Fundamental Study of High Step-down Non-isolated Multicellular DC-DC Converter for Future DC Distribution Systems

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Abstract: A novel high step-down non-isolated DC-DC converter has been proposed. The proposed converter consists of highly efficient non-isolated cell converters using bidirectional semiconductor power devices, and these cell converters are connected in ISOP (input series and output parallel). The non-isolated ISOP converter achieves high step-down ratio of $D/N$, operating $N$ cell converters under the duty ratio of $D$. Availability of the proposed converter has been shown by developing the 48 V-12 V laboratory prototype using two 24 V-12 V cell converters. Design consideration for the 48 V-3 V multicellular converter using four 12 V-3 V cell converters has been also conducted, and the potential to approach the efficiency of 97% has been discussed. The proposed topology is suitable for the POL (point of load) converters in the highly efficient next generation DC distribution system for data centers.

Key words: DC-DC converter, high step-down ratio, ISOP, GaN (gallium nitride).

1. Introduction

The amount of the network traffic in data centres has been rapidly increasing due to the widespread use of the ICT (information and communication technology) equipment [1, 2]. The energy and the resource savings in data centres will contribute to solving some of our global environmental problems. The NTT (Nippon Telegraph and Telephone) group has been proposing the next generation environmentally friendly DC distribution system to realize highly electrified future low-carbon societies [3-5].

Highly efficient and ultra-compact (high power density) power converters are indispensable to develop the next generation DC distribution system shown in Fig. 1 [4]. The PFC (power factor correction) converter with the efficiency of 99% and the DC-DC transformer with the efficiency of 98% have been already reported [6, 7]. Highly efficient and high step-down POL (point-of-load) converters are necessary for the DC distribution system.

The magnetic coupling such as the transformers and the coupled inductors are generally applied to develop the high step-down POL converters [8-10]. The performance of the high step-down converter largely depends on the characteristics of the magnetic material. The progress of the magnetic component determined by the material science is one of barriers to achieve future high power density converters [11].

The high step-down non-isolated DC-DC converter based on the multicellular converter topology is newly proposed here. The proposed converter consists of low-voltage and low-power cell converters using bidirectional semiconductor devices, and the cell converters are connected in ISOP (input series output parallel). One of features of the proposed converter is the lower stress for the magnetic components. The...
magnetic coupling is not applied in the proposed converter, and the stored energy in the inductors can be reduced by the interleaved control of the cell converters. In Section 2, the high step-down non-isolated DC-DC converter is introduced. The circuit configuration, the control method and the characteristics are shown here. In Section 3, the feasibility of the proposed converter is shown by fabricating the breadboard of 48 V-12 V multicellular converter using two 24 V-12 V cell converters. In the Section 4, the design consideration for the 48 V-3 V multicellular converter is carried out and the future prospect is discussed.

2. High Step-down Non-isolated Multicellular DC-DC Converter

2.1 High Step-down DC-DC Converter Based on Magnetic Coupling Topology

The step-down ratio (the input voltage/the output voltage) of the POL converter is e.g. 14.5 (= 48/3.3) or 40 (= 48/1.2) in the DC distribution system shown in Fig. 1. In the case of the general buck chopper circuit, the duty ratio of the main switch is calculated at 0.069 (= 1/14.5) or 0.025 (1/40). High-speed and ultra-low loss semiconductor power devices are indispensable to achieve the buck chopper operation under the extremely low duty ratio control. The buck converter with the efficiency of 80% to 86% using GaN-FETs has been reported for the single high-ratio step-down converter system [12].

The isolated DC-DC converter is one of solutions for the high step-down voltage transformation ratio. The turn ratio of the primary and the secondary windings of the high frequency transformer achieve the high voltage transformation ratio easily, and the high efficiency is accomplished by the soft-switching technology for the power devices. Highly efficient and ultra-compact magnetically coupled power converters over 90% have been reported in Refs. [8, 13].

The multicellular converter topology is also one of options to realize the high step-down DC-DC converter. The multicellular topology means the building block of the low-voltage, low-power cell converters. The power converters with low-voltage transformation ratio are available for the cell converters, and the possibility of the converter design can be expanded.

