

Letters

Series Stacked Modular DC–DC Converter Using Simple Voltage Balancing Method

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Abstract—This letter proposes a high output voltage dc–dc converter topology with series stacked converter modules. To implement the proposed modular dc–dc converter structure, output voltage balancing of the modules and simplification of the control circuitry were considered the major design objectives. To achieve voltage balancing between the modules, we proposed a split-secondary transformer winding structure and distributed connections to the rectifier circuit blocks. Each transformer includes two secondary windings, with each wire pair connected to a different rectifier circuit. Consequently, one rectifier receives ac power simultaneously by sharing the secondary windings fed from two different transformers. The proposed method was verified using a modular *LCC* resonant converter, which is widely employed in high-voltage applications. As a result, the control circuit was simplified by using a single controller to regulate the total output voltage and by applying a compact sensing circuit referenced to the output voltage of the module placed at the lowest grounding point.

Index Terms—DC–DC power converters, power transformers, high-voltage techniques, output feedback.

I. INTRODUCTION

MANY studies have been conducted to increase the output voltage or current of modular dc–dc converters [1]–[3]. In a modular dc–dc converter topology, to simplify the control circuit, the output voltages of the modules must be substantially identical. However, it is difficult to mass manufacture modules having identical parameters owing to the tolerances of their

constituent components. For example, with a core permeability tolerance of $\pm 20\%$, the magnetizing inductance of a transformer could differ significantly between individual modules.

Therefore, to develop a modular dc–dc converter, each module must include an individual controller and sensing circuit [4], [5]. To reduce the control system complexity, an additional compensating winding could be considered to achieve the required output voltage balancing, thus avoiding the need for an individual controller and sensing circuit [6], [7]. However, the insulation of the compensating wire should be designed to withstand the total output voltage of the dc–dc converter. As a result, the thickness of the compensating winding increases when the converter is employed in a high-voltage application.

To overcome the above-mentioned limitations, we propose a split-secondary transformer winding topology. The power transformer in each module contains two secondary parallel windings that are connected to different rectifier circuits. The proposed transformer winding topology achieved the necessary output voltage balancing and greatly simplifies the control and sensing circuit regulating the total output voltage. Section III describes the proposed design and method in detail.

The proposed method of sharing the secondary windings was applied to an *LCC* resonant converter, which is typically used in high-voltage applications [7], [8]. The proposed transformer winding topology was validated based on a modular *LCC* resonant converter design that can utilize the leakage inductance of the transformer as a resonant inductor and the parasitic capacitance of the transformer.

II. DC–DC MODULAR CONVERTER WITHOUT VOLTAGE BALANCING

Previously, dc–dc converters with a modular stacking structure have been developed for strategic mineral exploration [7]. Table I summarizes the specifications of a dc–dc converter and the tolerances of the resonant components. Four *LCC* resonant dc–dc converters (Modules 1–4) are connected in a series-output/parallel-input topology, as shown in Fig. 1(a). The modules consist of full-bridge inverters (using switches S_{1-16}), resonant tanks (resonant inductors: L_{s_1-4} , series resonant capacitors: C_{s_1-4} , parallel resonant capacitors: C_{p_1-16}), power transformers (TR_1–TR_4), and full-wave

