Contactless DC Connector Concept for High-Power-Density 380-V DC Distribution System

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A contactless DC connector concept has been proposed for next-generation 380-V DC distribution systems in data centers. An LLC resonant DC–DC converter topology with gallium nitride (GaN) power transistors has been applied to realize a highly efficient inductively coupled contactless connector. A prototype of a 1.2-kW 384 V–192 V contactless connector has been fabricated. An efficiency of over 95% and an ideal power density of over 5.0 W/cm³ have been confirmed experimentally under 500-kHz operation. Design considerations for the proposed connector have been also conducted, and the approach for achieving a higher power density of 10 W/cm³ has been presented. The proposed concept contributes to realizing a high-power-density DC distribution system because the functions for both the isolated DC–DC converter and conventional connector are integrated in a single instrument.

Keywords: Contactless power supply, DC Distribution, isolated DC–DC converter, Gallium Nitride

1. Introduction

The amount of network traffic in the data centers has recently been rapidly increasing due to the widespread use of information and communication technology (ICT) equipment⁽¹⁾. Energy saving in the data centers will contribute to solving some of our global environmental problems. Since 2008, the NTT (Nippon Telegraph and Telephone) Group has been developing 380-V DC distribution system that goes beyond the conventional 48 V DC distribution system to realize highly efficient and space-saving (high-power-density) power supply⁽²⁾⁽³⁾.

Intensive studies have been carried out for high-power-density power electronics converter, and the output power density of the converter for 380-V DC distribution system is now at a level of 1 W/cm³. In the field of R&D, power converters with more than 10 W/cm³ have been reported^{(4)–(6)}. As the power density of the power converter increases, the volume of peripherals such as connectors will not be negligible. The power density of the connector for several kW output power in 380-V DC distribution system is now at a level of 10 W/cm³. To realize higher power density 380-V DC distribution system, comprehensive design is indispensable taking the influence of peripherals into consideration.

The DC connector based on the inductively coupled contactless power transfer technology is one of solutions for future high power density DC distribution system. A socket and a plug of the DC connector can be developed by using the primary and the secondary circuits of the isolated DC–

DC converter respectively. This means that the high power density DC–DC converter which constitutes the 380-V DC distribution system can be integrated into the conventional DC connector to shrink the total component volume.

In the 380-V DC distribution system for data centers, high power density design methodology for the isolated DC–DC converter can be directly applied for the contactless DC connector because the loading apparatus is not mobile and the influence of the positioning gap don't have to be considered. The non-regulated converter topology is also available to achieve higher power density in case that the voltage regulation is achieved by front-end and back-end converters in the 380-V DC distribution system. Although the contactless power supply technology for DC connectors has been reported⁽⁷⁾⁽⁸⁾, the concept specialized for data center application has not been reported to realize high power density contactless DC connector.

In this paper, a contactless DC connector concept is proposed to realize high-power-density 380-V DC distribution system in data centers. The DC distribution system using proposed DC connectors is introduced in chapter 2. Then, details of the circuit configuration and characteristics of the connector with the short-distance and the inductively coupled contactless power transfer are described. The feasibility of the proposed connector is verified experimentally in chapter 3. In chapter 4, design consideration for the connector is conducted to achieve the power density of over 10 W/cm³.

2. Concept for Next-Generation 380-V DC Distribution System Using Contactless DC Connector

2.1 Concept to Realize Higher Power Density 380-V DC Distribution System Figure 1 shows the power density trend of isolated DC–DC converters for telecom power

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supply. In research and development level, power converters with 10 W/cm^3 has been developed for 380-V DC distribution system⁽⁹⁾. The power density of a connector for 380-V DC distribution system is also shown in Fig. 1. Volume of a socket in a connector is 100 cm^3 , and the power density per socket is 10 W/cm^3 in the case of the output power of 1 kW.

Figure 2 shows the schematic diagram of the conventional 380-V DC distribution system for data centers. In Fig. 2, connectors with metal contacts and isolated DC-DC converters are installed in low voltage (e.g. 380 V, 48 V and 12 V) DC distribution line for power supply units (PSU) and on-board power supplies behind the rectifier. The power density of power converters is now at a level of 10 W/cm^3 in R&D, and the converters over 50 W/cm^3 is now commercially available for on-board power supply. The influence of peripherals will become obvious in near future.

Figure 3 shows the schematic diagram of the proposed next-generation 380-V DC distribution system with inductively coupled contactless DC connectors. Contactless connectors are only installed in the 380-V DC distribution line

in front of power supply units. A primary and a secondary circuits of an isolated DC-DC converter are utilized as a pair of a socket and a plug respectively. The primary and the secondary circuits are connected via the inductive coupling in a short-distance.

