Design of Multi-Output DC-DC Converter for Electric Vehicle Application

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ABSTRACT

Multiport converters are essential in a range of applications, including portable electronic devices and electric vehicles (EVs). Numerous configurations of single-input multi-output (SIMO) converters have been explored in existing literature. However, these SIMO converters often face limitations such as constraints on duty cycle and inductor charging, as well as issues with cross-regulation. This work introduces a novel SIMO topology designed to overcome these limitations. The innovative design generates three distinct output voltages without imposing constraints on duty cycle or inductor currents, providing greater operational flexibility. Additionally, the design ensures effective isolation of loads during control, enhancing overall system performance and reliability.

1. INTRODUCTION

In the past decade, there has been a growing demand for renewable energy sources in applications such as electric vehicles (EVs), auxiliary power, and grid-connected systems. Multiport DC-DC converters are crucial in these applications as they hybridize energy sources, reducing the number of components, system complexity, and overall cost compared to using multiple separate single-input DC-DC converters [1-3].

Several Multiport Converter (MPC) designs have been introduced over the past decade. A notable SIMO converter proposed generates boost, buck, and inverted outputs simultaneously; each controlled independently [4]. However, this design requires n + 2 switches to produce 'n' voltage levels, increasing the converter's size and cost. Issues in calculating state-space equations and output voltages for the SIMO converter] were addressed and rectified [5].

A single coupled inductor-based SIMO buck converter offers less output inductor current ripple compared to single inductor SIMO converters [6]. Nayak and Nath provided a detailed comparison of Single Input Dual Output (SIDO) converters using coupled inductors versus single inductors, highlighting that coupled inductor SIDO converters exhibit better steady-state and transient performance. However, in single inductor SIMO configurations, the inductor is switched between the loads, which can lead to cross-coupling issues [7].

Various control approaches have been proposed in the literature to address the cross-regulation issue in single inductor-based SIMO converters. Current predictor controller is introduced in [8], which replaces the conventional charge-balance method. Although effective, generating duty ratios for the active switches with this method is quite complex. Deadbeat-based control method relies on an output current observer. This method, however, is sensitive to noise and significant parametric variations [9].

A SIMO converter using a multivariable digital controller is proposed to minimize voltage ripples, suppress cross-regulation issues, and regulate output voltages. While effective, this controller design can increase the system's overall complexity.

A non-isolated, single-switch SIMO converter topology featuring fewer components and reduced system cost is introduced [10]. However, regulating the outputs independently poses a challenge. To address the issues in single inductor SIMO converters, non-isolated SIMO converters have been proposed [11], which independently regulate output voltages without requiring an additional control circuit.

A high gain step-up and SEPIC converter-based SIMO configuration is suggested for PV applications [12-15]. This setup provides outputs higher than the supply voltage and enhances output voltage with additional capacitors and diodes, although it increases cost and conduction losses.

However, these systems exhibit lack of load isolation during operation. Additionally, grounding issues can arise when charging the battery with simultaneously active loads, increasing circuit complexity for converting one of the negative output voltages into buck-boost mode. To overcome these issues, the proposed converter is modeled with multi output.

2. METHODOLOGY

Figure 1(a) illustrates a proposed DC-DC configuration with a single input and three output channels. This configuration includes several key components: an input voltage source labelled as V_{DC}, switches (S_1-S_3), diodes (D_1-D_3), and passive elements (L_1-C_1, L_2-C_2, and L_3-C_3). Its primary function is to generate three distinct output voltages: a boost voltage (V_{01}), a buck-boost voltage (V_{02}) with a positive polarity, and a buck voltage (V_{03}).

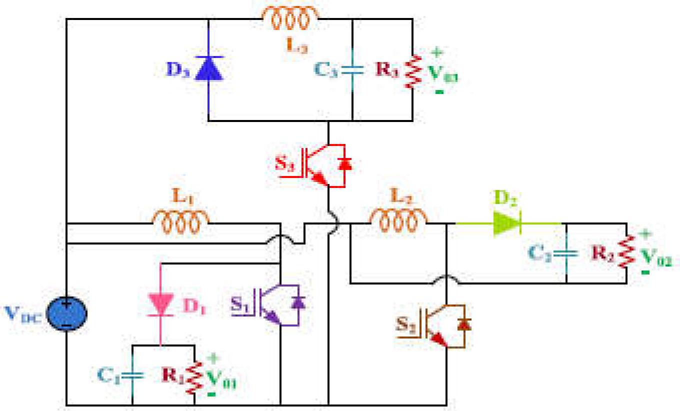


FIGURE 1a. Proposed configuration

This versatile converter is well-suited for the independent regulation of the output voltages using the duty cycles D_1, D_2, and D_3, respectively.

