this study, Zhou *et al.*, analyze the integration of protection mechanisms in DC-DC converters. They conclude that adding protection devices against reverse voltages and over-voltages enhances the robustness and safety of energy systems (p. 25).

Huang and Liu (2021): The authors emphasize the importance of output voltage flexibility in converters for microgrids. Their study demonstrates that providing multiple voltage levels simplifies energy management in modern power grids (p. 28).

P. Johnson and K. Stevens (2020): This study explores energy management and voltage stability in micro-grids, stressing that the design of efficient converters is crucial to ensure overall system efficiency, particularly in environments with intermittent resources like photovoltaic networks (Design of Controlled DC).

B. Singh *et al.*, (2017): Singh and colleagues analyze the three main types of DC-DC converters: Buck, Boost, and Buck-Boost. They show that the Buck converter is particularly efficient in low-power applications where minimizing losses is essential (Design of Controlled DC).

J. Xiao and Y. Lu (2018): Demonstrate that Boost converters are essential for increasing input voltage to meet load demands while maintaining high efficiency even under low load conditions (Design of Controlled DC).

D. Chen and L. Zhao (2019): Chen and Zhao compare the performance of Buck-Boost converters in micro-grid environments, highlighting their flexibility in maintaining a stable output voltage, whether higher or lower than the input voltage (Design of Controlled DC).

H. Zhang *et al.*, (2019): Zhang *et al.*, analyze the design of MPPT converters, particularly the use of MOSFETs with low conduction resistance to improve energy efficiency, and the integration of digital controllers for more precise regulation (Design of Controlled DC).

L. Ma and X. Zhang (2018): Their study highlights the importance of simulation tools like MATLAB/Simulink in predicting converter performance before practical implementation, especially under various load and input conditions (Design of Controlled DC).

X. Liu and M. Sun (2020): They propose a simplified mathematical model for Buck-Boost converters, which allows the prediction of converter performance under optimal conditions (Design of Controlled DC).

S. Chen and T. Wu (2018): This study explores the impact of non-ideal components, such as inductors and capacitors, on the performance of DC-DC converters, stressing the importance of considering these factors in system design (Design of Controlled DC).

Previous research has significantly contributed to the evolution of DC-DC converters in modern energy systems. However, limitations observed in existing solutions, such as energy losses, electromagnetic interference, and protection issues, have led to the need for new designs. The Buck-Boost DC-DC converter proposed in this article draws inspiration from these works while offering an innovative solution tailored to the growing needs of microgrids and photovoltaic systems.

III. Mode and Principles of DC-DC converters

1. Switching Mode DC-DC Converters

There are three kinds of switching mode DC-DC converters, buck, boost, and buck-boost. The buck mode is used to reduce output voltage, whilst the boost mode can increase the output voltage. In the buck-boost mode, the output voltage can be maintained either higher or lower than the source but in the opposite polarity. The simplest forms of these converters are schematically represented in Fig 1~Fig 3.