Table 1 shows the power densities of installed components in the current 380-V DC distribution system and the proposed DC distribution system with the contactless DC connector. The transformer for the fundamental frequency of 50 Hz or 60 Hz is removed and the contactless DC connector plays a role in both the metal contact connector and the PSU in the proposed DC distribution system. By removing the transformer, the power density in the AC interface can be improved from 0.39 W/cm^3 ($= (0.66 \times 0.95)/(0.66 + 0.95)$) to 0.95 W/cm^3 which corresponds to the power density of the rectifier. By employing the contactless DC connector, the power density in the DC interface can be improved from 5 W/cm^3 ($= (10.0 \times 10.0)/(10.0 + 10.0)$) to 10 W/cm^3 . Higher power density DC distribution system will be achieved because the number of installed instruments can be reduced in the next-generation DC distribution system.

2.2 Required Performance for Contactless DC Connector

Environment of the 380-V DC distribution system in data centers affects the specifications for the contactless DC connector. The 380-V DC distribution system has following characteristics.

Table 1. Power densities of installed components in 380-V DC distribution system

	Current 380-V DC Distribution		Next-Generation DC Distribution	
	Component	W/cm ³	Component	W/cm ³
AC Interface	Transformer	0.66	HV Rectifier	0.95
	Rectifier	0.95	Rectifier	
DC Interface	Connector	10.0	Contactless DC Connector	10.0
	PSU	10.0

Fig. 1. Power density roadmap for isolated DC-DC converters for telecom power supply and DC connector for 380-V DC distribution system

Fig. 2. Configuration of conventional 380-V DC distribution system

Fig. 3. Configuration of next-generation 380-V DC distribution system using contactless DC connector

- Installed loading apparatus is known. The ICT equipment as the servers is mainly assumed and its electrical behavior is also well-known.
- The connection and the disconnection of the ICT equipment are infrequent. These actions are mainly conducted in the case of the trouble and the scheduled maintenance.
- The installed loads are utilized in a room. The ambient temperature and the humidity are strictly controlled by the external air-conditioning machines.

Usage environment for the contactless DC connector are summarized as follows taking the aforementioned characteristics into account.

- Electric power through the connector is basically stable and the rapid load variation is infrequent.
- The operating temperature and the humidity are stable. The forced-convection cooling is available for the connector because of the air-conditioning equipment in the room.
- The input voltage of the connector can be controlled by the front end converters as Rectifiers in Figs. 2 and 3. The output voltage can be compensated by the DC-DC converter in ICT equipment. The function of the voltage regulation is not required for the contactless DC connector. The functions of the galvanic isolation and the voltage transformation are essential.
- The output voltage of the connector should be compatible with some voltage levels as 380 V, 48 V and 12 V.
- The position gap between the primary transmitter and the secondary receiver in the connector is controllable because the connected loads are utilized fixedly. This means that the coupling coefficient of the transformer and the circuit parameters for the resonant circuits are also controllable.

The LLC resonant DC-DC converter topology has been applied for the contactless DC connector here. The advantages and disadvantages of its topology are summarized as follows.

- High efficiency can be achieved by ZVS (zero voltage switching) of the main switches and ZCS (zero current switching) of the rectifier diodes. The commercially available isolated DC-DC converter based on the LLC topology has achieved the maximum efficiency of 98% and the power density of several tens of W/cm³ ⁽¹⁰⁾.
- ISOP (input series and output parallel) and IPOS (input parallel and output series) topologies are available in the LLC converter topology. Arbitrary input and output voltages are selectable by ISOP and IPOS topologies with low voltage LLC converters ⁽¹¹⁾.
- The LLC converter may not achieve ZVS and ZCS in the case of the rapid load variation, because the conditions for the soft switching depend on the load condition significantly. The transient response of the output voltage control may have large delay because the voltage gain also depends on the load condition largely and the frequency modulation control is generally applied in the LLC converter.

The LLC resonant converter has disadvantages for the soft switching operation and the voltage regulation under the rapid load variation. However, these disadvantages do not have to be considered in the contactless DC connector appli-

cation in the 380-V DC distribution system. Highly efficient DC connector will be developed by taking full advantages of the LLC resonant converter topology.