The conceptual diagram of the multicellular DC-DC converter is shown in Fig. 2. The multicellular converter
consists of a lot of standardized, low-voltage isolated DC-DC cell converters mainly. These cell converters are connected in ISOP to achieve the high step-down voltage transformation ratio, and cell converters are connected in IPOS (input parallel output series) to achieve the high step-up transformation ratio. Features of the multicellular DC-DC converter are summarized as follows.

- The efficiency $\eta$ (%) and the power density $D_p$ (W/cm$^3$) of the multicellular DC-DC converter corresponds to the performances of the single cell converter ideally.
- The I/O (Input/Output) voltages of the multicellular converter are designed arbitrarily by the number of cell converters connected in ISOP and IPOS.
- The ISOP-IPOS connected multicellular converters using non-regulated DC-DC converters inherently achieve the balanced input voltage sharing and the balanced output current sharing among cell converters without any complicated controls [14].
- The low voltage stress of the cell converter enables to employ the low-voltage and ultra-low loss semiconductor power devices [15].

The high power density DC-DC converter based on the multicellular converter topology has been already reported [7]. However, the magnetic components as the high frequency transformer are generally utilized in the cell converter, and the performance of the cell converter depends on the magnetic components largely. The performance of the magnetic component determined by the material science is one of barriers to achieve high power density converters [11]. The converter circuit topology which reduces the stress of the magnetic components is attractive for future DC distribution systems.

2.2 Multicellular DC-DC Converter Based on Non-isolated Circuit Topology

Fig. 3 shows the circuit configuration of the proposed multicellular DC-DC converter. The proposed converter consists of the non-isolated cell converters and these cell converters are connected in ISOP. The circuit configuration of each cell converter is based on the conventional buck chopper circuit and the bidirectional semiconductor switches $Q_{ik}, Q_{ok}$ in two lines substitute for the single unidirectional transistor in the conventional buck chopper circuit.

The control scheme of the proposed multicellular converter is shown in Fig. 4. The electric power is provided from one of the cell converters ($Cell_k, k = 1, 2, \ldots, N$) to the load by turning on the switches $Q_{ik}, Q_{ok}$ at a certain time, preventing the electrical short circuit among cell converters. Pairs of $Q_{ik}, Q_{ok}$ are turned on alternately as shown in Fig. 4, and the pairs of the bidirectional switches under the turn-off condition make the isolation barrier. The applied voltages to the bidirectional switches $Q_k, Q_{ok}$ are time-variant and these stresses depend on the circuit operating condition.

From Fig. 4, the duty ratio of each cell converter $D$ is limited by the number of cell converters $N$ connected in ISOP. The maximum duty ratio $D_{\text{max}}$ is $1/N$ to prevent the short circuit among cell converters. In the case of $D < 1/N$, the voltage transformation ratio $V_{\text{OUT}}/V_{\text{IN}}$ is calculated as the following equation, taking the input voltage of the multicellular converter $V_{\text{IN}}$ is shared by the cell converters equally into account.

$$\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{D \cdot V_{ik}}{N \cdot V_{ok}} = \frac{D}{N} \leq D_{\text{max}}$$

The characteristics of the proposed non-isolated multi-cellular converter are summarized as follows.
The magnetic coupling is not applied. The design for the magnetic components can be simplified under the high frequency operation condition.

- The stress of the magnetic components can be reduced because of the interleaved control among cell converters.

- The proposed converter achieves higher step-down ratio compared with the conventional chopper circuit in the case of the corresponding duty ratio of $D$. In other word, larger duty ratio is applicable to realize the high step-down converter.

- High speed and ultra-low loss bidirectional devices are indispensable because large numbers of power devices whose rated voltages depend on the input voltage $V_{\text{IN}}$ are utilized.