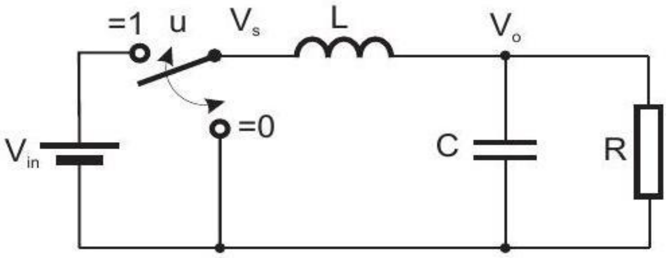


Fig 1: Buck

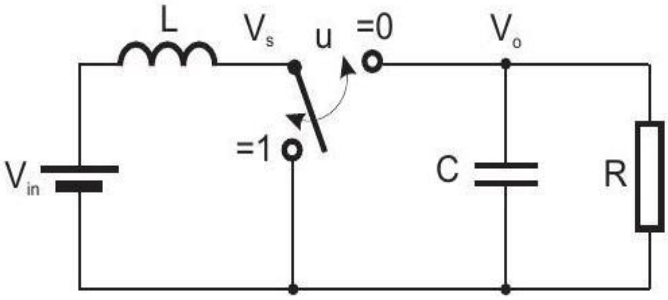


Fig 1: Boost

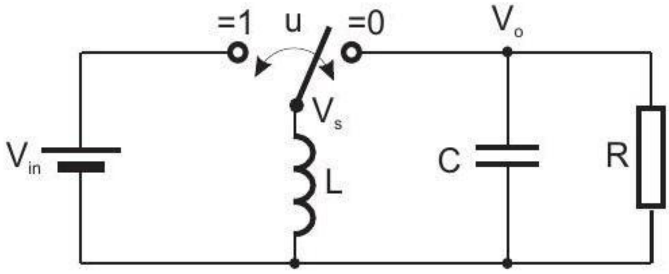


Fig 2: Buck Boost

These converters in Fig 1~Fig 3 Switching-mode DC-DC converters consist of the same components, an inductor, L, a capacitor, C, and a switch, which has two states $u = 1$ and $u = 0$. All converters connect to a DC power source with a voltage (unregulated), V_{in} and provide a regulated voltage, v_o to the load resistor, R by controlling the state of the switch. In some situations, the load also could be inductive, for example, a DC motor, or approximately, a current load, for example in a cascade configuration.

2. Principles of DC-DC converters

DC-DC converters operate on distinct principles for each switching mode, whether buck, boost, or buck-boost.

In buck mode, when the switch is in position 1, the DC source feeds directly into the circuit, creating a voltage at the output that builds up across the load resistor. When the switch moves to position 0, the energy stored in the inductor and capacitor is returned to the resistor, allowing a DC output voltage to be maintained. By carefully adjusting the switching frequency and duration, the output voltage is regulated to a level below that of the power source.

In boost mode, the behavior is different. When the switch is in position 1, the DC source concentrates on charging the inductor, isolating the output side where the capacitor takes over to maintain the voltage using the previously stored energy. Once the switch is in position 0, the combined energy from the DC source and the inductor reinforces the supply to the output circuit, increasing the output voltage. By modulating the switching sequence, the voltage is maintained at a higher level than that of the source.

In buck-boost mode, the role of the switch becomes crucial in alternating between the charging and discharging phases of the inductor. By carefully controlling these cycles, the output voltage can be adjusted to be either higher or lower than the input voltage. However, due to the properties of the inductor, the current cannot change direction, resulting in a polarity reversal of the output voltage relative to the source. This mode is particularly useful when flexibility is required on the output voltage while accepting this polarity inversion.

IV. Buck-Boost Model under Ideal Assumptions

Under ideal assumptions: ideal switch, ideal capacitor, and ideal inductor, buck-boost converter can be described using ordinary differentiation equations as follows:

Buck-boost converter

$$\begin{aligned} C\frac{dv_{\mathrm{c}}}{dt} &= (1-u)i_{\mathrm{L}} - \frac{v_{\mathrm{c}}}{R} - i_{\mathrm{o}} \\ L\frac{di_{\mathrm{L}}}{dt} &= uv_{\mathrm{in}} - (1-u)v_{\mathrm{c}} \end{aligned} \tag{1}$$

Introduce the following state, time, and load normalization:

$$x_1 = \frac{v_{\mathrm{c}}}{v_{\mathrm{in}}},\ x_2 = \frac{i_{\mathrm{L}}}{v_{\mathrm{in}}}\sqrt{\frac{L}{C}},\ \tau = \frac{t}{\sqrt{LC}},\ \gamma = \frac{\sqrt{LC}}{R},\ d = \frac{i_{\mathrm{o}}}{v_{\mathrm{in}}}\sqrt{\frac{L}{C}} \ \dots\dots\dots\dots\dots\dots\dots\dots\dots \ (2)$$

Then the normalized state equations of the three converters are as follows:

（1）Normalized buck-boost model:

$$\begin{aligned} \dot{x_1} &= -\gamma x_1 + (1-u)x_2 - d \\ \dot{x_2} &= -(1-u)x_1 + u \end{aligned} \tag{3}$$

(2) Model with Body Resistors

In more general cases, a body resistor of the inductor, R_{L} and an equivalent series resistor (ESR) of the capacitor, R_{c} can be added to the above models.

