Highly Scalable Sensorless Multicellular AC-DC Transformer (ADX) for the DC Distribution System in Data Centers

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This paper proposes a novel multicellular ac-dc transformer (ADX). The proposed ADX consists of sensorless isolated ac-dc cell converters based on the multicellular converter topology and a non-isolated dc-dc converter for power factor correction (PFC). A single ac-dc cell converter is composed of a diode rectifier and a dc-dc transformer (DCX) with no feedback controllers. These cell converters are connected in input-series-and-output-parallel (ISOP) and input-parallel-and-output-series (IPOS) configurations to achieve various voltage transformation ratios. One of the features of the proposed ADX is the high scalability with no master-slave control. Each power converter in the ADX requires its own local information, and no additional auxiliaries are required for the global control of the multicellular converter, because the ISOP and the IPOS connection topologies in the multicellular converter inherently achieve balanced voltage and equalized current among the cell converters. The proposed ADX has a simplified control system and accomplishes high scalability without requiring additional components. A simplified circuit analysis is carried out to show the feasibility of the proposed ADX, and an ac 60 V - dc 40 V laboratory prototype, with three pairs of cell converters connected in ISOP, is fabricated to verify the analysis. The proposed approach contributes to realizing future dc distribution systems in data centers, taking into account the prevalence of the standardized high-power-density converters.

Keywords: ac-dc transformer (ADX), multicellular converter topology, ISOP (input series output parallel), IPOS (input parallel output series)

1. Introduction

Environmentally friendly data centers have been proposed by Nippon Telegraph and Telephone (NTT) group to realize future low-carbon society (1). The energy- and the resource-savings in the data centers are achieved by the 380 V dc distribution system which goes beyond the conventional 48 V dc distribution system (2)(3). Compatibility of the dc distribution system with the distributed generators also pushes a smoother transition of the renewable energy sources such as the solar photovoltaic power generations to reduce an environmental impact. The dc distribution system is an attractive option for the low-carbon society, and the prevalence of the power electronics (PE) converters are indispensable for the flexible control and the effective use of the electric power.

The standardization and the componentization taking the scalability into account are the key issues for the widespread use of the PE converters. The output-power-density (OPD) of the PE converters has been linearly increasing by a factor of two figures over a few decades (4), and the high OPD converters using SiC and GaN semiconductor power devices have been already reported (5)–(9). However, these power converters are generally customized for the designated applications. The approach for the prevalence of the PE converters must be discussed.

A multicellular converter topology is one of options for the prevalence of the PE converters. The series-parallel connection of the cell converters achieves various levels of the rated voltage and high output power. The voltage and the current stresses of each cell converter are reduced and the widespread use of the standardized cell converters is promoted. These low-voltage converters (e.g. 48 V) are now highly integrated, and the componentized converter modules over the OPD of 50 W/cm³ are commercially available (10). The dc-dc and ac-dc multicellular converters have been proposed to enhance their performances (11)(12). One of issues to achieve the high scalability of the multicellular converter is the complicated control system with a lot of auxiliaries such as the voltage sensors, the current sensors, the controllers and the signal lines. Each cell converter in the multicellular converter requires not only its local information but also the global information to accomplish the balanced voltages and the equalized currents among cell converters. The local control for each cell converter is dependent on the master control based on the global information of the multicellular converter, and the mutually utilized master-slave control causes the decrease of the converter reliability (13)(14).

In this paper, the multicellular ac-dc transformer (ADX) is newly proposed to develop highly scalable isolated ac-dc transformers using SiC and GaN semiconductor power devices.
converter without the additional auxiliaries. In Section 2, the concept of the multicellular ADX is introduced. In Section 3, the reliability of the proposed ADX is briefly discussed. In Section 4, the behaviour of the multicellular ADX is described and the analysis for the voltage sharing among cell converters is carried out. In Section 5, the laboratory prototype of the multicellular ADX is developed and the feasibility of the proposed approach is verified.