3. Demonstration of Contactless DC Connector Using GaN Power Device

3.1 Contactless DC Connector Based on LLC Resonant DC-DC Converter Topology The circuit configuration of the LLC converter for the connector is shown in Fig. 4. The availability of LLC converter has been reported and this topology has been applied for the wireless power transfer ⁽¹²⁾⁽¹³⁾. The zero voltage switching (ZVS) of transistors and the zero current switching (ZCS) of diodes achieve high efficiency. In the case that turn ratio of the transformer n is 1, the voltage gain M and the phase angle θ are calculated by following Eqs. (1), (2).

$$M = \left| \frac{V_2}{V_1} \right| = \left| \frac{s^2 N_1}{s^3 D_1 + s^2 D_2 + s D_3 + D_4} \right| \dots \dots \dots (1)$$

$$D_1 = \{L_1 L_2 + (L_1 + L_2) L_m\} C, \quad D_2 = R (L_1 + L_m) C$$

$$D_3 = (L_2 + L_m), \quad D_4 = R, \quad N_1 = R L_m C$$

$$\tan \theta = \frac{N'_2 D'_1 - N'_1 D'_2}{N'_1 D'_1 + N'_2 D'_2} \dots \dots \dots (2)$$

$$D'_1 = -\omega^2 (L_2 + L_m) C, \quad D'_2 = \omega R C$$

$$N'_1 = R - \omega^2 R (L_1 + L_m) C$$

$$N'_2 = -\omega^3 \{L_1 L_2 + (L_1 + L_2) L_m\} C$$

Parameters V_1 and V_2 in Eq. (1) are respectively input and output voltages of LLC resonant tank in Fig. 4. Primary and secondary leakage inductances of the transformer are L_1 and L_2 respectively. They are utilized as the resonant inductances in this circuit. The magnetizing inductance of the transformer is L_m . The resonant capacitance is C and R means the load resistance in the fundamental frequency analysis. In the case the coupling coefficient of the transformer k is high, the influence of L_2 on the voltage gain M is negligible.

Parameters for realizing the connector based on LLC converter topology are shown in Table 2. Figures 5 and 6 show the calculation results of the voltage gain M and the phase angle θ characteristics of the impedance in the LLC resonant tank. The voltage gain was drawn when the switching frequency f_{sw} varied from 100 kHz to 10 MHz in Fig. 5. The phase angle θ was also drawn for the switching frequency in Fig. 6. In Fig. 6, the positive value means the impedance has the inductive characteristics because the phase angle of the current has the delay against that of the voltage. The voltage gain and the phase angle were drawn when the load factor changed from 5% to 200%. Here, the load factor of 100%

Fig. 4. Circuit configuration of contactless DC connector based on LLC resonant converter topology

Table 2. Parameters for contactless DC connector based on LLC resonant converter topology

Symbol	Meaning	Value
P_{out}	Output power	1,200 W
V_{in}, V_{out}	Input / output voltage	384 V / 192 V
f_{rL}, f_{rH}	Resonant frequency	220 kHz, 550 kHz
f_{sw}	Switching frequency	500 kHz
k	Coupling coefficient	0.98
L_m	Magnetizing inductance	19.6 μ H
L_1, L_2	Resonant inductance	3.4 μ H, 0.4 μ H
C	Resonant capacitance	22.1 nF
n	Turn ratio	1

Fig. 5. Voltage gain characteristics of LLC resonant tank for contactless DC connector

Fig. 6. Phase angle characteristics of LLC resonant tank (positive: inductive, negative: capacitive)

corresponds to the rated output power of 1,200 W.

The frequency f_{rH} which the voltage gain is independent of the load resistance is set at 550 kHz and the switching frequency f_{sw} is determined by using the resonant frequencies f_{rL} and f_{rH} in the LLC resonant converter. These resonant frequencies are calculated by using parameters L_1 , L_2 , L_m and C in the LLC converter circuit as follows.

$$f_{rL} = \frac{1}{2\pi\sqrt{(L_1 + L_m) \cdot C}} \cong 220 \text{ kHz} \quad (3)$$

$$f_{rH} = \frac{1}{2\pi\sqrt{(L_1 + L_2) \cdot C}} \cong 550 \text{ kHz} \quad (4)$$

To apply the LLC converter for the DC connector, the output voltage should be independent of the load condition and

Fig. 7. Experimental apparatus of inductively coupled contactless DC connector

be proportional to its input voltage as the conventional connector with the metal contact. The switching frequency f_{sw} should be set at around the resonant frequency f_{rH} .

The soft switching operation has to be achieved in the LLC circuit to realize the highly efficient DC connector. To achieve the ZVS soft switching operation for the main switch, the impedance of the LLC resonant circuit has to be the inductive characteristics (i.e. the phase angle must have the positive value in Fig. 6). The switching frequency f_{sw} should be between resonant frequencies f_{rL} and f_{rH} . Additionally, the switching frequency f_{sw} has to be lesser than the resonant frequency f_{rH} to achieve the ZCS soft switching operation for the rectifier diode. Therefore, the switching frequency f_{sw} has been set at 500 kHz in case the resonant frequency f_{rH} is 550 kHz.