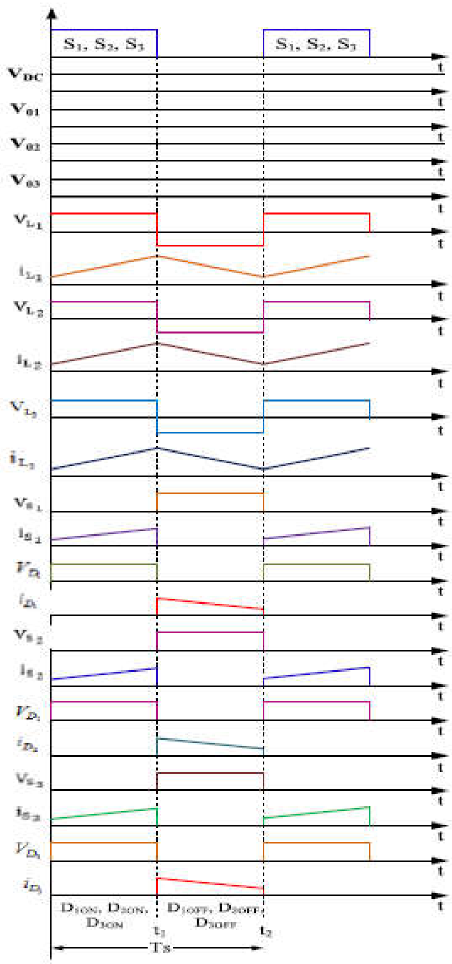


FIGURE 1b. Theoretical waveforms.

Figure 1b provides a visual representation of the theoretical waveforms of the circuit elements, offering insights into their dynamic behavior and performance characteristics. The proposed circuit configuration significantly differs from the conventional parallel combination of buck, boost, and buck-boost converters. In the proposed design, load isolation is achieved during simultaneous control. This control strategy ensures that all loads remain isolated from each other, regardless of the operational mode. Such load isolation is not achievable in conventional parallel combinations of buck, boost, and buck-boost converters. Although this circuit configuration may appear simple, it introduces a novel and valuable approach.

2.1 Operating stages

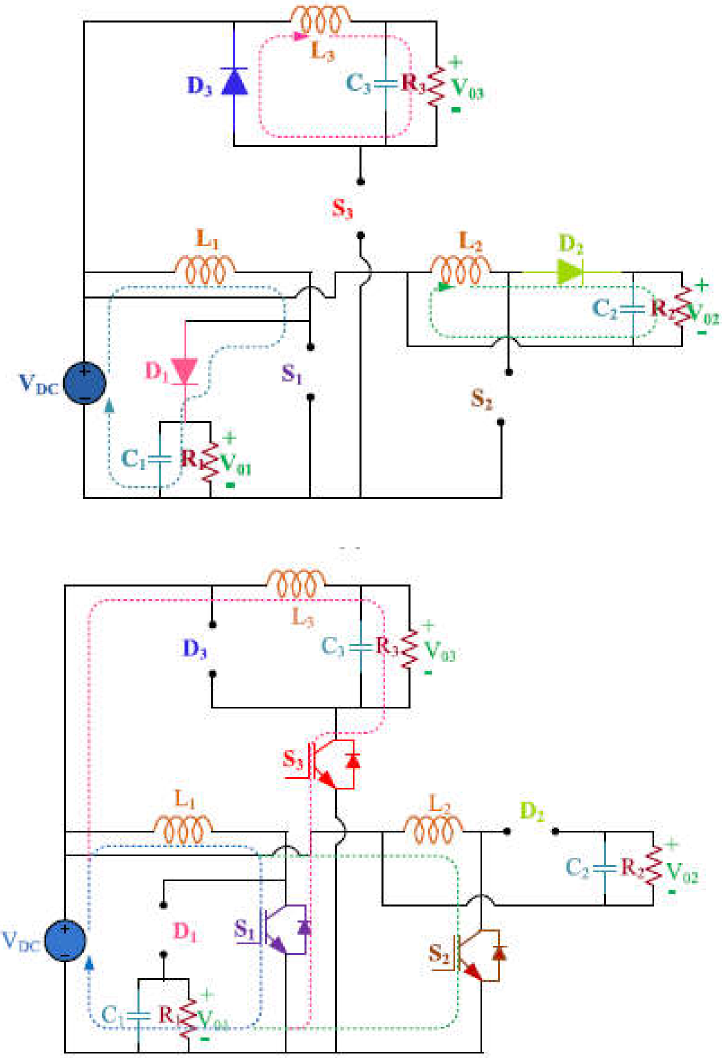


FIGURE 2. Operating states: (a) Switching state-1 and (b) Switching State-2.