2. Highly Scalable and Sensorless Multicellular AC-DC Transformer for DC Distribution System

2.1 Conventional 380 V DC Distribution System and Multicellular AC-DC Converter

The configuration of the conventional 380 V dc distribution system is shown in Fig. 1(3). The overall schematic diagram from the ac input to the ICT loads is shown in Fig. 1(a), and the detailed circuit configuration of the power converters in the Rectifier (RF) is shown in Fig. 1(b). The medium voltage of ac 6.6 kV is transformed to the low voltage of ac 200 V by the 50 Hz/60 Hz distribution transformer, and the low voltage of ac 200 V is converted to the dc 380 V by the Rectifier which consists of the power factor correction (PFC) converters and the isolated dc-dc converters. Characteristics of the Rectifier are summarized as follows.

- The single-phase power conversion topology is applied to keep providing the electric power in the case of the ac accidents such as the one-line-to-ground faults at the input ac side.
- Three pairs of the PFC converter and the isolated dc-dc converter are installed to the ac lines, and the output terminals of the isolated dc-dc converters are connected in parallel.
- The PFC converters improve the input current waveform sinusoidally, and the isolated dc-dc converters control the output dc voltage at the nominal voltage of dc 380 V.

Intensive studies have been conducted to develop highly efficient and ultra-compact PFC converters and isolated dc-dc converters. The PFC converter using GaN transistors has accomplished the efficiency of approximately 99%16, and the power density over 10 W/cm³ has been reported for the isolated dc-dc converters17. These converters are attractive for the conventional dc 380 V power feeding system connected into ac 200 V power feeder.

The multicellular converter topology is one of approaches to take full advantage of the above high performance power converters not only for ac 200 V to dc 380 V distribution system but also for various voltage levels of future distribution systems (e.g. ac 100 V, ac 200 V, ac 400 V, ... to dc 12 V, 48 V, 380 V, 600 V, ...). The features of the multicellular converter topology are summarized as follows.

- The input and output (I/O) voltages and the output power of the multicellular converter are scalable by connecting the low-voltage and low-power cell converters in series-parallel.
- The low-voltage ultra-low loss semiconductor power devices such as GaN transistors are available to develop highly efficient cell converters.
- The output power density and the conversion efficiency of the multicellular converter ideally correspond to the power density and the efficiency of the single low-voltage and low-power cell converter.

Figure 2 shows an example of the circuit configuration for the multicellular ac-dc converter15). In Fig. 2, a pair of a single-phase full-bridge ac-dc converter and an isolated dc-dc converter comprises a single cell converter, and a number of cell converters are connected in input-series-output-parallel (ISOP). The ac-dc converters are controlled to keep the output dc voltage at the designated feeding voltage, and the isolated dc-dc converters are controlled to achieve the balanced input voltage and the shared output current among cell converters.

In the multicellular converter topology, the master-slave control is generally applied to avoid the voltage and the current unbalances among cell converters. The modulation index for the ac-dc converters and the duty ratio for the isolated dc-dc converters are calculated at the master controller.
using the global information of the total input ac voltage and the output dc voltage. The control signals for the modulation index and the duty ratio are wired to all local controllers from the master controller. The auxiliaries such as the additional controllers, the voltage sensors and the current sensors are required. The control system becomes complicated and the master controller becomes one of key issues to discuss the converter reliability because its information is mutually utilized in all of the cell converters.

2.2 Concept of Multicellular AC-DC Transformer and Detailed Circuit Configuration  
Figure 3 shows the configuration of the proposed multicellular ac-dc transformer (ADX) to develop the multicellular ac-dc converter without the additional auxiliaries. The conceptual diagram is shown in Fig. 3(a) and the detailed circuit configuration is shown in Fig. 3(b). The proposed ADX consists of the diode full-bridge rectifier, the unregulated isolated dc-dc converter (DCX) and the non-isolated boost dc-dc converter. The roles of these converters are summarized as follows.

- Each diode full-bridge circuit rectifies the divided ac voltage and the rectified uni-directional voltage is applied to the DCX.
- The DCX is utilized for the isolation and the voltage transformation without the voltage regulation. The constant duty ratio control is applied to the DCX and the voltage waveform which is proportion to the rectified input voltage is delivered to the secondary side.
- The isolated rectifiers composed of the above diode rectifiers and the DCXs are connected in ISOP and input-parallel-output series (IPOS) to interface various voltage levels of ac and dc distribution systems.
- The non-isolated boost dc-dc converter is installed behind the isolated rectifiers. This converter is utilized to improve the power factor, and the input current is controlled to be sinusoidal synchronizing with the rectified input voltage.