The magnetizing inductance L_m is determined to suppress the magnetizing current as shown in Eq. (5). Leakage inductances L_1 and L_2 are calculated by using L_m and the coupling coefficient of the transformer k as shown in Eq. (6). The resonant capacitor C is designed as the resonant frequency caused by L_1 , L_2 and C corresponds to the designated frequency of 550 kHz as Eq. (7). In Fig. 6, these parameters make the impedance characteristics inductive (i.e. positive phase angle) at the switching frequency of 500 kHz under the load factor from 5% to 120%. This means ZVS can be accomplished at the rated power of 1,200 W.

$$V_{L_m} = L_m \frac{di_{L_m}}{dt} \quad (5)$$

$$L_1 = L_2 = \frac{1-k}{k} L_m \quad (6)$$

$$2\pi f_r = \sqrt{\frac{L_2 + L_m}{\{L_1 L_2 + (L_1 + L_2) L_m\} C}} \quad (7)$$

3.2 Prototype of Contactless DC Connector Using GaN Power Device

The prototype of the inductively coupled DC connector was fabricated. Figure 7 shows the experimental apparatus. The output power is 1.2 kW, the input and the output voltages are 384 V and 192 V, respectively. Circuit parameters were based on Table 2 and components shown in Table 3 were employed to develop the prototype.

GaN-HEMT (600 V, 16 A) from Transphorm was utilized in this experiment. The switching loss energy is smaller than Si power devices and the turn-off energy is independent of the drain current⁽¹⁴⁾⁽¹⁵⁾. In LLC converter topology, the turn-on energy can be eliminated by ZVS and the turn-off energy

Table 3. Hardware for experiment

Symbol	Meaning	Specification
Q_1, Q_2	GaN–HEMT	600 V, 16 A (Transphorm) $R_{ON} = 150 \text{ m}\Omega$
D_1 – D_4	SiC–SBD	600 V, 12 A (Infineon) $V_D = 1.4 \text{ V}$
X	Transformer	MC2 (JFE Ferrite) PQ 40 PQ 50
N_P, N_S	Turn No. of windings	$N_P = N_S = 12$ $N_P = N_S = 8$ Copper ($\rho = 1.68 \mu\Omega \cdot \text{cm}$) $J_W = 3 \text{ A/mm}^2$
C_{in}, C_{out}	MLCC	630 V, 22 μF (Murata)
C	MLCC	1000V, 3.3 μF * 7 (Murata)

Fig. 8. Measurement results of turn-off energy for GaN–HEMT, Si–SJ MOSFET and SiC–MOSFET

has to be minimized taking the turn-off time for ZVS into account. The constant turn-off energy for the drain current makes the LLC converter design simple. SiC–SBD (600 V, 12 A) from Infineon was also utilized for the rectifier diode. The magnetic core material of MC2 from JFE Ferrite was applied for developing the DC connector. Two cores of PQ40 and PQ50 were employed for the experiment.

Figure 8 shows the measurement result of the turn-off switching energies for GaN–HEMT, SiC–MOSFET and Si–SJ (Super Junction) MOSFET. Turn-on switching energies are not shown in Fig. 8 because the ZVS operation in the LLC converter makes the turn-on energy negligible. The double-pulse test was applied to measure the switching loss energies under the inductive load condition. The turn-off switching loss energies for SiC–MOSFET and Si–SJ MOSFET increase as the drain current becomes larger. The aforementioned characteristics which the turn-off energy is independent of the drain current can be seen in the turn-off switching loss energy of only GaN–HEMT.

Figure 9 shows the steady state waveform of the DC connector based on the LLC converter topology under the output power of 1,200 W and the switching frequency of 500 kHz. LLC input voltage means the drain to source voltage of the low-side GaN–HEMT. The LLC input current means the current through the leakage inductance L_1 and the resonant capacitor C . Rectifier input current is through the leakage inductance L_2 . The output voltage of 192 V was obtained and the LLC input voltage was pure square wave which changed from 0 V to 384 V. ZVS operation was achieved because the LLC input voltage changed from 384 V to 0 V when the LLC

Fig. 9. Steady state waveforms of contactless DC connector under 1,200-W and 500-kHz operation

Fig. 10. Measured and estimated efficiencies for DC connector under 500-kHz operation

input current was positive. ZCS was also confirmed because the rectifier input current was nearly equal to 0 A when the LLC input voltage changed.

