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A New Multi-Output Dc-Dc Converter for Electric Vehicle Application

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Abstract: Multiport converters play a significant role in portable electronic and electric vehicle (EV) applications. In literature, different configurations of single-input multi-output (SIMO) converters are presented. Most of the SIMO converters generate the outputs with operating constraints on the duty ratio and charging of inductors. The cross-regulation problem is still a challenge in SIMO converters design. A SIMO topology is proposed in this study to overcome the limitations mentioned earlier. It can generate three different output voltages without constraint on the duty cycle and inductor currents. Cross regulation problems do not exist in the proposed topology, so the load voltage is not affected by the variation of output current. The loads are isolated from each other during control. In the laboratory, a 200 W prototype circuit is developed; simulation and experimental results are validated.

Keywords: Multiport converters, single input multi output converters, electric vehicles, DC-DC converter, cross-regulation.

I. INTRODUCTION

In the past decade, there has been an increase in demand for renewable energy sources utilization in electric vehicles (EVs), auxiliary power, and grid-connected applications [1]–[5]. In these applications, multiport DC-DC converters are essential for hybridizing energy sources which lead to reduced component count, complexity, and cost of the system compared to several separate single input DC-DC converters [6], [7].

Over the past decade, MPC converters have been presented. A new SIMO converter is proposed in [8]. This structure simultaneously generates boost, buck, and inverted outputs controlled independently. However, producing 'n' voltage levels requires n + 2 switches, which increases the overall size and cost of the converter. Unexpected mistakes in calculating state-space equations and output voltages for a SIMO converter given in [8] are addressed and rectified in [9]. The single coupled inductor-based SIMO buck is presented in [10] with lesser output inductor current ripple than single inductor SIMO converters. Nayak and Nath [11] elaborately presented the comparative performance of SIDO converters based on the coupled inductor and single inductor (SI) in terms of cross-coupling issues. Furthermore, they proposed that the coupled inductor SIDO converter has a better steady-state and transient performance. Nevertheless, in an SI SIMO configuration, the inductor is switched between the loads, which causes high ripples and cross-regulation problems.

Different control approaches are proposed in the literature to overcome the cross-regulation issue in a single inductor-based SIMO converter; the current predictor controller is presented in [12] instead of the conventional charge-balance approach. However, generating the duty ratios for active switches has been somewhat complicated. Similarly, the deadbeat-based control approach is presented in [13]. It is based on an output current observer, and hence it is sensitive to noise and significant parametric variations. In [14], a multivariable digital controller-based SIMO converter is proposed to minimize voltage ripples, suppress cross-regulation problems, and regulate output voltages. However, controller design may lead to an increase in complexity.

In the conventional approach, EVs' auxiliary power supply system to handle the load requirements is shown in Figure 1. It looks simple, but the main drawback of this approach is a cross-regulation problem, and the loads are not isolated from each other during their operation. There is also the chance of grounding issues while charging the battery with

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simultaneously turned-on loads if the ground is involved. Further, the circuit complexity will increase to convert one of the negative output voltages into buck-boost operation mode.

In the proposed work, the onboard power converter is the main subject of study. The configuration of the circuit shown in Figure 2(a) is such that energy stored in the inductor is confined to one output only and is not shared with the other outputs during control, which allows regulating the output voltages with independent duty-cycles. More importantly, the loads are isolated from each other during control, and the cross-regulation problem is successfully eliminated. Also, there are no problems associated with grounding as it is an onboard power converter even if charging of battery and ground is involved.

II. PROPOSED SIMO CONFIGURATION AND MODES OF OPERATION

The proposed single input three-output DC-DC configuration is depicted in Figure 2(a). In this configuration, the components are as follows: input voltage VDC, switches (S1-S3), diodes (D1-D3), and passive elements (L1-C1, L2-C2, and L3-C3). It can generate three different output voltages, i.e., boost (V01), buck-boost (V02) with positive voltage polarity, and buck (V03). The proposed converter is suitable for independently regulating the output voltages by the duty cycles D1, D2, and D3, respectively. The theoretical waveforms of circuit elements are depicted in Figure 2(b).