As shown in Fig. 3, the sensors to detect the voltage and the current are utilized for only the local control of the non-isolated boost dc-dc converter. There are no controllers in the diode rectifiers, and the DCXs also require no sensors and auxiliaries for the control of the multicellular converter because of the constant duty ratio control. In the ISOP connection topology, the divided voltage and the shared current among cell converters are inherently balanced under the steady state operation condition in case that the unregulated dc-dc converters are employed.

The features of the proposed multicellular ADX are summarized as follows.

- The multicellular converter topology achieves high scalability. Multicellular ADX with various I/O voltages and the output power can be developed by stacking the standardized cell converters in a unified way.
- The proposed ADX simplifies the control systems. The master-slave control correlated with all of the cell converters can be removed and the local controller for the boost converter is only required.
- The reliability of the multicellular converter can be improved. The proposed ADX needs smaller number of controllers and the switching power devices than the number of these components in the multicellular converter shown in Fig. 2.

In the following chapters, two analyses are conducted to show the availability of the proposed ADX. One is the analysis for the reliability of the multicellular converters. The other is the analysis for the input voltage sharing among the ISOP connected cell converters under the full-wave rectification input.

3. Relative Estimation of Reliability for Multicellular AC-DC Transformer

The part count reliability prediction of JEITA is available to estimate the failure rate of the power converters. In this chapter, the reliability and the failure rates of the multicellular converters are relatively compared to show the availability of the proposed ADX.

Generally, the reliability of the equipment $R$ is formulated by using the failure rate $\lambda$ and the duration $t$ as follows. Here, the failure rate of each component is regarded as the constant value taking only the random failure into account.

$$R = e^{-\lambda t}$$  \hspace{1cm} (1)

The multicellular converters based on the ISOP connection topology in Fig. 2 and Fig. 3(b) have no redundancy because of the series connection at the input side. The reliability of the ISOP connected converter is simply estimated based on the characteristics of the series system. Figure 4 shows the schematic illustration to estimate the reliabilities of ISOP connected multicellular converters. The auxiliaries for the master-slave control affects the reliability of the multicellular...
converter directly.

Figure 4(a) shows the block diagram for the reliability of the conventional multicellular converter in Fig. 2. The subscripts of $AD$, $DCX$, $Sc t r l$ and $Mctrl$ are applied to the full-bridge ac-dc converters, the isolated dc-dc converters, the slave controllers and the master controller respectively. The reliability of the multicellular converter $R_{MCC}$ is calculated as follows.

$$R_{MCC} = \left( R_{AD}R_{DCX}R_{Sc t r l} \right)^N R_{Mctrl}$$

$$= e^{-[\lambda_{AD}t + \lambda_{DCX}t + 2\lambda_{Sc t r l}t + \lambda_{Mctrl}t]} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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In the case of the turn ratio of the transformer \( n = 1 \), the behavior of the dc-dc converter is described as follows by using the state-space averaging method [15,16].

\[
\frac{d}{dt} \left[ \frac{i_L}{V_o} \right] = \begin{bmatrix} 0 & -D'/L_M \\ D'/C & -1/C \end{bmatrix} \left[ \frac{i_L}{V_o} \right] + \begin{bmatrix} D/L_M \\ 0 \end{bmatrix} v_i \cdots (11)
\]

The input inductor and the output capacitor of the converter are expressed by \( L_M \) and \( C \) respectively. The symbols of \( i_L \) and \( v_o \) means the input inductor current and the output capacitor voltage respectively. The input voltage is \( v_i \) and the resistive load is \( R \). The duty ratios of the converter are \( D \) and \( D' \) \((0 \leq D \leq 1, \ D' = 1 - D)\). The duty ratios \( D \) and \( D' \) are constant because the unregulated dc-dc converter is considered here.