Figure 10 shows the measured and the estimated efficiencies for the connector. In this experiment, the maximum conversion efficiency of 96.1% was confirmed in case PQ50 was utilized and the maximum efficiency of 95.6% was also obtained in the case of PQ40. These efficiencies were measured by using the power meter WT3000 from YOKOGAWA.

The conversion efficiency was estimated by calculating power losses generated from the transistor Q , the transformer X , the rectifier diode D and the resonant capacitance C as the following equation.

$$\begin{aligned}
 P_T &= P_Q + P_X + P_C + P_D \\
 &= (P_{COND} + P_{OFF}) + (P_{Cu} + P_{CORE}) + P_C + P_D \\
 &= (R_{ON} \cdot I^2 + f_{SW} \cdot E_{OFF}) \\
 &\quad + \{(R_{WP} + R_{WS}) \cdot I^2 + f_{SW} \cdot E_{CORE}\} \\
 &\quad + R_C \cdot I^2 + V_D \cdot I \dots \dots \dots (8)
 \end{aligned}$$

The total power loss is P_T . The power loss generated from transistors, the transformer, the capacitor and the diode are P_Q , P_X , P_C and P_D , respectively. The power losses from transistor P_Q consist of the conduction loss P_{COND} and the turn-off switching loss P_{OFF} . The conduction loss of the transistor P_{COND} depends on the on-resistance R_{ON} and the converter

Fig. 11. Core loss energy characteristics of magnetic core material

resonant current I . The turn-off switching loss P_{OFF} is determined by the operating switching frequency f_{SW} and the turn-off energy E_{OFF} as shown in Fig. 8. The losses from the transformer consists of the winding copper loss P_{Cu} and the core loss P_{CORE} . The copper loss P_{Cu} depends on the winding resistances R_{WP} , R_{WS} and the resonant current I . The core loss is calculated by using the frequency f_{SW} and the core loss energy E_{CORE} in Fig. 11. The resistance R_C means the equivalent series resistance (ESR) of the resonant capacitor C and the voltage V_D shows the forward voltage drop of the rectifier diode D . Here, the current I through the resonant circuit is commonly utilized to estimate the losses P_Q , P_X , P_C and P_D because the turn ratio of the transformer is 1.

The static parameters of the semiconductor power device are given from the published datasheet and they are shown in Table 3. The winding resistances of the transformer R_{WP} , R_{WS} and the equivalent series resistance (ESR) of the resonant capacitor R_C were measured by using impedance analyzer PSM1735 from N4L. These impedances at 500 kHz were utilized to calculate winding losses. The winding resistance and the ESR were 1.5 mΩ/cm and 33 mΩ respectively at the frequency. The core loss of the transformer P_{CORE} is calculated by using the core loss energy per unit volume E_{CORE} taking the magnetic flux density ΔB , the switching frequency f_{SW} and the core dimensions into account. The core loss energy E_{CORE} in this experiment is shown in Fig. 11 and the approximation formulae have been developed to estimate the loss.

The magnetic flux density ΔB is calculated by using the turn number at the primary side of the transformer N_P , the cross section area of the magnetic core S_e , the injected voltage to the transformer V_X and the injected time determined by the switching frequency T_{ON} . Two magnetic cores of PQ40 and PQ50 have been applied for the experiment. The turn number of the winding has been selected as the magnetic flux density has been smaller than 100 mT for both magnetic cores.

In the case of PQ40, the cross section area of the transformer core S_e was 201 mm² from the published datasheet and the magnetic flux density ΔB was calculated to be 79.6 mT as the following equation.

$$\Delta B_{PQ40} = \frac{1}{N_P \cdot S_e} \int_0^{T_{\text{ON}}} V_X dt = \frac{384 \text{ V}/2}{12 \cdot 201 \text{ mm}^2} \cdot \frac{1}{500 \text{ kHz} \cdot 2}$$

Fig. 12. Power loss distribution for 1,200-W DC connector under 500-kHz operation

$$= 79.6 \text{ mT} \dots\dots\dots (9)$$

In the case of PQ50, the cross section area of the transformer core S_e was 328 mm² and the magnetic flux density ΔB was calculated to be 73.2 mT.

$$\Delta B_{PQ50} = \frac{1}{N_P \cdot S_e} \int_0^{T_{\text{ON}}} V_X dt = \frac{384 \text{ V}/2}{8 \cdot 328 \text{ mm}^2} \cdot \frac{1}{500 \text{ kHz} \cdot 2} = 73.2 \text{ mT} \dots\dots\dots (10)$$

