A 10kW Transformer with A Novel Cooling Structure of A Contactless Power Transfer System for Electric Vehicles

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***Abstract*— A contactless power transfer system for electric vehicles is required to have high efficiency, a large air gap, good tolerance to misalignment in the lateral direction, and to be compact and lightweight. A new 10kW transformer with double-sided winding for fast charging has been developed. The proposed transformer has a novel cooling structure using aluminum bars, aluminum junctions, and aluminum plates. In this paper, the design concept, specifications, and test results of the new transformer are described. The other feature of this transformer is its interoperability with a 3kW transformer. The interoperability test results are also shown.**

I. INTRODUCTION

Recently, due to environmental concerns, plug-in hybrid electric vehicles (PHVs) and electric vehicles (EVs) have gradually become more common. PHVs and EVs need to be connected to power supplies by electrical cables to charge their batteries. A contactless power transfer system would have many advantages, including the convenience of being cordless and safety during high-power charging [1].

A contactless power transfer system for EVs is required to have high efficiency, a large air gap, good tolerance to misalignment in the lateral direction, and to be compact and lightweight. We have revealed that a transformer with rectangular or H-shaped cores and double-sided winding has many advantages applicable to the above specification in comparison with transformers with circular cores and single-sided windings [1, 2]. An H-shaped core transformer, which is more compact and lightweight than a circular core transformer, was developed [1, 2].

However, compact transformers have problems such as the temperature rise caused by the charging loss in continuous power transferring. A small-capacity transformer with double-sided windings can dissipate the heat generated at the winding by transferring heat to the aluminum plate in the back of the transformer. A 3kW transformer for normal charging with an H-shaped core has been developed, and it can transfer 3kW power continuously without a temperature problem [2].

A 10kW transformer for fast charging with an H-shaped core has also been developed in order to reduce the charging time [3]. The test result showed that the temperature rise of the ferrite core surrounded by the winding was a serious issue, and so a more effective heat dissipation method must be developed for 10kW transformers.

Inserting an aluminum plate between the core and winding is effective for the heat dissipation of the ferrite core. However, this method cannot be used for H-shaped cores because an eddy current might be generated in the aluminum plate.

Additionally, two transformers (a normal charging transformer and a fast charging transformer) cannot be installed on the same vehicle because of the increase in cost, weight, and space. Therefore, the fast-charging transformer should be interoperable with the normal-charging transformer.

In this paper, the design concept, specifications, and test results of a new 10kW transformer with a novel cooling structure for fast charging that is interoperable with a 3kW transformer for normal charging are described. In order to improve the heat dissipation of the ferrite core, aluminum bars are inserted in the core, and aluminum junctions are attached to connect the aluminum bars and aluminum plate in the back of the transformer. The heat generated at the ferrite cores is transferred to the aluminum plate through these aluminum bars and aluminum junctions. This new transformer achieved a transfer of 10kW continuously for 150 minutes or more and maintained a high efficiency.

The new 10kW transformer was designed to have almost the same dimensions and the same number of turns on the primary and secondary windings as the 3kW transformer. Consequently, both the 10kW and 3kW transformers have similar parameters. Even when the primary or secondary winding is replaced with that of the 3kW transformer, the 10kW transformer can transfer and receive 3 kW with an efficiency of 91% or more.

Section II describes the contactless power transfer system and the heat dissipation problem of the transformer with

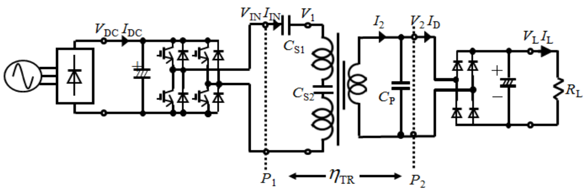


Figure 1. Contactless power transfer system.

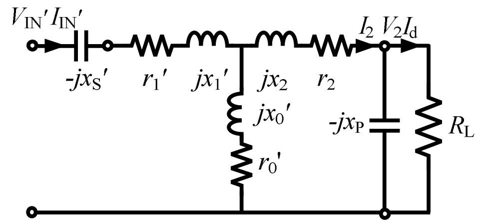


Figure 2. Detailed equivalent circuit.

double-sided winding. Sections III and IV show the design of the transformer with a novel cooling structure, the simulation results, and the temperature rise test. Section V presents the design with interoperability between normal and fast charging and the corresponding test results.

II. Characteristics of Contactless Power Transfer System for EVs

A. Series and Parallel Resonant Capacitor Methods

Figure 1 shows a schematic diagram of the contactless power transfer system with series and parallel resonant capacitors (SP methods) [1-5]. A full-bridge inverter is used as a high-frequency power supply. The cores are made of ferrite, and the windings are Litz wires.