### 3. Experiment for Non-isolated Multicellular DC-DC Converter

The laboratory prototype has been developed to verify the feasibility of the proposed non-isolated multicellular DC-DC converter. Fig. 5 shows the circuit configuration for the experiment and Fig. 6 shows the experimental apparatus. The multicellular converter consists of two cell converters and these cell converters are connected in ISOP. Each cell converter consists of the main switches $Q_k$, $Q_{xk}$, the free-wheeling diode $D_k$, the input capacitor $C_{ik}$ and the output inductor $L_{ok}$. The output capacitances for two cell converters are bundled to the capacitance $C_{\text{OUT}}$.

Here, the subscript $k$ means the number of the cell converters and $k = 1, 2$ in this experiment.

The parameters for the experiment are summarized in Table 1. The input voltage of the multicellular converter $V_{\text{IN}}$ is 48 V and the prospective output voltage $V_{\text{OUT}}$ is 10.8 V because the number of cell converters $N$ is 2 and the duty ratio of each cell converter $D$ is 0.45 $(10.8 = 48/2 \times 0.45)$. Si-MOSFETs

<table>
<thead>
<tr>
<th>Table 1 Parameters for experiment.</th>
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<tr>
<td><strong>Input voltage</strong></td>
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<tr>
<td><strong>Output voltage</strong></td>
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<tr>
<td><strong>Number of cells</strong></td>
</tr>
<tr>
<td><strong>Duty ratio</strong></td>
</tr>
<tr>
<td><strong>Switching frequency</strong></td>
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<tr>
<td><strong>Main switch</strong></td>
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<tr>
<td><strong>Free-wheeling diode, Auxiliary switch</strong></td>
</tr>
<tr>
<td><strong>Input capacitor</strong></td>
</tr>
<tr>
<td><strong>Output inductor</strong></td>
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<tr>
<td><strong>Resistive load</strong></td>
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<td><strong>Controller</strong></td>
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</table>

$k = 1, 2$. 

Fig. 4 Control scheme of non-isolated multicellular DC-DC converter.

Fig. 5 Circuit configuration of non-isolated multicellular DC-DC converter using two cell converters.

Fig. 6 Experimental apparatus for non-isolated multicellular converter.
(100 V, 2.8 mΩ/IRF7769 from IR) are utilized for the main switch \(Q_{a1}, Q_2\) and Si-SBDs (200 V, 15 A/D15XBN20 from Shindengen) are employed to realize the diode bridges by the pair of \(Q_1\) and \(D_1\) and the pair of \(Q_{a2}\) and \(D_2\). In this experiment, the unidirectional transistors and the diodes substituted for the bidirectional semiconductor switches in Fig. 3, because the unidirectional voltage stress is applied to the switches \(Q_k, Q_{a_k}\) in the case of \(N = 2\).

Fig. 7 shows the experimental result of the non-isolated multicellular DC-DC converter using two cell converters. The input voltage of the multicellular converter \(V_{IN}\) was 48 V and the input voltages of cell converters \(V_{i1}, V_{i2}\) were 24 V, respectively. This means the input voltage of the multicellular converter was shared equally by the series connected two cell converters. The output voltage \(V_{OUT}\) was 10.3 V. The measured output voltage was lower than the prospective output voltage of 10.8 V because of the forward voltage drops of the diodes \(Q_1, Q_{a2}, D_1,\) and \(D_2\) mainly. From this experiment, the efficiency of the converter was estimated at 95.4% (= 10.3 V/10.8 V) under the resistive load of 2 Ohms.

The symbols of \(V_{Q_{a1}}, V_{Q_{a2}}\) mean the drain to source voltage of Si-MOSFETs. The applied voltages to the main switches were higher than the input cell voltages \(V_{i1}, V_{i2}\) of 24 V because the input DC voltage \(V_{IN}\) was blocked by the main switches under the turn-off state. The output current \(I_{OUT}\) was 5.2 A and this output current was total amount of the inductor current \(I_{L_{i1}}, I_{L_{i2}}\). Because two cell converters deliver the electric power to the load alternately as shown in \(V_{Q_{a1}}, V_{Q_{a2}}\) of Fig. 7, the interleaved waveforms were observed in the inductor currents.