The estimated efficiencies from 300 W to 1,200 W had good agreement with the measurement result as shown in Fig. 10. Figure 12 shows the power loss distributions for two magnetic cores of PQ40 and PQ50 under 1,200-W and 500-kHz operation. Power losses calculated by using Eq. (8) are shown in this figure. The legends of P_{COND} (Q) and P_{OFF} (Q) mean the conduction loss and the turn-off switching loss from the transistor Q respectively. The legends of P_{Cu} (X) and P_{CORE} (X) are respectively the winding loss and the core loss from the transformer X . The P_C (C) means the loss caused by the ESR in the resonant capacitor C and the P_D (D) means the loss from the rectifier diode D .

The conversion efficiency of the connector using PQ40 was lower than the efficiency of PQ50. The core loss generated from the transformer using PQ40 was larger than that of PQ50 because of larger magnetic flux density taking the core volume into account. The winding loss of the transformer using PQ 40 was also larger because the winding length was totally longer than that of PQ50 taking the turn number and the winding radius into account.

The power loss generated from the transformer was influential in the total converter loss as shown in Fig. 12. The transformer has some controllable structural parameters as the core dimensions and the turn numbers of the windings. These parameters affect not only the efficiency but also the power density of the connector. It is important to evaluate the influence of the transformer parameters on the connector volume for achieving higher power density.

4. Design Consideration for 10 W/cm³ Contactless DC Connector

The fundamental electric performance has been confirmed by fabricating the 1.2-kW breadboard with the maximum efficiency of 96.1% under 500-kHz operation. High efficiency and ultra-compact DC connector with more than 10 W/cm³ is necessary to realize high-power-density 380-V DC dis-

tribution system as shown in Table 1. In this chapter, the feasibility of the 10 W/cm³ contactless DC connector is investigated through the design consideration.

The design methodology for high-power-density converters has been proposed^{(16)–(18)}. The relationship between the power density and the efficiency is essential to evaluate the barrier of power converter performance. Authors have already proposed the design methodology for realizing high-power-density converter. The parameter design to maximize the power density has been also conducted for the DC-DC converter drawing relationship between the power density and the conversion efficiency using power loss limit model for the novel power device and the loss map for the magnetic core material which estimate exact power losses under real circuit operation condition^{(18)–(21)}. Here, the above design methodology is applied for the 1.2-kW 384 V–192 V contactless DC connector and the possible power density is estimated taking the influences of parameters related to the transformer into account.

4.1 Relationship between Power Density and Conversion Efficiency The power density barrier under the ideal conditions is estimated for the 1.2-kW 384 V–192 V experimental breadboard in the previous chapter to evaluate the feasibility of the 10 W/cm³ contactless DC connector. Ideal conditions to estimate the barrier means the following postulations.

- Semiconductor power devices, gate drivers and auxiliary circuits can be constructed by the highly integrated power modules although discrete power devices and auxiliary components are utilized in the experiment in Fig. 7.
- Power density is calculated by the total amount of components' pure volumes. Interspaces among components are not taken into account to estimate the power density.

Highly integrated power modules are now available and the progress of the integration technology makes the effect of the interspace negligible. Through the postulations, the influence of the design parameters related to the transformer can be discussed simply and the potential of the connector using GaN power transistor and MC2 magnetic core can be seen.

The power density of the connector D_P and the efficiency η are estimated simply by using the following equations.

$$D_P \left[\frac{\text{W}}{\text{cm}^3} \right] = \frac{P_{OUT} [\text{W}]}{V_{OT} [\text{cm}^3]} = \frac{P_{OUT}}{V_{OM} + V_{OX} + V_{OC} + V_{OHS} (P_T)} \dots (11)$$

$$\eta [\%] = \frac{P_{OUT}}{P_{OUT} + P_T} \times 100 \dots (12)$$

The output power of the connector is P_{OUT} and the total volume of the connector is V_{OT} . The total volume V_{OT} consists of volumes of the power module V_{OM} including semiconductor power devices and the auxiliary circuit, the transformer V_{OX} , the resonant capacitor V_{OC} and the heat sink V_{OHS} . The heat sink volume V_{OHS} is simply estimated by using the total power loss P_T and the heat dissipation efficiency k_{HS} ⁽²²⁾.

The total power loss P_T consists of the loss from the main switch P_Q , the transformer loss P_X , the capacitor loss P_C and

Fig. 13. Measurement result of winding resistance per 1 cm in transformer using PQ core

Table 4. Parameters for design consideration.