1) Equivalent Circuit

Figure 2 shows a detailed equivalent circuit. It consists of a T-shaped circuit to which the primary series capacitor C_S, secondary parallel capacitor C_P, and load resistance R_L have been added. The primary values are converted into secondary equivalent values using the turn ratio $a = N_1/N_2$. Since the winding resistances r'_1 and r_2 and the ferrite core loss r'_0 are considerably lower than the leakage reactance x'_1 and x_2 and the mutual reactance x'_0 at the resonant frequency, the winding resistances and the ferrite core loss are ignored.

2) Characteristics of Series and Parallel Resonant Capacitor Methods

The secondary parallel capacitor C_P is determined to achieve resonance with the self-inductance of the secondary winding L_2 at the frequency f_0 ($=\omega_0/2\pi$). C_P is given by:

$$\frac{1}{\omega_0 C_P} = \omega_0 L_2 = x_P = x_0' + x_2 \tag{1}$$

The primary series capacitor C_S (C'_S denotes its secondary equivalent) is given by:

$$\frac{1}{\omega_0 C_S'} = x_S' = x_1' + \frac{x_0' x_2}{x_0' + x_2} \tag{2}$$

The input voltage V'_{IN} and the input current I'_{IN} can be expressed by:

$$V_{IN}' = V_{IN}/a = bV_2, \quad I_{IN}' = I_D/b, \quad b = \frac{x_0'}{x_0' + x_2} \tag{3}$$

These equations suggest that the equivalent circuit of a transformer with these capacitors is the same as an ideal transformer with a voltage ratio of b at the resonant frequency.

Ignoring the ferrite core loss ($r_0 = 0$), the efficiency can be approximated by:

$$\eta = \frac{R_L I_L^2}{R_L I_L^2 + r_1' I_{IN}^2 + r_2' I_2^2} = \frac{R_L}{R_L + \frac{r_1'}{b^2} + r_2\left\{1 + \left(\frac{R_L}{x_P}\right)^2\right\}} \tag{4}$$

The maximum efficiency η_{max} is obtained when $R_L = R_{Lmax}$.

$$R_{L\max} = x_p\sqrt{\frac{1}{b^2}\frac{r_1'}{r_2} + 1}, \quad \eta_{\max} = \frac{1}{1 + \frac{2r_2}{x_p}\sqrt{\frac{1}{b^2}\frac{r_1'}{r_2} + 1}} \tag{5}$$

3) Maximum Efficiency of Series and Parallel Resonant Capacitor Methods using k and Q

The primary winding's quality factor Q_1, and the secondary winding's quality factor Q_2 are represented by:

$$Q_1 = \frac{\omega_0 L_1}{r_1}, \quad Q_2 = \frac{\omega_0 L_2}{r_2} \tag{6}$$

Here, L_1 and L_2 are the self-inductances of the primary and secondary winding, respectively, and ω_0 is the resonant angular frequency. If the coupling coefficient k is lower than 0.3 and $Q_1 \cong Q_2$,

$$\frac{1}{k^2}\frac{Q_2}{Q_1} >> 1 \tag{7}$$

Then, equations (5) can be expressed using k and Q.

$$R_{L\max} = \frac{r_2 Q_2}{k}\sqrt{\frac{Q_2}{Q_1}}, \quad \eta_{\max} = \frac{1}{1 + \frac{2}{k\sqrt{Q_1 Q_2}}} \tag{8}$$

Equation (8) indicates that the maximum efficiency η_{max} depends simply on the winding's quality factor Q and the coupling coefficient k if the core loss can be ignored [6].

B. Contactless Power Transformer

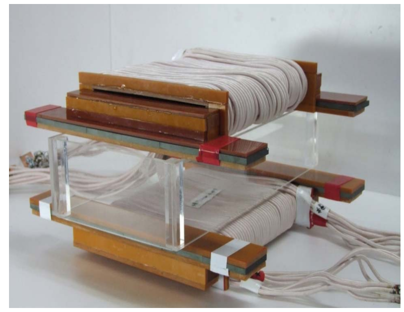
Contactless power transformers can have two different types of structures: circular cores with single-sided winding [7, 8] and rectangular cores with double-sided windings [1-5, 9, 10]. Double-sided winding transformers have leakage flux at the back of the core, and consequently, they have low coupling coefficient k. However, this problem was solved using an aluminum plate attached to the back of the transformer. Since the leakage flux is shielded by the aluminum plate, the coupling coefficient k can be large. For the same coupling coefficient k, the core width (winding width + pole width) of the double-sided winding needs to be only half that of the single-sided winding. A transformer with a double-sided winding can be made smaller than one with a single-sided winding. Furthermore, the coupling coefficient k of a single-sided winding transformer becomes zero when the lateral misalignment is approximately 40% of the core diameter [8]. For the double-sided winding transformer, if the secondary transformer is moved laterally from the center of the primary transformer, the total flux penetrating the secondary winding will decrease only slightly, and the reduction in the coupling coefficient k will also be small. Therefore, the double-sided winding transformer has good tolerance to lateral misalignment.