From Eq. (11), the relationship between the input and the output voltages are calculated as follows via the Laplace transformation.

\[
\frac{V_o(s)}{V_i(s)} = \frac{D}{D'} \left( \frac{1}{\omega_c s + \frac{1}{\omega_c^2}} \right) \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (12)
\]

\[
\omega_c = 2\pi f_c = \frac{D'}{\sqrt{L_M C}} \quad \zeta = \frac{1}{2D'R \sqrt{L_M / C}}
\]

Equation (12) means that the voltage transformation ratio \( |V_o(s)/V_i(s)| \) and the phase angle difference of the DCX has the frequency characteristics of the 2nd order low pass filter. In Eq. (12), the symbols of \( f_c \) and \( \zeta \) are the cutoff frequency and the damping factor respectively. To describe the equivalent circuit of the DCX simply by using the dependent sources, the voltage transformation ratio of 1.0 and the phase angle difference of 0 are indispensable at the frequencies which the full-wave rectified input voltage contains.

Figure 6 shows the calculation results of the voltage transformation ratio \( |V_o(s)/V_i(s)| \) and the phase angle difference of the 48 V–48 V 300 W buck–boost converters whose switching frequencies \( f_{sw} \) are 50 kHz, 100 kHz, 1 MHz and 3 MHz. The detailed parameters for this calculation are summarized in Table 1. The circuit parameters \( L_M \) and \( C \) are designed to suppress the switching ripples of the inductor current \( i_L \) and the capacitor voltage \( v_o \). These parameters depend on the switching frequency \( f_{sw} \) and they are calculated as follows.

\[
L_M = \frac{v_i \cdot \Delta t}{\alpha \cdot i_L} = \frac{v_i \cdot D}{\alpha \cdot i_L \cdot f_{sw}} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (13)
\]

Figure 6 means that the high frequency converter with the small inductance \( L_M \) and the capacitance \( C \) achieves the high responsibility. The voltage transformation ratio and the phase angle difference are 1.0 and 0 respectively at the frequency of 600 Hz for the converter operated at the frequency of 3 MHz, however, the transformation ratio varies and the phase angle difference is about 90 degrees at the frequency around 600 Hz for the 50 kHz converter.

The full-wave rectified input voltage waveform of the DCX in the multicellular ADX is formulated by using the Fourier series expansion as follows.

\[
v_o = |V_{im} \sin \omega_{bf}| = V_{im} \frac{2}{\pi} \sum_{i=1}^{\infty} \frac{\cos 2i\omega_0 t}{4i^2 - 1} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (15)
\]

In the above equation, the amplitude and the fundamental angular velocity of the input voltage are \( V_{im} \) and \( \omega_0 \) respectively. The integer \( n \) means the order of the harmonic voltage contained in the input voltage \( v_i \). The dc component and the harmonics up to 10th order have to be considered to recreate the full-wave rectified sinusoidal voltage. In case that the fundamental frequency \( f_0 \) (= \( \omega_0 / 2\pi \)) is 60 Hz, the voltage transformation ratio and the phase angle difference should keep 1.0 and 0 under the frequency of dc to 600 Hz. Based on the design in this section, the switching frequency over 1 MHz is required to regard the isolated dc-dc converter as an ideal transformer. The equivalent circuit using the dependent voltage source and the dependent current source as
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shown in Fig. 5(c) is available for the high frequency unregulated dc-dc converter.

Now, the switching frequency of the commercially available isolated dc-dc converters with the voltage class of 48 V and the output power of several hundred watts is at a level of 1 MHz. The low-voltage and high frequency converters are strong candidates for the multicellular ADX.

4.2 Behavior of Multicellular Isolated Rectifier Based on ISOP Connection Topology In the proposed multicellular ac-dc transformer, pairs of the diode bridge rectifier and the DCX are connected in ISOP and the capacitors are optionally connected in both the input side and the output side. In this section, the input voltage sharing among series connected DCXs is discussed in case the full-wave rectified voltage is applied to the multicellular converter.

Figure 7(a) shows the circuit configuration of ISOP connected multicellular ADX using two pairs of the diode full-bridge rectifier D1, D2 and the isolated buck-boost dc-dc converter DCX1, DCX2. The equivalent circuit for the voltage sharing analysis is also shown in Fig. 7(b). The equivalent circuit using the dependent voltage source and the dependent current source is available for the high frequency isolated dc-dc converter, taking the analysis in the previous section into account. In Fig. 7(b), the diode rectifiers under the on-sate are expressed by using the resistances, and the positive rectified waveform $V_{IN}$ is considered to simplify the analysis.