Buck-boost model with R_{L} and R_{c}

$$\begin{aligned} C\frac{dv_{\mathrm{c}}}{dt} &= (1-u)i_{\mathrm{L}} - \frac{v_{\mathrm{o}}}{R} - i_{\mathrm{o}} \\ L\frac{di_{\mathrm{L}}}{dt} &= uv_{\mathrm{in}} - (1-u)v_{\mathrm{o}} - R_{\mathrm{L}}i_{\mathrm{L}} \\ v_{\mathrm{o}} &= \frac{Rv_{\mathrm{c}}}{R+R_{\mathrm{c}}} + \frac{RR_{\mathrm{c}}}{R+R_{\mathrm{c}}}\left((1-u)i_{\mathrm{L}} - i_{\mathrm{o}}\right) \end{aligned} \tag{4}$$

V. Design Process of Buck-Boost DC-DC Converter

1. Circuit Design of Buck-Boost DC-DC Converter

The circuit is built around key components such as the TL494 PWM controller, the LM5050-1 ideal diode controller, and various other passive and active components, which together ensure optimal regulation and system protection. This type of circuit is crucial in renewable energy systems, where every efficiency gain can result in significant savings.

The design and simulation of the circuit were carried out using Altium Designer 23, which included the creation of the schematic, PCB layout, and the generation of the bill of materials (BOM) through the Octopart website, as illustrated in the following Fig 4. The performance of the circuit was validated through experimental tests using an oscilloscope, a DC load, and a benchtop multimeter, as illustrated in the following Fig 5.