Mode-1 Operation (Figure 2(a)):

- Only load R_3 is connected to the input power supply through switch S_3.
- All other loads are intentionally isolated from the power supply.

Mode-2 Operation (Figure 2 (b)):

- Only load R_1 is connected to the input supply via diode D_1.
- Again, all other loads are deliberately isolated from the power supply.

Switching state 1

Switches S_1, S_2, and S_3 are in the ON position, establishing the current flow path as illustrated in Figure 2(a). This configuration results in the activation of energy ports V_{DC}, causing inductors L_1, L_2, and L_3 to become magnetized. As a consequence, capacitors C_1 and C_2 discharge their stored energy to supply power to the respective loads represented by R_1 and R_2. Simultaneously, capacitor C_3 undergoes a charging process.

Switching state 2

In this state, L_1, L_2; and L_3 are de-magnetized and deliver their energy to the load through D_1, D_2 and D_3, respectively.

3. RESULTS AND DISCUSSION

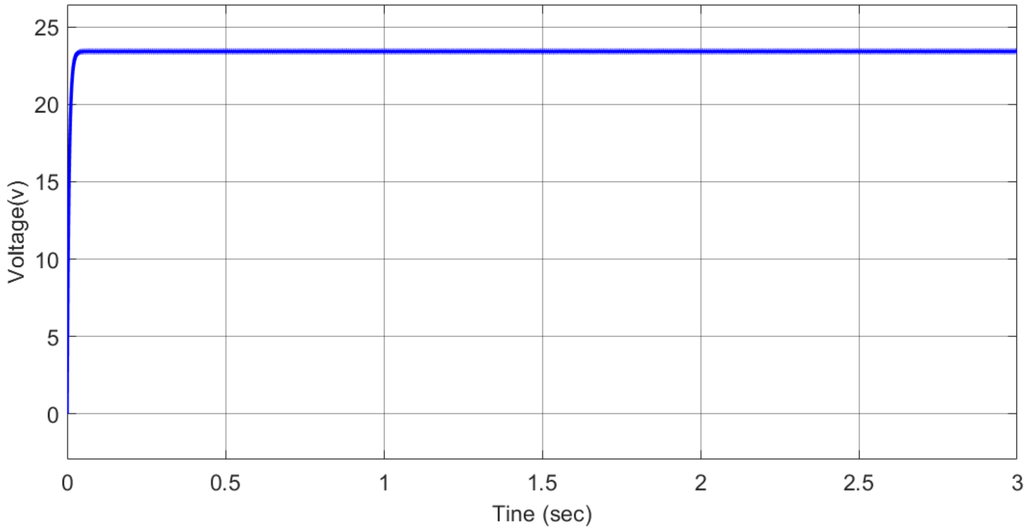
The model has been built in MATLAB environment to verify the proposed system with V_{DC} 50 V, frequency is 50 kHz, and the duty ratio is 50%. The parameter details are as follows,

Table 1

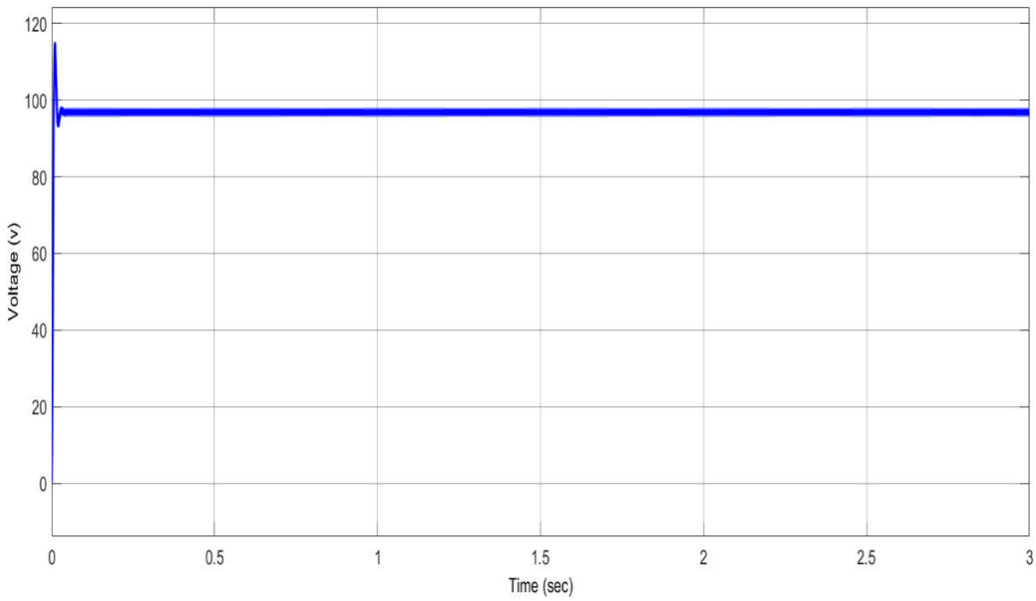
Simulation Parameters

Parameter	Simulation
Input voltage(V_{DC})	50 V
Output voltage($v_{01}/v_{02}/v_{03}$)	100/50/25 V
Output currents($I_{01}/I_{02}/I_{03}$)	2/2/2 A
Switching frequency(f)	50kHz
Inductor($L_1/L_2/L_3$)	0.6/0.9/1 mH
Capacitor($C_1/C_2/C_3$)	200/470/360 uF