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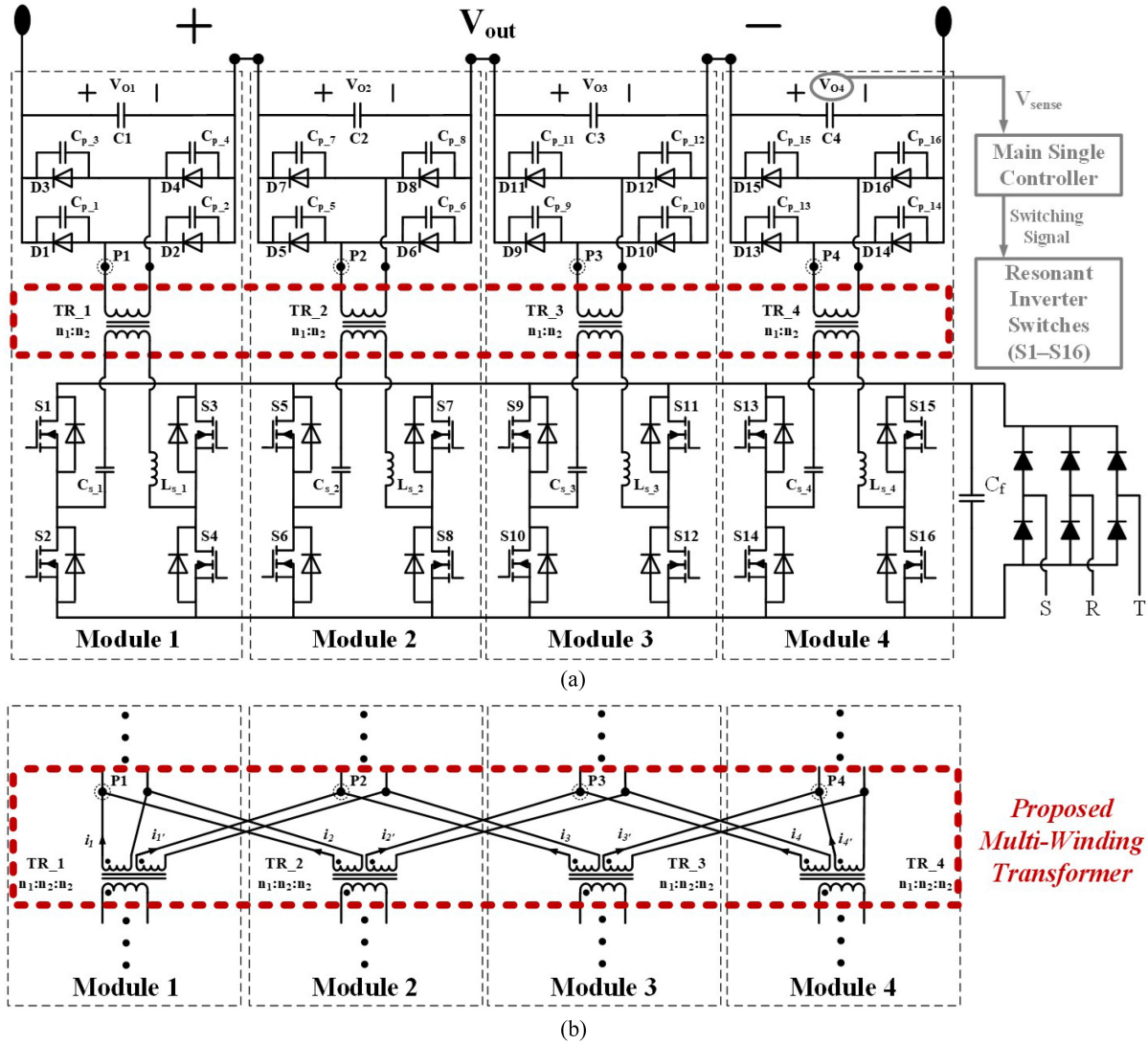


Fig. 1. Comparison between conventional winding and proposed split-secondary winding. (a) Overall circuit diagram of the conventional dc-dc modular converter (without split-secondary transformer winding). (b) Proposed split-secondary transformer winding topology, with only transformers depicted (circuitry not shown here is unchanged).

TABLE I
SPECIFICATIONS OF A DEVELOPED *LCC* RESONANT CONVERTER

Parameter / Item Descriptions	Value
Rectified Input Voltage	513V ± 10%
Switching Frequency (S1-S16)	150-550 kHz
Resonant Inductors (L _{s,1} -L _{s,4})	19 μH ± 10%
Series Resonant Capacitors (C _{s,1} -C _{s,4})	1.5 μF ± 5%
Parallel Resonant Capacitors (C _{p,1} -C _{p,16})	15 nF ± 5%
Power Transformer Turns Ratio (n ₁ :n ₂)	21: 18
Unit Module Output Voltage, Current	500 V, 12.5 A
4 Series Modules Output Voltage, Current	2000 V, 12.5 A

rectifiers (D1-D16). The detailed operation and design of an *LCC* resonant converter has been previously described in [8].