The voltages of the free-wheeling diodes \(V_{D_{i1}}, V_{D_{i2}}\) were also shown in Fig. 7. The applied voltages to the \(V_{D_{i1}}, V_{D_{i2}}\) correspond to the input cell voltages \(V_{i1}, V_{i2}\). This result means that the multicellular converter topology contributes to reducing the voltage stresses for the free-wheeling diodes and the passive components.

The amplitude of the applied voltages to the power devices \(Q_1, Q_{a2}\) were 10.3 V from Fig. 7. Difference between \(Q_k\) and \(Q_{a_k}\) \((k = 1, 2)\) corresponds to the input cell voltage \(V_{i_k}\) and the total amount of \(Q_k\) and \(Q_{a_k}\) means the blocking voltage for the isolation barrier.

Fig. 8 shows the simulation result using PSIM software. The circuit configuration and the circuit parameters correspond to the circuit in Fig. 5 and the parameters in Table 1 respectively. The characteristics of the on-resistance and the forward voltage drop of the semiconductor power devices \(Q_k, Q_{a_k}, D_k\) were not taken into account and the constant values obtained from the published datasheet for the equivalent capacitances were applied to the junction capacitance of \(Q_k, Q_{a_k}, D_k\). The simulation result had good agreement
Parameters for this design are shown in Table 2. The breakdown voltage of the bidirectional main switch is based on the total input voltage $V_{\text{IN}}$ for the isolation barrier, and the GaN-FETs (100 V, 7 mΩ) were assumed for the main switches here. The GaN-FETs (30 V, 1.3 mΩ) were assumed for the transistors $Q_{\text{SR}k}$ ($k = 1, \ldots, 4$) to achieve the synchronous rectification. The design for the output inductors $L_{\text{ok}}$, the input capacitors $C_{ik}$ and the output capacitors $C_{ok}$ are based on the conventional 12 V-3 V, 52.5 W (= 210 W/4) buck chopper circuit. The passive components $L_{\text{ok}}, C_{ik}, C_{ok}$ are determined to suppress the current ripple within 20% and the voltage ripple within 3% under the condition that the switching frequency varied from 100 kHz to 1 MHz.

Fig. 10 shows the simulation result of the non-isolated multicellular 48 V-3 V converter in case that the bidirectional switches $Q_k, Q_{\text{ok}}$ ($k = 1, 2, 3, 4$) were driven at the switching frequency of 100 kHz. The total input voltage $V_{\text{IN}}$ of 48 V is shared by four cell converters and the output voltage $V_{\text{OUT}}$ of 3 V was applied to the load. The output inductor currents $I_{\text{lok}}$ with the experimental result. This means that the behavior of the non-isolated multicellular converter using N cell converters is predicted exactly.

4. Design Consideration for Highly Efficient Multicellular DC-DC Converter

Design consideration for 48 V-3 V, 210 W non-isolated multicellular DC-DC converters is conducted here. The circuit configuration is shown in Fig. 9 and four cell converters are connected in ISOP. The rated I/O voltages of each cell converter are 12 V and 3 V respectively, and each cell converter is driven by the duty ratio $D$ of 0.25. Here, the transistors $Q_{\text{SR}k}$ ($k = 1, \ldots, 4$) substituted for the free-wheeling diodes to reduce the conduction loss by the synchronous rectification.

![Fig. 8 Simulation result for non-isolated multicellular converter.](image1)

![Fig. 9 Circuit configuration of multicellular DC-DC converter using four cell converters.](image2)
Table 2 Parameters for design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Input voltage $V_{IN}$</td>
<td>48 V</td>
</tr>
<tr>
<td>Input cell voltage $V_{ik}$</td>
<td>12 V</td>
</tr>
<tr>
<td>Output voltage $V_{OUT}$</td>
<td>3 V</td>
</tr>
<tr>
<td>Output power $P_{OUT}$</td>
<td>210 W</td>
</tr>
<tr>
<td>Number of cells $N$</td>
<td>4</td>
</tr>
<tr>
<td>Duty ratio $D$</td>
<td>0.25</td>
</tr>
<tr>
<td>Switching frequency $f_{SW}$</td>
<td>100 kHz to 1 MHz</td>
</tr>
<tr>
<td>Main switch $Q_k, Q_{xk}$</td>
<td>(EPC2001C/EPC)</td>
</tr>
<tr>
<td>Synchronous rectifier $Q_{SRk}$</td>
<td>30 V, 1.3mΩ (EPC2023/EPC)</td>
</tr>
<tr>
<td>Output inductor $L_{ok}$</td>
<td>Ripple 17.5 A ± 20% (SER, SLC/Coilcraft)</td>
</tr>
<tr>
<td>Input capacitor $C_{ik}$</td>
<td>Ripple 12 V ± 1.5% (MLCC/TDK)</td>
</tr>
<tr>
<td>Output capacitor $C_{OUT}$</td>
<td>Ripple 3 V ± 1.5% (MLCC/TDK)</td>
</tr>
</tbody>
</table>