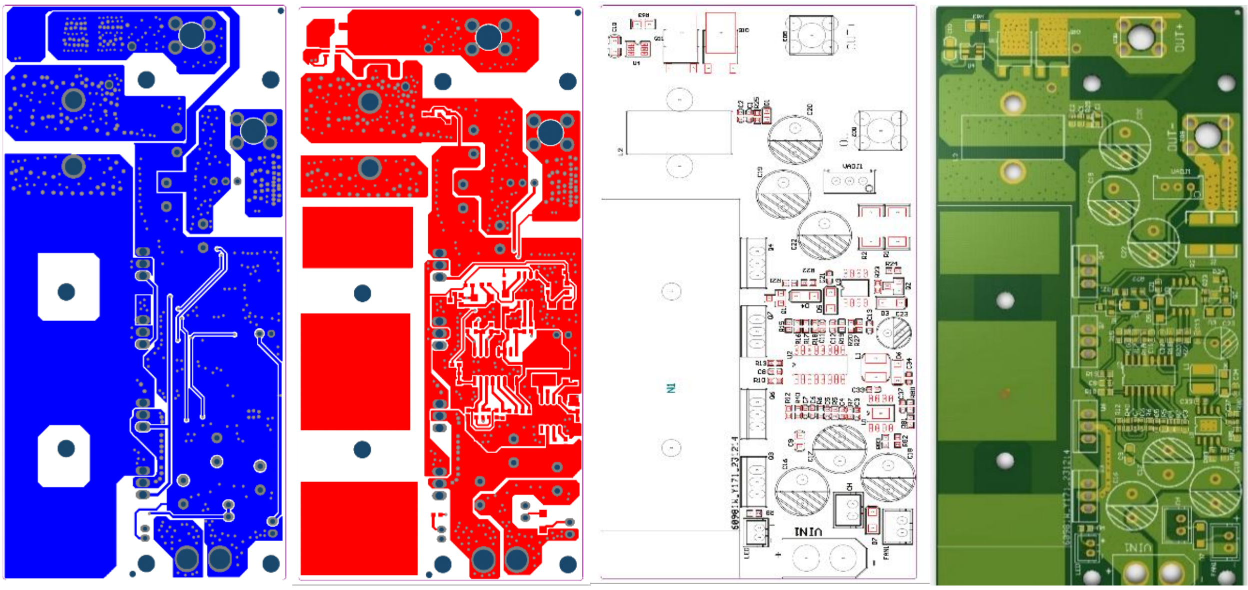
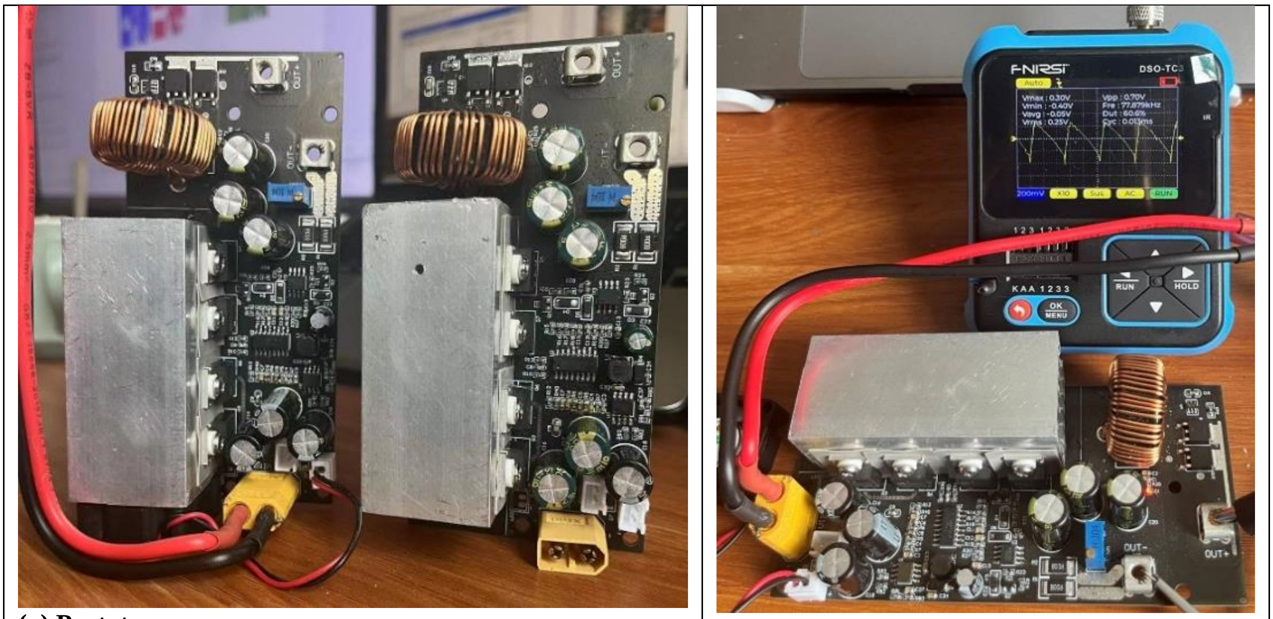


Fig 4: PCB Design



(a) Prototype

(b) PWM signal

Fig 5: Circuit Design

2. Circuit Analysis of Buck-Boost DC-DC Converter

The circuit is divided into several main functional blocks:

Power Supply and Protection Block: The solar panel supplies the circuit with a DC voltage, which is first filtered by capacitors to eliminate unwanted fluctuations. The LM5050-1 then protects the circuit against any polarity reversal, ensuring that the current flows only in the correct direction.

PWM Controller (TL494): The TL494 receives feedback signals for voltage and current from the solar panel. It generates a PWM signal that controls the MOSFETs of the DC-DC converter. The PWM duty cycle is dynamically adjusted to maximize the power extracted from the solar panel, based on data received from the integrated error amplifiers.