A single controller, as shown in Fig. 1, transfers identical driving signals at the switching frequency to each resonant

inverter switch (S1-S16). Ideally, upon providing the same switching signals to each module, if all design parameters are identical, the output voltages of all modules should be the same. However, owing to the tolerances of the parameters summarized in Table I, the output voltage of each module is different, as indicated by the experimental results shown in Fig. 2. These results show that the waveform shapes of the resonant current are completely different, leading to a voltage imbalance between individual modules. The output voltage imbalance is expected owing to the tolerance of components, such as capacitors and semiconductor devices. In addition, the transformer's ferrite core has a permeability tolerance of ±20%; thus, the resonant leakage inductance can take different values in the practical implementation of the transformers. In this case, to control the output voltage differences, individual controllers and sensing circuits should be employed for individual modules, leading to the increased complexity of the modular dc-dc converter.

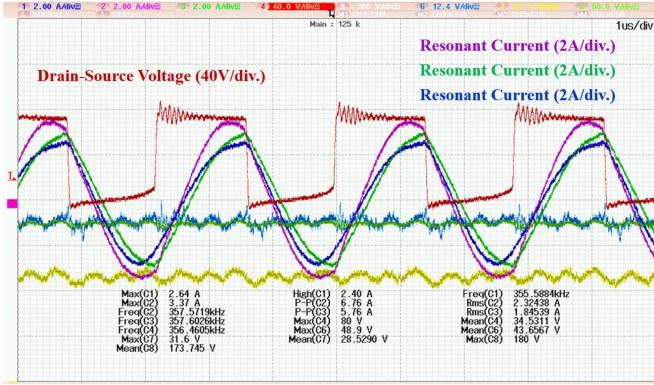


Fig. 2. Experimental result without voltage balancing between modules including waveforms of resonant current.

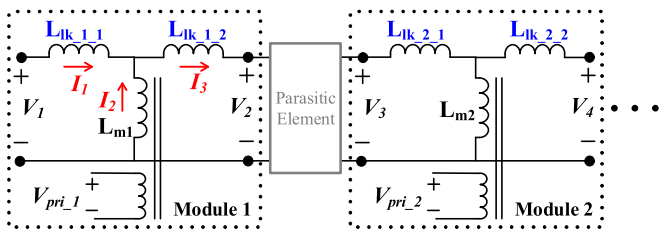


Fig. 3. Summarized equivalent circuit of the proposed winding.

To avoid additional controller and sensing circuit complexity, a modular dc–dc converter for strategic mineral exploration has been developed to achieve output voltage balancing by using the compensating winding. By achieving output balancing between modules, only one controller is required for driving all the modules [7]. Advantageously, the main controller can sample the sensing voltage (V_{sense}) from the lowest grounding potential output voltage module (V_{O4}).

However, even though the compensating winding to address the output voltage imbalance has been implemented on the secondary side of the power transformer, a proper insulation of the compensating wire should be designed to withstand the total output voltage [7]. As the thickness of the compensating wire increases, the volume of the power transformer increases as well. Furthermore, voltage imbalance would still occur at specific switching frequencies, owing to different high-frequency module-to-module resonant points [9].

To solve the problems of additional winding volume and output voltage nonlinearity in the high-frequency domain, a simple method for transformer winding is proposed.

III. PROPOSED METHOD AND SOLUTION FOR VOLTAGE BALANCING

Fig. 1(b) shows the proposed split-secondary transformer winding topology. The secondary side of the power transformers (TR₁–TR₄) is wound using two wires.