Parameter	Min.	Max.	Step
Switching frequency	100 kHz	1 MHz	100 kHz
Magnetic Flux Density	50 mT	150 mT	10 mT
Transformer Core Shape	PQ20	PQ50	–
Core Width	20.0 mm	50.0mm	1.0 mm
Core Depth	14.0 mm	32.0 mm	–
Core Height	20.0 mm	50.0 mm	–
Heat Dissipation Efficiency		0.45 W/cm ³	

the rectifier diode loss P_D as shown in Eq. (8). The heat sink volume V_{OHS} is calculated as follows. Here, electrical parameters for semiconductor power devices were fixed because the output power of the designed connector was 1,200 W. Hardware shown in Table 3 were assumed and their parameters were obtained from the published datasheet.

$$V_{OHS} [\text{cm}^3] = \frac{P_T [\text{W}]}{k_{HS} [\text{W/cm}^3]} = \frac{P_Q + P_X + P_C + P_D}{k_{HS}} \dots (13)$$

$$P_Q [\text{W}] = (R_{ON} \cdot I^2 + f_{SW} \cdot E_{OFF})$$

$$P_X [\text{W}] = \{(R_{WP} + R_{WS}) \cdot I^2 + f_{SW} \cdot E_{CORE}\}$$

$$P_C [\text{W}] = R_C \cdot I^2$$

$$P_D [\text{W}] = V_D \cdot I$$

The current density J_W of the primary and the secondary solenoidal copper windings for the transformer was also fixed at 3.0 A/mm² because of the constant output power. In this case, the winding resistances per unit length were approximately equal for different dimensions of PQ magnetic core taking the influences of the skin effect and the proximity effect into account as shown in Fig. 13. Figure 13 shows the measurement result of the winding resistances per 1 cm using the LCR meter PSM1735 from N4L in case the magnetic core shapes of PQ 40, PQ 50 and PQ 107 were employed to develop the transformer windings for the connector. The winding resistances R_{WP} and R_{WS} of the transformer were calculated by using the measurement result in this figure.

Table 4 shows variable parameters for this design. The magnetic flux density ΔB , the core dimensions of the transformer and the switching frequency f_{SW} were varied. Parameters related to the transformer were mainly varied because the power loss generated from the transformer was influential in the experiment. Heat dissipation efficiency k_{HS} was

Fig. 14. Relationship between power density and efficiency for 1.2-kW 384 V–192 V Connector

Fig. 15. Estimated power loss and efficiency for 1.2-kW 384 V–192 V DC Connector

0.45 W/cm³ taking the cooling condition of forced air cooling in data center into account.

To change the core shape, just the core width is controlled here. The core depth and the core height were proportion to the core width based on the determined core shape. The core shape of the transformer was fixed here and the PQ type magnetic core was applied for the connector to achieve the high coupling coefficient (e.g. larger than 0.9). Although the leakage inductances L_1 and L_2 vary in case that the core dimensions changes, they are relatively smaller than the required resonant inductance. The inductance value for the resonant circuit can be controlled by installing the external inductance. In this design, the effect of the leakage inductance on the resonant circuit condition is negligible because of the high coupling coefficient using the magnetic core transformer.

Figure 14 shows the relationship between the power density and the efficiency for design parameters in Table 4. Totally 3000 samples (10 switching frequencies, 10 magnetic flux densities and 30 transformer core shapes) were plotted in this figure. This figure means that the power density and the efficiency are limited to 10.5 W/cm³ and 96.7% respectively in the case of design parameters shown in Table 4.

Figure 15 shows the estimated efficiency to maximize the power density D_P and the loss distribution for varied switching frequencies from 100 kHz to 1,000 kHz. Power losses generated from the main switch Q , the rectifier diode D , the transformer X and the resonant capacitor C are shown here. The maximum efficiency of 96.7% appears at the frequency of 400 kHz and 500 kHz.

Fig. 16. Estimated volume and power density for 1.2-kW 384 V–192 V DC Connector

Fig. 17. Calculated power density and efficiency for 1.2-kW 384 V–192 V Connector under 500-kHz operation

Figure 16 shows the detailed volume distribution and the power density. Body (Q), Body (X) and Body (C) in this figure mean component's volumes of the power module V_{OM} , the transformer V_{OX} and the resonant capacitor V_{OC} in Eq. (11) respectively. Heat sink volumes caused by the power losses from the main switch Q , the rectifier diode D and the transformer X are also shown. Here, the volume of power module for a socket and a plug was set at 14.2 cm³ (= 3.8 cm × 3.4 cm × 0.55 cm × 2) taking the commercially available power module for 600 V 15 A (e.g. DIP-IPM from MITSUBISHI) into account. The maximum power density of 10.5 W/cm³ appears around the frequency of 800 kHz.