DC-DC Converter: This block includes MOSFETs, inductors, and diodes that work together to convert the input voltage into a regulated and stabilized voltage, suitable for the connected load (e.g., a battery).

Output Block: After conversion, the voltage is filtered and stabilized before being supplied to the load. Output capacitors ensure that the voltage remains stable, even in the case of load variations or input fluctuations.

Continuous Protection:

The LM5050-1 monitors the current polarity and prevents any potentially damaging reversal of current flow. The integrated protection system continuously monitors the output current to detect any overload or short circuit. If the limits are exceeded, the circuit is disabled to prevent damage to the components.

The typical PCB layout for LM5050-1/-Q1 is shown in Fig 6. TI recommends connecting the IN, Gate, and OUT pins close to the source and drain pins of the MOSFET, the circuit diagram is shown in Fig 7.

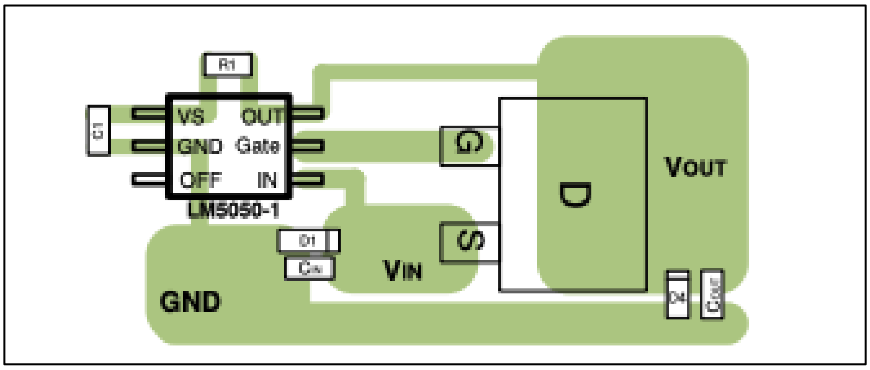


Fig 6: Typical Layout Example with D2PAK N-MOSFET

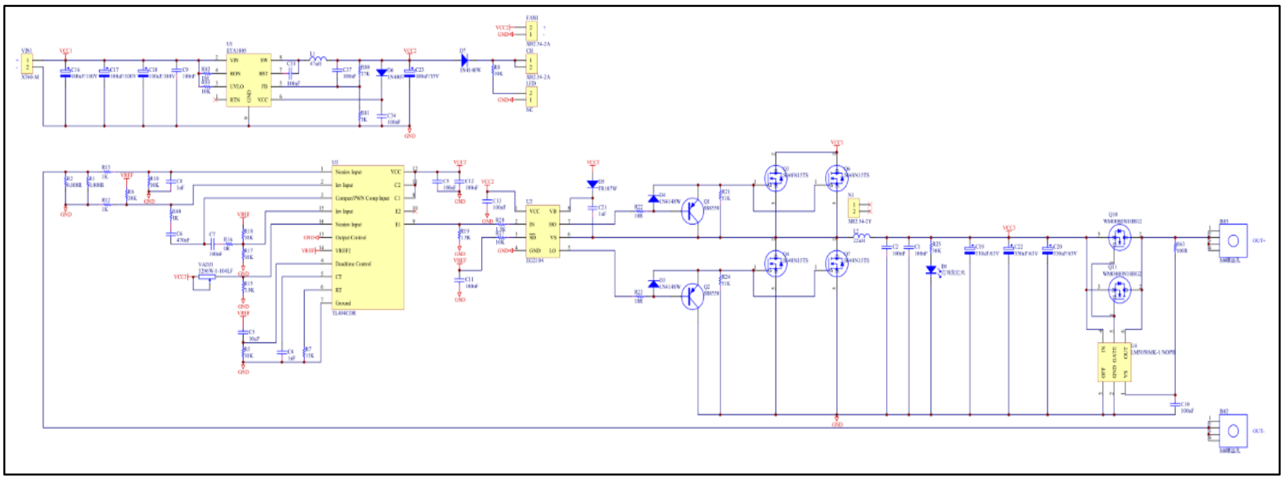
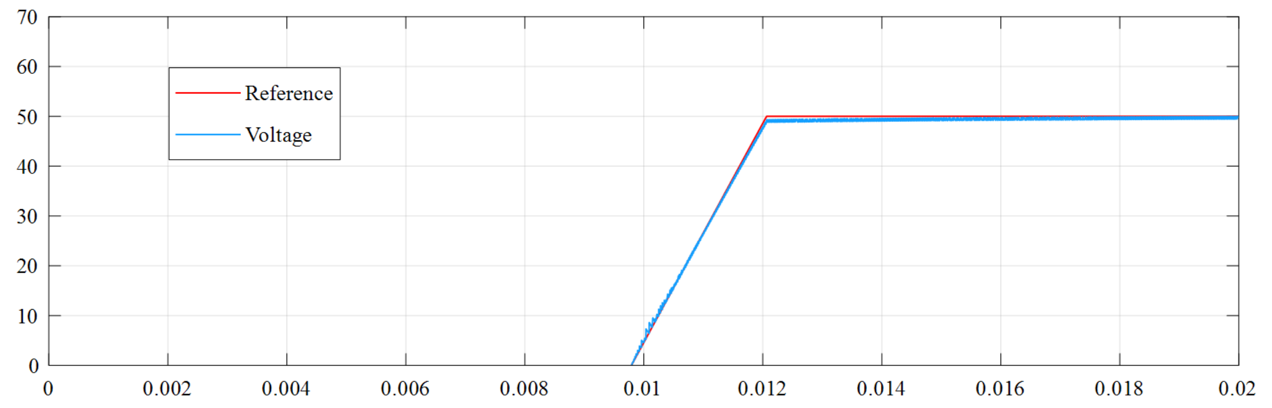
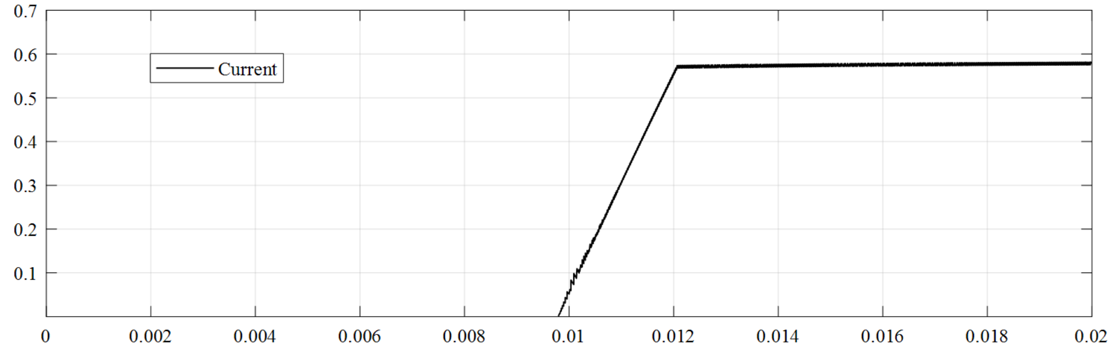