However, the double-sided winding transformer has poor heat dissipation from the ferrite core compared with the single-sided winding transformer, because the single-sided winding transformer can be directly attached to a heat dissipation device on the back of the core, and it has a large heat capacity due to its large size. On the other hand, the double-sided winding transformer's core is covered with its winding, which makes its heat dissipation disadvantageous.

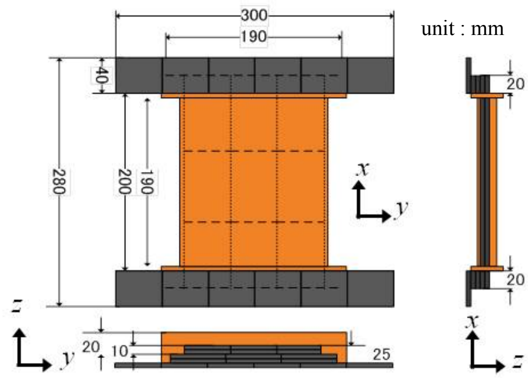
C. *Conventional 10kW Transformer for Fast Charging*

In a previous study, a 10kW transformer that has interoperability with a 3kW transformer (later shown in Fig. 5(b)) was developed. The transformer is shown in Fig. 3. This transformer is small in size (280×300×45mm) and so the heat dissipation area of the core is also small. Additionally, the core is covered with the winding. Moreover, the heat conductivity of ferrite (5W/m・K) is much smaller than those of other metals like aluminum (237W/m・K) and copper (401W/m・K). Therefore, the temperature rise due to iron loss and copper loss becomes a serious problem in the case of compact and large-capacity transformers, which have a core made of ferrite.

Assuming actual charging, a contactless power transformer is required for continuous operation. For example, a 10kW transformer needs about two hours of operation to charge a 24kWh battery. An experiment of continuous 10kW power transfer was performed in the circuit shown in Fig. 1. In this test, the transformer temperature was measured with thermocouples. The operating frequency f_0 was 30kHz, and it was constant during the experiments. A full-bridge rectifier circuit and a load resistance R_L were connected to a secondary transformer. Sixty minutes later, the temperature of the secondary core was about 100°C, and the coil was about 85°C (as shown by the dashed lines in Fig. 8). These temperatures still show an upward trend. Considering a temperature limit of the Litz wire's insulating surface coating, a solution for suppressing the temperature rise is necessary.



(a) A photograph of a conventional 10kW transformer



(b) Measurements

Figure 3. Conventional 10kW transformer for fast charging.

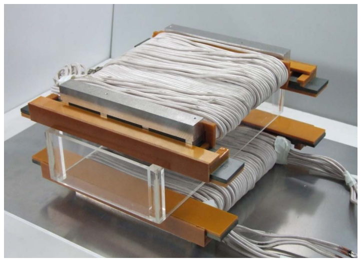
III. A New 10kW Transformer with a Novel Cooling Structure

A. *Cooling Methods*

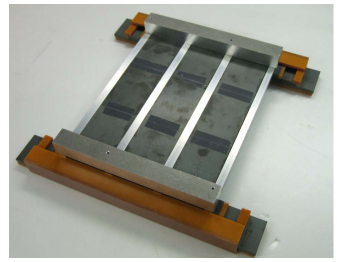
The transformer's windings, ferrite cores, and aluminum plates are heat generation sources. The windings and aluminum plates can be cooled down by cooling fans and fins. However, air cannot access the ferrite cores which is covered with winding, so the ferrite cores covered with winding cannot be cooled that way. Therefore, a heat sink, which can directly transfer heat away from the ferrite cores covered with winding, is considered. However, it is necessary to pay attention to the flow of the magnetic flux. The heat sink shoud be attached in such a way that it can transfer heat effectively and does not couple with the magnetic flux.

B. *A Novel Cooling Structure*

Figure 4 shows a new 10kW transformer with a novel cooling structure constructed of aluminum bars and junctions. The ferrite core was constructed with ferrite blocks (50mm L × 80mm W × 5mm T). Therefore, the core can be divided into three columns. Two aluminum bars were inserted into both of the ferrite core sides, and two aluminum bars were inserted between the ferrite cores (as

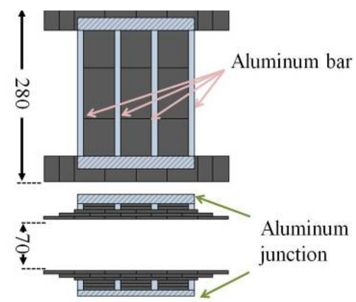


(a) New 10kW transformer

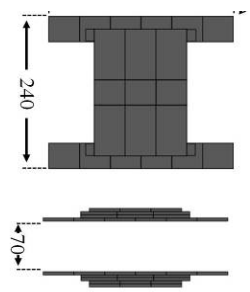


(b) Core without the winding

Figure 4. Photograph of new 10kW transformer with cooling structure.