From Fig. 7(b), the relationship between the voltages and currents are formulated as follows:

$$V_{IN} = V_{i1} + V_{i2} \quad \cdots \quad (16)$$

$$V_{i1} = V_{OUT} + r_{o1} \cdot I_{o1} \quad \cdots \quad (17)$$

$$V_{i2} = V_{OUT} + r_{o2} \cdot I_{o2} \quad \cdots \quad (18)$$

$$V_{OUT} = R_o/2 \cdot I_{OUT} \quad \cdots \quad (19)$$

$$I_{IN} = I_{o1} + sC_{i1} \cdot V_{i1} \quad \cdots \quad (20)$$

$$I_{IN} = I_{o2} + sC_{i2} \cdot V_{i2} \quad \cdots \quad (21)$$

$$I_{OUT} = I_{o1} + I_{o2} - sC_o \cdot V_{OUT} \quad \cdots \quad (22)$$

Here, the symbols of $V_{i1}, V_{i2}$ are the input voltages of DCX1, DCX2 respectively. The input capacitances for DCX1, DCX2 are $C_{i1}, C_{i2}$ respectively, and the output resistances are $r_{o1}, r_{o2}$. The output capacitances for two DCXs are bundled and the bundled output capacitance is $C_o$. The load resistance corresponds to the rated output power for each DCX is $R_o$. The relationship between the total input voltage $V_{IN}$ and the divided input voltage for DCX1 $V_{i1}$ is finally obtained as follows.

$$\frac{V_{i1}}{V_{IN}} = \frac{s^2r_o r_{o2} C_o + sK_2 + 2 \left(1 + \frac{r_o}{R_o}\right)}{s^2r_o r_{o2} (C_{i1} + C_{i2})C_o + sK_1 + 2 \left(1 + \frac{r_o + r_{o2}}{2R_o}\right)} \quad \cdots \quad (23)$$

$$K_1 = \left\{(r_{o1} + r_{o2})(C_{i1} + C_{i2}) + C_o (r_{o1} + r_{o2})\right\}$$

$$K_2 = \left\{(r_{o1} + r_{o2})C_{i2} + r_{o1}C_o + \frac{2r_o r_{o2} C_{i2}}{R_o}\right\}$$

The voltage unbalance under the steady state operation condition is estimated by applying the final value theorem to Eq. (23). The following equation shows the input voltage of the DCX 1 under the steady state.

$$\lim_{s \rightarrow 0} sV_{i1} = \frac{1}{2} \cdot \left\{1 + \frac{r_{o1}}{R_o} \right\} \quad \cdots \quad (24)$$

The mismatch of the output resistances $r_{o1}, r_{o2}$ of two DCXs affects the unbalanced input voltage, however, the influence of the mismatch is negligible because the output resistances $r_{o1}, r_{o2}$ are sufficiently smaller than the load resistance $R_o$ in general. The total input voltage $V_{IN}$ is equalized approximately and the equally divided voltages are applied to all DCXs in the dc circuit condition.

The unbalanced voltage in transient is estimated by applying the initial value theorem to Eq. (23). The following equation means the input voltage of the DCX 1 in transient.

$$\lim_{s \rightarrow \infty} sV_{i1} = \frac{r_{o1} r_{o2} C_{i2} C_o}{r_{o1} r_{o2} (C_{i1} + C_{i2})C_o} = \frac{1}{C_{i1}} + \frac{1}{C_{i2}} \quad \cdots \quad (25)$$

The mismatch of the input capacitances $C_{i1}, C_{i2}$ of two DCXs determines the voltage unbalance directly and the variation in these capacitances should be minimized. The influence of the input capacitances $C_{i1}, C_{i2}$ has to be discussed in the case of the accidents such as the voltage sag and line-ground fault.