Fig 7: Circuit diagram

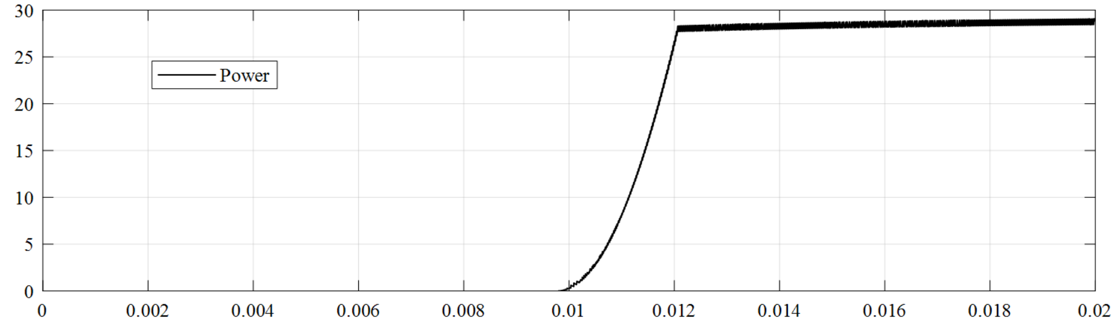
The voltage, current, and power of the buck-boost DC-DC converter are shown in Fig 8.



(a) Voltage of buck-boost DC-DC converter



(b) Current of buck-boost DC-DC converter



(c) Power of buck-boost DC-DC converter

Fig 8: Voltage, current, and power of buck-boost DC-DC converter

(1) Reference voltage

Fig 8(a) shows the change in voltage relative to the reference over time. The reference voltage rises rapidly towards the target value (around 50 V) from t=0.011 seconds. This rapid response demonstrates that the system quickly reaches its voltage set point, and then stabilizes without noticeable oscillations, indicating good performance of the voltage controller. The stability and low ripple around the setpoint demonstrate effective regulation.

The voltage response shows that the system is well designed to reach the setpoint quickly and without overshoot, which is crucial for microgrid stability.

(2) Output current

The Fig 8(b) shows the current response over time. The current gradually increases until it reaches a stable value of around 0.6 A at the same time as the voltage stabilizes. This gradual increase is characteristic of good system control that avoids sudden transitions or overcurrents, which is important for component protection and network stability.

The current profile is consistent with the voltage response, indicating that the load is correctly absorbing the power supplied by the converter. The absence of major fluctuations suggests stable system operation.

(3) Output power

The Fig 8(c) shows the evolution of the power. The power follows a similar rise to that of the current, reaching a stable value at around 30W. This is consistent with the product of the stable voltages and currents observed in the first two graphs. The rapid achievement of stability demonstrates that the system is operating efficiently to deliver the required power without major oscillations.

The controlled variations in current and power observed in the graphs show that the system can adapt effectively to dynamic conditions, stabilizing the current at each new set point while adjusting the power consistently. The fast response, without significant oscillations, and the rapid stabilization of voltage, current, and power demonstrate the effectiveness of the regulation system, which is essential for smooth operation in fluctuating environments such as microgrids. This performance underlines the inverter's ability to maintain stability and energy efficiency, ensuring optimum energy management in a variety of situations.

VI. CONCLUSIONS

This report has presented a novel design of a high-gain Buck-Boost DC-DC converter, specifically suited to applications in micro-grids, where efficient voltage and power management is paramount. In response to the limitations of traditional converters, this work has demonstrated the ability of the new converter to provide a robust and flexible solution for managing energy flows in modern electricity networks.

Simulations and experiments have shown that the proposed converter effectively meets the requirements of micro-grid systems, particularly in terms of voltage stabilization and adaptation to a wide range of input voltages. In particular, the integration of advanced functionalities, such as pulse width modulation (PWM) and reverse voltage protection, has improved the safety and energy efficiency of the system, while guaranteeing dynamic adjustment to variations in operating conditions, such as fluctuations in solar irradiation in photovoltaic systems.

The converter has proved particularly effective in managing the power extracted from renewable sources, optimizing the energy recovered while maintaining a stable output voltage that is adapted to the needs of microgrids. Its ability to provide variable voltage levels for different DC buses offers crucial flexibility in environments with highly variable loads.

This represents a significant advance for energy management systems in microgrids, contributing to the transition towards more sustainable and resilient electricity grids capable of taking full advantage of renewable energy sources which is the central objective for a microgrid charge controller.

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