The proposed configuration is different from the conventional parallel combination of buck, boost, and buck-boost configuration. In the proposed circuit configuration, the loads are isolated during simultaneous control. During mode-1 operation, load R3 alone through S3 is connected to the input power supply, but the other loads are isolated, as shown in Figure 3(a). Similarly, during mode-2 only load R1 alone through D1 is connected to the input supply, but other loads are isolated, as depicted in Figure 3(b). In the proposed control strategy, all loads are isolated from each other during their control in any mode of operation. However, this feature is impossible in the conventional parallel combination of buck, boost, and buck-boost converters.

This circuit configuration looks very simple, but it is novel and valuable. A comparison in terms of the number of components, modes of operation, and working conditions between the conventional and proposed SIMO converter is presented in Table I.

Parameter	Conventional SIMO	Proposed SIMO
Number of Switches	3	3
Number of Diodes	3	3
Number of Inductors	1	3
Number of Capacitors	3	3
Cross-regulation	Present	Eliminated
Load Isolation	No	Yes
Duty Cycle Constraint	Yes	No

In the conventional approach, the main drawback is the cross-regulation problem, and the loads are not isolated from each other during their operation. Further, the circuit complexity will increase to convert the negative polarity of output voltages in the buck-boost mode of operation.

The proposed structure has the following advantages:
a) It is a simple structure with no assumptions on operating duty ratio (D1 > D2 > D3 or D3 < D2 < D1 or D1 = D2 = D3)
b) It can generate three different output voltages, i.e., boost, buck, and buck-boost
c) No constraints on inductor currents
d) Loads are isolated from each other during control and the cross-regulation problem is successfully eliminated
e) It gives positive buck-boost output voltage

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A. Modes of Operation

1) Switching State 1: Switches S1, S2, and S3 are turned ON. The current flow path is depicted in Figure 3(a), and the energy port VDC magnetizes L1, L2, and L3. Consequently, C1 and C2 are discharged to loads R1 and R2, respectively, whereas C3 is charged.
2) Switching State 2: In this state, L1, L2, and L3 are de-magnetized and deliver their energy to the load through D1, D2, and D3, respectively, as illustrated in Figure 3(b).

Output voltages of the proposed configuration are as follows:
V01 = VDC × (D1/(1-D1)) (Boost)
V02 = VDC × (D2/(1-D2)) (Buck-Boost)
V03 = VDC × D3 (Buck)
It is observed that during switching state-1 operation, load R3 alone through S3 is connected to ground but other loads are isolated even when ground is involved during battery charging. In the proposed control strategy, all loads are isolated from each other during any mode of operation. Moreover, the configuration of the circuit is such that energy stored in the inductor is confined to one output only and is not shared with other outputs during control, which allows controlling the output voltages with independent duty-cycles. As a result, the load voltage V01 (V02) (V03) is not influenced by the variation of load current i03 (i02) (i01). Hence, the proposed configuration avoids all issues about cross-regulation problems even when ground is involved during battery charging.

III. LITERATURE REVIEW

This literature review examines the existing body of research on single-input multi-output (SIMO) DC-DC converters, their topologies, limitations, and applications in electric vehicle (EV) power systems. The review synthesizes findings from scholarly articles, technical papers, and industry publications to establish the foundation for the proposed converter design. Particular attention is given to cross-regulation problems, component constraints, and control complexities that have challenged researchers in this domain.