The output capacitance $C_o$ affects the cutoff frequency of the frequency characteristics in Eq. (23). The cutoff frequencies $f_{CD}, f_{CN}$ for the denominator and the numerator in Eq. (23) are calculated as follows. These cutoff frequencies
The laboratory prototype of the multicellular ac-dc transformer has been developed to confirm the feasibility of the proposed circuit. The circuit configuration is shown in Fig. 9 and the experimental apparatus is shown in Fig. 10. The diode rectifiers D15XBN20 (200 V, 15 A/SHINDENGEN) and the DCXs V048F480M006 (48 V-48 V, 300 W/VICOR) were utilized for the isolated rectifiers. No external capacitors were connected to apply the full-wave rectified voltage to the non-isolated dc-dc converter. No sensors and no controllers were installed for the isolated rectifiers to simplify the circuit configuration. The sensors for the voltage and the current detections were employed for the non-isolated dc-dc converter behind the multicellular isolated rectifier to control the input inductor current sinusoidally synchronizing with the input rectified voltage.

Table 3 shows the parameters for the experiment. The input voltage of the multicellular ADX $V_{IN}$ is ac 60 V and the input voltages $V_{i1}$, $V_{i2}$, $V_{i3}$ for three diode rectifiers connected in series are ac 20 V ideally. The divided voltages of ac 20 V are rectified by three diode full-bridge circuits and these are also isolated by the DCXs. The output terminals of DCXs are connected in parallel and the output voltages of DCXs are bundled. The bundled output voltage of DCXs $V_{rec}$ corresponds to the full-wave rectification of the divided ac 20 V. The output voltage $V_{OUT}$ is controlled at dc 40 V by the non-isolated boost converter, synchronizing the input inductor current $I_L$ with its input voltage $V_{rec}$. For the control of the boost converter, the voltage sensor ACPL-C87, the current sensor ACPL-C79 from AVAGO and the digital controller PE-Expert IV form MYWAY PLUS were utilized here.

Figure 11 shows the experimental result of the multicellular ac-dc transformer from the start-up operation to the steady state condition. As mentioned above, the input voltage $V_{IN}$ should be designed to keep the voltages $V_{i1}$, $V_{i2}$ at the value obtained from the final value theorem and to keep the phase angle difference approximately 0 under the frequencies contained in the full-wave rectification.

\begin{align} f_{2D} &= \frac{1}{2\pi} \sqrt{\frac{2^2 (1 + \frac{r_1 r_2}{2r_0})}{r_0 r_2 (C_{i1} + C_{i2}) C_o}} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (26) \\
\end{align}

\begin{align} f_{2N} &= \frac{1}{2\pi} \sqrt{\frac{2 (1 + \frac{r_o}{r_0 r_2 C_o})}{r_0 r_2 C_o}} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (27) \\
\end{align}

Figure 8 shows the input voltages and phase angle differences for two DCXs in Fig. 7. The circuit parameters for the input capacitances $C_{i1}$, $C_{i2}$, the output resistances of DCXs $r_{o1}$, $r_{o2}$, the load resistance $R_L$ and the output capacitance $C_o$ are summarized in Table 2. These circuit parameters were determined based on the commercially available low-voltage high frequency dc-dc converter. The output capacitance $C_o$ was varied from 12 μF to 1.2 mF here. The voltage ratio of $V_{ak}/V_{IN}$ (k = 1, 2) means the amplitudes of the input voltages for two DCXs in case the amplitude of the total input voltage $V_{IN}$ is 1. The voltage ratio of 0.5 means the total input voltage is equally divided by two series connected DCXs. The phase angle differences mean the shifted phase angle of the voltages $V_{i1}$, $V_{i2}$ based on the phase angle of the total input voltage $V_{IN}$. The voltage ratio of 0.5 and the phase angle of 0 are required under the frequency up to 600 Hz (10th order harmonics) for the ISOP connected two DCXs. In this calculation, the output capacitance of 120 μF is maximum and the smaller output capacitance is recommended for the stable behavior of the multicellular ac-dc transformer.

5. Experiment for Multicellular AC-DC Transformer

The laboratory prototype of the multicellular ac-dc transformer is shown in Fig. 8 and the experimental apparatus is shown in Fig. 10. The diode rectifiers D15XBN20 (200 V, 15 A/SHINDENGEN) and the DCXs V048F480M006 (48 V-48 V, 300 W/VICOR) were utilized for the isolated rectifiers. No external capacitors were connected to apply the full-wave rectified voltage to the non-isolated dc-dc converter. No sensors and no controllers were installed for the isolated rectifiers to simplify the circuit configuration. The sensors for the voltage and the current detections were employed for the non-isolated dc-dc converter behind the multicellular isolated rectifier to control the input inductor current sinusoidally synchronizing with the input rectified voltage.
Highly Scalable Sensorless Multicellular AC-DC Transformer (Yusuke Hayashi et al.)