4.2 Performance of Experimental Breadboard and Approach to Realize 10 W/cm³ Contactless DC Connector

Figure 17 shows the calculation result of the power density and the conversion efficiency for the 1.2-kW, 384 V–192 V contactless DC connector under the condition that the magnetic flux density varied from 50 mT to 150 mT, the core width varied from 20.0 mm to 50.0 mm and the switching frequency was fixed at 500 kHz. The calculation result for the frequency of 500 Hz has been extracted from Fig. 14 to evaluate the performance of the experimental breadboard. The magnetic flux density ΔB affects the efficiency and the magnetic core dimensions determines the connector total volume mainly. The optimal core dimension exists in each operating magnetic flux density and smaller magnetic core tends to achieve higher power density. The power density and the efficiency are limited to 10.1 W/cm³ and 96.6% respectively

under 500-kHz operation.

Experimental results shown in the previous section have been also plotted on Fig. 17. The experimental result using the core shape of PQ40 was plotted at the coordinate of the power density of 5.7 W/cm³ and the efficiency of 94.8% at 1,200-W output power. The ideal power density of the experiment was calculated by using the following equation, taking the heat dissipation efficiency k_{HS} for the heat sink volume into account. Here, the total transformer volume V_{OX} by using PQ40 was 51.2 cm³ (= 4 cm × 4 cm × 3.2 cm) and the influence of the resonant capacitor C was not considered because its volume was negligible.

$$5.7 \text{ W/cm}^3 = \frac{1,200 \text{ W}}{14.2 \text{ cm}^3 + 51.2 \text{ cm}^3 + \frac{65.8 \text{ W}}{0.45 \text{ W/cm}^3}} \quad \dots\dots\dots (14)$$

The experimental result using PQ 50 was also plotted at the coordinate of the power density of 4.9 W/cm³ and the efficiency of 95.4% at 1,200 W. The ideal power density was calculated as follows with the transformer volume V_{OX} of 100 cm³ (= 5 cm × 5 cm × 4 cm).

$$4.9 \text{ W/cm}^3 = \frac{1,200 \text{ W}}{14.2 \text{ cm}^3 + 100 \text{ cm}^3 + \frac{57.9 \text{ W}}{0.45 \text{ W/cm}^3}} \quad \dots\dots\dots (15)$$

Relationships between the power density and the efficiency were shown for two experimental results using PQ40 and PQ50. The connector using smaller magnetic core of PQ40 has the potential to achieve higher power density compared with the result using PQ50. However, the efficiency decreases because of the higher operating magnetic flux density. This figure means that the two experimental results are not on the design limit and the parameter design of the transformer has the potential to increase the power density of the connector. From Figs. 16 and 17, the transformer volume is around 15.8 cm³ and the utilization of PQ26 is assumed to realize the maximum power density of 10.1 W/cm³ under 500-kHz operation.

Figure 18 shows the illustrations of the DC connectors. The connector for DC 380-V DC distribution system, the contactless DC connector from the experimental breadboard and the connector from design consideration to achieve 10 W/cm³ were shown. Discrete components with PQ40 magnetic core utilized in the experiment were arranged for the illustration of the experimental breadboard. The transformer from the optimal design in Figs. 16 and 17 were utilized to draw the illustration for design consideration to achieve 10 W/cm³. The magnetic core shape of PQ26 was assumed and the highly integrated power modules was also considered for the illustration. From Fig. 18, the transformer design has the potential to improve the power density of the contactless DC connector. The power density of 10 W/cm³ will be accomplished not only by the optimal design of the transformer but also the aforementioned postulations for the integration technology. The contactless DC connector using GaN transistors and MC2 magnetic core material will contribute to realizing future high-power-density 380-V DC distribution system.

Fig. 18. Illustrations of 380-V DC connectors with metal contact, contactless DC connector from experimental breadboard and connector from 10 W/cm³ design.

5. Conclusions

The contactless DC connector has been proposed to realize the future high-power-density 380-V DC power feeding system in data centers. The LLC resonant circuit topology was applied to realize the short-range inductively coupled contactless power transfer. The prototype of 1,200-W 384 V–192 V DC connector was fabricated using GaN–HEMT and the efficiency of 96.1% was achieved. The design consideration for the contactless DC connector was also conducted, and the potential to achieve 10 W/cm³ was shown. This means the proposed contactless DC connector will be realized in the same volume as the conventional DC connector. This contributes to realizing future high-power-density DC distribution system.

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