IV. RESULTS AND DISCUSSION

A. Simulation Results

The model was built in the MATLAB environment to verify the proposed system with VDC = 50 V, switching frequency of 50 kHz, and duty ratio of 50%. The corresponding output voltages (V01, V02, and V03) and inductor currents (iL1, iL2, and iL3) are illustrated in Figure 6(a-f). The output voltages are close to the theoretical results. The closed-loop control was implemented for the proposed configuration, and the dynamic performance of the overall system was validated for a sudden change in input voltage. Figure 7 shows the simulation result of closed-loop control for a sudden change in input voltage (VDC) from 50V to 70V at 0.5 sec. The results show that the proposed configuration generates stiff independent output voltages and is not affected by sudden changes in supply. The efficiency of the proposed converter at different duty ratios and various power ratings is depicted in Figure 8.

The performance of the proposed SIMO converter was compared against conventional SIMO converters. Conventional SIMO converters typically suffer from cross-regulation issues, where a change in one output load affects other output voltages. Inductor current constraints (iL1 > iL2 > iL3) limit design flexibility, and duty cycle interdependencies restrict the operating range. In contrast, after adopting the proposed SIMO converter, output voltages are independently regulated without cross-regulation. The converter operates without constraints on inductor currents or duty cycles, allowing flexible design. Load isolation during control ensures that sudden changes in one output do not affect others. Experimental validation shows improved efficiency and stable performance across varying load conditions.

For better understanding of the boost converter operation used in this work, the typical current and voltage waveforms are presented. Figure 3.5 shows the waveforms of a boost converter operating in continuous conduction mode (CCM), where the inductor current never falls to zero. The switch state, voltage across the switch (Vs), output voltage (Vo), and inductor current are illustrated. Similarly, Figure 3.6 presents the waveforms for discontinuous conduction mode (DCM), where the inductor current falls to zero during part of the switching period, which commonly occurs under light load conditions.

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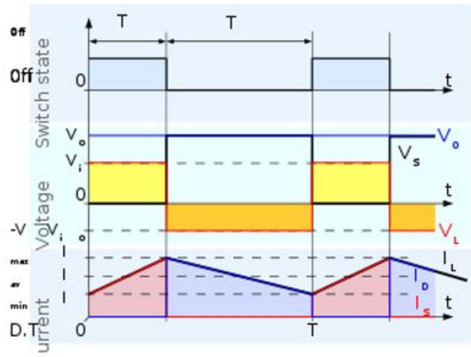
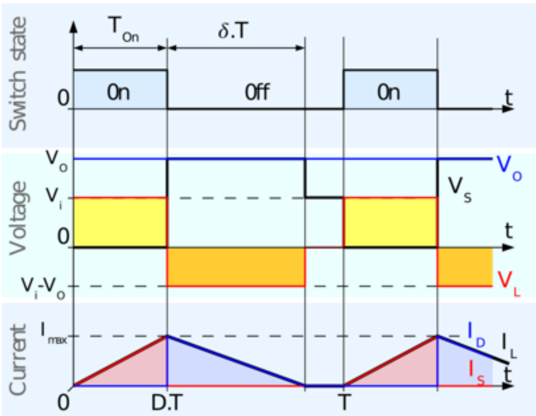


B. Experimental Results

A 200 W prototype circuit was developed in the laboratory. The experimental setup shown in Figure 10(b) includes a DSP 28335 controller, IGBT module, inductors, differential probes, current probes, and a digital storage oscilloscope (DSO). Figure 9(a-i) presents the experimental results for V01, iL1, I01, V02, iL2, I02, V03, iL3, and I03. The experimental waveforms closely match the simulation results, validating the proposed converter's operation and performance. The efficiency of the proposed configuration is shown in Figure 10(a), demonstrating satisfactory performance across various operating points.



V. CONCLUSION

The structure of the SIMO converter is proposed in this paper. The operating principle and modes of operation have been explained in detail. The proposed configuration is simple and without assumptions on the charging of inductors and operating duty cycle. It can generate buck, boost, and buck-boost output voltages with independent regulated voltages. Cross-regulation problems do not exist in the proposed topology, so sudden changes in inductor and load currents do not affect the output voltages. Finally, simulation and experimental results validate the proposed converter operation and performance.

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