Table 3. Parameters for experiment

<table>
<thead>
<tr>
<th>Multicellular converter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Input voltage $V_{IN}$</td>
<td>ac 60 V, 60 Hz</td>
</tr>
<tr>
<td>Output voltage $V_{OUT}$</td>
<td>dc 40 V</td>
</tr>
<tr>
<td>Output resistance</td>
<td>30 $\Omega$</td>
</tr>
<tr>
<td>Capacitance $C$</td>
<td>43.4 $\mu$F</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single cell converter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode rectifier</td>
<td>Si-SBD (200 V, 15 A)</td>
</tr>
<tr>
<td>DCX</td>
<td>D15XBN20 from SHINDENGEN</td>
</tr>
<tr>
<td>L of the non-isolated dc-dc converter</td>
<td>CMF20120D from CREE</td>
</tr>
<tr>
<td>Capacitance $C_1$, $C_2$, $C_3$</td>
<td>0 F (no external capacitors)</td>
</tr>
</tbody>
</table>

Non-isolated boost dc-dc converter
- Semiconductor switches: SiC-MOSFET (1.2 kV, 80 m$\Omega$)
- Switching frequency: 100 kHz
- Input inductor: 500 $\mu$H
- Output capacitor: 4700$\mu$F
- Voltage sensor: ACPL-C87 from AVAGO
- Current sensor: ACPL-C79 from AVAGO
- Digital controller: PE-Expert IV from MYWAY PLUS

was ac 60 V and this was divided equally among three by the ISOP connected isolated rectifiers. The voltages $V_{rec1}$, $V_{rec2}$, $V_{rec3}$ were approximately ac 20 V and these voltages were fully rectified as shown in $V_{rec}$. Based on the rectified voltage $V_{rec}$, the inductor current $I_{IN}$ of the non-isolated dc-dc converter was controlled to be synchronized with $V_{rec}$. The rectified power was converted to the dc power by the boost converter based on the classical feedback control, and the dc voltage of the average 40 V smoothed by the output capacitance $C_o$ was obtained. The output current of three DCXs $I_{rec1}$, $I_{rec2}$, $I_{rec3}$ were equally shared, and the total amount of these three currents appears at the ac input side. The input current $I_{IN}$ was approximately sinusoidal and the power factor of the multicellular ADX was 0.987. The peak current of $I_{IN}$ which affects the input apparent power was higher than the peak current for the input active power because of the controllability around zero current. The total harmonic distortion (THD) of the input current was also obtained and the calculation result of the THD affected by the 3rd and 5th order harmonics mainly was 3.85%.

6. Conclusions

The multicellular ac-dc transformer (ADX) was newly proposed to realize highly scalable and sensorless isolated ac-dc converters. The circuit configuration based on the ISOP connection topology with no auxiliaries such as sensors and master-slave controllers was introduced and the behaviour of the proposed multicellular ADX was briefly described. The reliabilities of the multicellular ac-dc converters were qualitatively discussed and the potential of the ADX to improve the reliability was shown. The voltage unbalance issue in the ISOP connection topology was also discussed, and the simplified circuit analysis was conducted to show the feasibility of the proposed topology, taking the frequency characteristics of the unregulated isolated high frequency dc-dc converter into account. The laboratory prototype of the ac 60 V - dc 40 V ADX using three isolated rectifiers and the non-isolated boost converter was fabricated, and the fundamental conversion behaviour with the balanced voltages and the equally shared currents among the cell converters was confirmed.

The proposed multicellular ac-dc transformer achieves high scalability because of no complicated controls and no additional auxiliaries. The proposed topology is available not only for the 380 V dc distribution system but also for various voltage levels of future distribution systems. This approach expands the possibility of the converter design and pushes the prevalence of PE converters by introducing a lot of standardized lower-voltage and lower-power cell converters. Lower voltage stress of the cell converter enables to apply low-voltage ultra-low loss semiconductor power devices and it helps to develop high OPD converters taking highly integrated packaging technologies into account. The proposed multicellular converter approach contributes to realizing future low-carbon society.

References


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