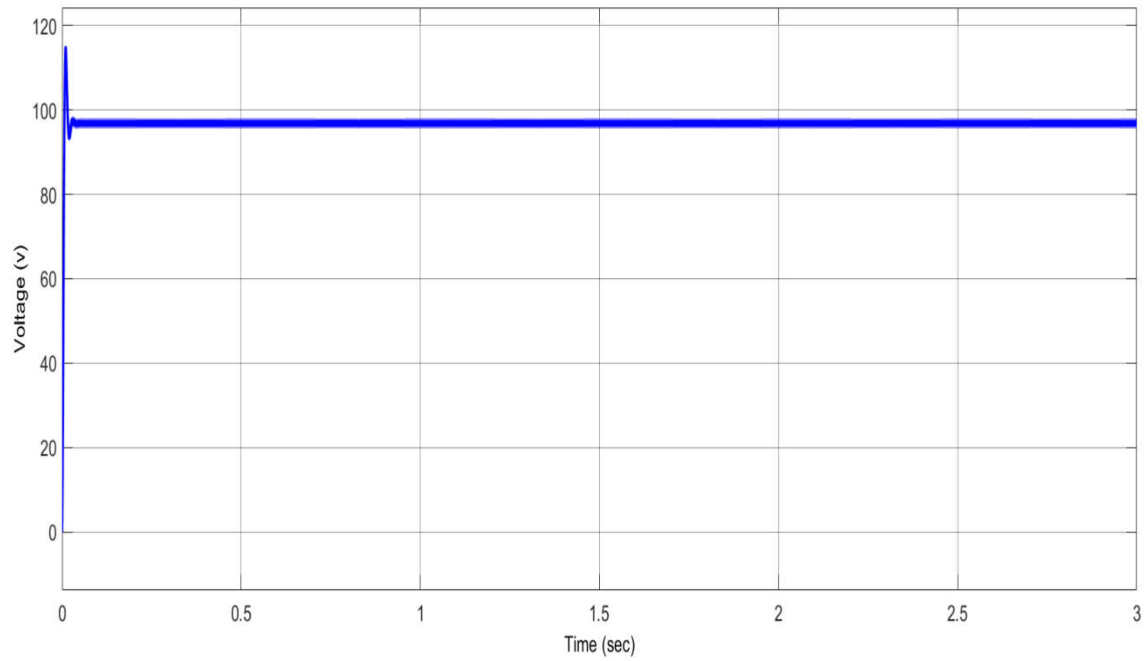
The corresponding output voltages (V_{01}, V_{02}, and V_{03}) are illustrated in Figure 4.1(a-c), respectively.



(a) Buck Converter Operation



(b) Boost Converter Operation



(c) buck-boost configurations

The results demonstrate that the proposed configuration generates stable, independent output voltages that are unaffected by sudden changes in supply.

4. COMPARATIVE ANALYSIS

The comparison of the proposed converter with a conventional SIMO converter in terms of several key factors, as summarized in Table 2 below.

TABLE 2. Comparison between the conventional and proposed SIMO converter.

Comparison different aspects	Conventional	Proposed
Number of components	6	6
Output voltage	Buck, Boost and Buck-Boost(Negative output voltage)	Buck, Boost and Buck-Boost(Positive output voltage)
Inverting circuit is required for the positive output voltage	Yes	No
Loads are isolated to each other during control	No	Yes

This comparison highlights the advantages of the proposed SIMO converter in terms of reduced component count, lower circuit complexity, and effective handling of cross-regulation, among other factors.

5. CONCLUSION

This work introduces a novel SIMO (Single Input Multiple Output) converter architecture, thoroughly explaining its operational principles and modes. The proposed configuration is notable for its simplicity, as it operates without assumptions regarding inductor charging or operating duty cycles. This versatility allows it to generate output voltages in buck, boost, and buck-boost configurations, all with independent voltage regulation. Importantly, the topology effectively ensures that sudden variations in inductor and load currents do not adversely impact the output voltages. To validate its functionality and performance, the paper presents simulation results, demonstrating the efficacy of the proposed converter design.

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