Fig. 3 shows the equivalent circuit of the proposed split winding [10]. Because the split secondary wires are connected to each other in parallel, the secondary voltages V_1 , V_2 , V_3 , and

TABLE II
CURRENT DISTRIBUTION SIMULATION RESULTS FOR THE PROPOSED POWER TRANSFORMER TOPOLOGY

Resonant Inductor (L_{s_i} , μH)	Primary RMS Current (I_i , A)	Secondary Average Current (i_i , A)		Secondary Rectifier Average Current ($i + i'$, A)
18 (L_{s_1})	21.72 (I_1)	2.75 (i_1)	2.89 (i'_1)	P1: 5.20 ($i_1 + i'_1$)
19 (L_{s_2})	20.56 (I_2)	2.45 (i_2)	2.88 (i'_2)	P2: 5.19 ($i_2 + i'_2$)
20 (L_{s_3})	19.53 (I_3)	2.30 (i_3)	2.73 (i'_3)	P3: 5.19 ($i_3 + i'_3$)
21 (L_{s_4})	18.59 (I_4)	2.31 (i_4)	2.46 (i'_4)	P4: 5.19 ($i_4 + i'_4$)

V_4 are equal. For example, if a voltage imbalance occurs owing to a lower voltage V_3 during operation, voltage V_2 also becomes lower because it is connected in parallel. In this case, because voltage V_1 is higher than voltage V_2 , the compensating current I_3 ($I_1 + I_2$) is naturally distributed to maintain an equal voltage value. However, if the secondary leakage inductances ($L_{lk_1_1}$ and $L_{lk_1_2}$) are high, the compensating current cannot quickly flow to the node of V_2 and V_3 . Therefore, in terms of reliability, it is very important to reduce the secondary leakage inductance and parasitic element. To minimize the leakage and parasitic component, the shortened split-secondary wires should be wound to be close as much as possible. In the real implementation of the proposed transformer method, the secondary leakage inductance is measured to be a low value of 1.6 μH . Therefore, the proposed method has been verified through both simulations and experiments.

A. PSpice Simulation for Analysis of Compensating Circuit

To understand how the power transformers (TR₁–TR₄) compensate each other to achieve output voltage balancing, a PSpice simulation has been conducted. As shown in Table II, the different resonant inductors' values (L_{s_1} – L_{s_4}) were intentionally chosen to generate the imbalance of the primary rms current (I_1 – I_4). Module 1 has the highest value of 21.72 A (I_1) with a resonant inductance of 18 μH , whereas Module 4 has the lowest value of 18.59 A (I_4) with a resonant inductance of 21 μH . The secondary average currents are measured to confirm that the power conversion stage achieves proper voltage module-level balancing.

Based on the simulation results shown in Table II, the secondary current $i_{N'}$ has a higher value than the secondary current i_N to compensate for the mismatches between modules. Finally, in the secondary rectifiers (P1–P4), the sum of the secondary average currents ($i + i'$) is substantially the same owing to the voltage balancing. As shown in Fig. 4, owing to the use of the split-secondary winding power transformer topology, the currents flowing out of the secondary rectifiers (P1–P4) are matched. Therefore, as the power transformers share the secondary voltage as a single transformer, the secondary currents are distributed to compensate for the modules' output mismatches.

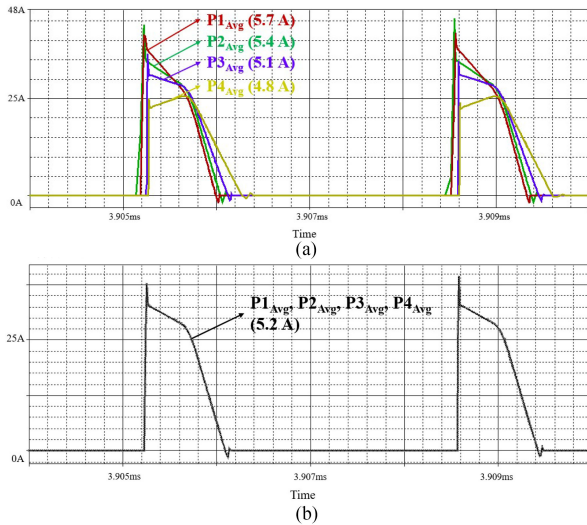


Fig. 4. Simulation results of the secondary rectifier current (P1–P4) for the proposed transformer split-secondary winding topology. (a) Without transformer split-secondary winding. (b) With transformer split-secondary winding.