$k = 1, 2, 3, 4.$

Fig. 10 Simulation result for 48 V-3 V non-isolated multicellular converter using four cell converters.

were balanced and the low ripple output current $I_{OUT}$ was obtained because of the interleaved control. The applied voltage to the bidirectional switches $V_{Qk}, V_{Qxk}$ were also shown in Fig. 10. The turn-on loss energies generated from the bidirectional switches can be estimated from the simulation result. In this simulation, the influence of the parasitic parameters was not considered to confirm the fundamental behavior of the proposed circuit.

The calculation result of the converter loss was shown in Fig. 11. The conduction loss $P_{con(Q)}$, the switching loss $P_{sw(Q)}$ were considered for the bidirectional switch $Q_k, Q_{xk}$ ($k = 1, \ldots, 4$). The power loss limit model for the high-speed ultra-low loss power devices was applied to estimate the switching loss, and the minimum switching loss caused by the stored energy in the junction capacitance was calculated [16, 17]. The copper loss $P_{cu(Lo)}$ and the core loss $P_{core(Lo)}$ were also considered for the output inductor $L_{ok}$ ($k = 1, \ldots, 4$), and these losses were estimated by using the published datasheet and the design tool provided from the manufacturer. The power losses generated from the capacitors were not considered here. As shown in Fig. 11, the conduction losses generated from the bidirectional switches were dominant because of the numerical quantity of the bidirectional switch whose voltage stress depends on the input voltage $V_{IN}$ for the isolation barrier. To accomplish higher efficiency, lower on-resistance of the transistors for the bidirectional switch and the novel
power device configuration to realize the bidirectional switch by using the single transistor is indispensable [18].

The estimated converter volume was shown in Fig. 12. Volumes for the output inductor $Vol(L_{ok})$, the input capacitor $Vol(C_{ik})$ and the output capacitor $Vol(C_{OUT})$ were considered. The heat sink volume was also simply estimated under the condition that the heat dissipation efficiency was 0.65 W/cm³ [19, 20]. The volume for the heat sink was approximately constant in case that the switching frequency varied from 100 kHz to 1 MHz because of the dominant conduction loss in Fig. 11. The inductor volume was influential on the power density and the higher switching frequency operation contributes to realizing the higher power density converter. Larger current ripple for the output inductor contributes to minimizing the inductor volume, taking the effect of the interleaved control into account.

Fig. 13 shows the prospective conversion efficiency and the output power density of the proposed multicellular converter. The bidirectional switch was assumed to be developed by the single power device. The output inductor was designed to achieve the BCM (boundary current mode) for minimizing the inductor volume. The performances for the power dissipation and the converter volume were improved and the efficiency approaches the designated 97% in Fig. 1.

5. Conclusions

The non-isolated multicellular DC-DC converter was newly proposed for highly efficient high step-down POL converters in the next generation DC distribution system. The circuit configuration, the control scheme and the characteristics of the proposed converter were briefly introduced. The 48 V multicellular converter using two cell converters connected in ISOP was developed and the feasibility of the proposed converter was confirmed experimentally. Design consideration for the 48 V-3 V multicellular converter using four cell converters was carried out, and the potential for higher efficiency and higher power density was shown. The proposed multicellular converter contributes to the energy—saving of the DC distribution system for future low carbon society.

References

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