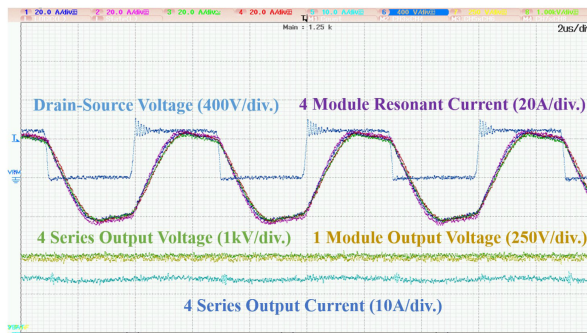


Fig. 5. Experimental result with voltage balancing between each module based on simple method of transformer multiwinding.

B. Experimental Results for a Modular DC–DC Converter

Based on the simulation result and analysis, a voltage balancing experiment was performed, as shown in Fig. 5. Compared with Fig. 2, the four resonant current waveforms are nearly identical. This result indicates that the output voltages of the four modules were balanced. A total output voltage of 2 kV at 500 V per module was confirmed using a load resistance of 160 Ω .

Previously, upon performing a balancing experiment with a compensating winding, an imbalance occurred at a specific frequency owing to a high-frequency resonant point mismatch between the modules. In contrast, the proposed method was confirmed to maintain the output voltage balancing from 150 to 550 kHz, that is, the switching frequency range satisfying load conditions from 100% to 10%.

By achieving voltage balancing, the output voltage of the module with the lowest voltage grounding point (V_{O4}) could be sensed using a single controller to regulate the entire output voltage of the module stack, as shown in Fig. 1. These experimental results verified the proposed transformer split-secondary winding method.

IV. SUMMARY OF THE PROPOSED SPLIT-SECONDARY WINDING TRANSFORMER TOPOLOGY

A. Advantages

- 1) The proposed split-secondary winding topology simplifies the design of the modular converter.
- 2) No additional active component is required to achieve voltage balancing.
- 3) The insulation of the secondary windings does not need to withstand the total output voltage.
- 4) It is possible to operate at high switching frequency while preserving the output voltage matching.

B. Disadvantages

- 1) The proposed split-secondary winding topology is difficult to manufacture and maintain.
- 2) Designing and manufacturing the split-secondary winding transformer to minimize the leakage inductance between secondary wires is challenging.
- 3) Split-secondary windings occupy more winding area.
- 4) The proposed topology is not suitable for high-accuracy applications because it relies on an indirect measurement of the total output voltage.

V. CONCLUSION

Owing to the tolerance of the components of each module, an unwanted output imbalance occurs. In this letter, to achieve output voltage balancing, we propose a transformer split-secondary winding topology. This topology has a simpler control circuit design, and therefore, the size and complexity of the developed dc–dc converter can be greatly reduced.

Although the developed dc–dc converter employs only four modules, by using the proposed split-secondary winding method, it is possible to increase the output voltage to the practical limitations of the physical implementation. The output voltage of the module with the lowest grounding point (V_{O4}) is sensed with one controller to regulate the total output voltage. In addition, for designing the insulation of the secondary windings of the transformer, only the voltage difference between the modules on both sides needs to be considered regardless of the total output voltage. Finally, the PSpice simulation confirmed that the proposed transformer split-secondary winding method can be applied to other converter topologies, such as a series resonant converter and transformer-based flyback converter.

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