(a) New 10kW transformer for fast charging



(b) 3kW transformer for normal charging

Figure 5. Dimensions of cores of transformers.

shown in Fig. 5(a); Fig. 5(b) shows a 3kW transformer core without a cooling structure). Aluminum junctions were attached on the back side of the magnetic poles. The heat generated at the ferrite cores is transferred to the aluminum plate in the back of the transformer through these aluminum bars and aluminum junctions. Aluminum bars with a width of 10mm were used.

These aluminum bars were inserted in a direction perpendicular to the magnetic pole. In a double-sided winding transformer, the flux inside the winding proceeds between the pole through the ferrite core. Thus, the losses in the aluminum bars are very small.

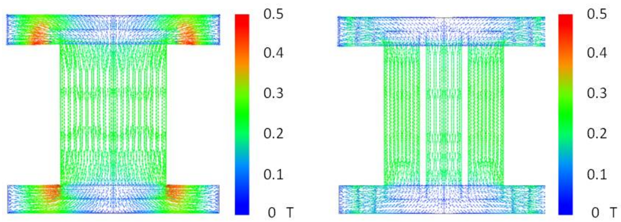
C. Specifications of the 10kW Transformer with Cooling Structure

Table I lists the parameters of the conventional 10kW transformer and the new 10kW transformer at their normal position (no misalignment and a mechanical gap length of 70mm). The resistance and inductance values were measured with LCR meters and were calculated. The inductance values were not significantly influenced even though the aluminum cooling structures were attached.

To see the flow of the main flux in the cores, the conventional 10kW transformer and the new 10kW transformer with the cooling structure were simulated (using the FEM software package JMAG). The simulation results are shown in Fig. 6, and Table II lists the results for the losses, power, and efficiency. As shown in Fig. 6, there is

TABLE I. PARAMETERS AT NORMAL POSITION

Type	Conventional for fast charging	New proposal for fast charging	for normal charging
Cooling Structure	×	○	×
Power[kW]	10	10	3
r_1[mΩ]	107	121	106
r_2[mΩ]	9.1	8.9	9.3
l_0[μH]	58.4	60.5	55.4
l_1[μH]	110	110	115
l_2[μH]	9.8	9.9	9.7
C_S[μF]	0.19	0.188	0.189
C_P[μF]	1.86	1.83	1.91
k	0.35	0.35	0.33
b	0.35	0.35	0.34
R_{Lmax} [Ω]	8.9	9.5	8.69
η_{max} [%]	98	98	98



(a) Conventional core (a) New core

Figure 6. Flow of the main magnetic flux.

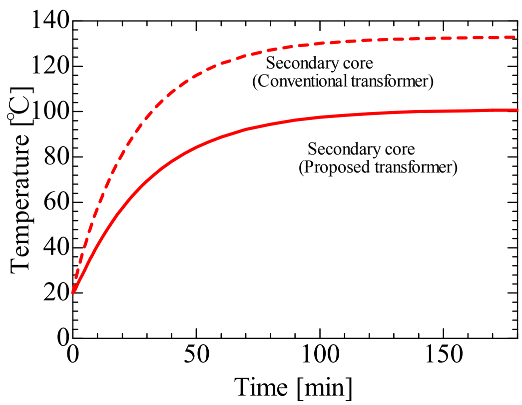


Figure 7. Simulation results for the temperature of the ferrite cores.

TABLE II. SIMULATION RESULTS

			Conventional transformer	Proposed transformer
Copper loss [W]	Primary	Coil	33.7	32.8
		Al plate	51.0	50.4
		Al bar	-	8.0
	Secondary	Coil	36.8	36.6
		Al plate	51.7	52.8
		Al bar	-	6.6
Iron loss [W]	Primary		74.1	55.6
	Secondary		93.6	77.0
P_{OUT} [W]			10084	10124
η_{TR} [%]			96.7	96.9

TABLE III. EXPERIMENTAL RESULTS

P_{OUT} [kW]				10
η[%]	Normal position			95.1
	Gap length		100mm	93.7
	Tolerance to misalignment	x	60mm	94.2
		y	150mm	94.0

little interlinkage flux with aluminum bars. In Table II, the primary and secondary aluminum bar losses were 14.6 W, which were less than 5% of the total loss. Therefore, the eddy current loss in the aluminum bars is very small because the aluminum bars were inserted in the same direction as the main flux.

Table III lists the experimental results of the new 10kW transformer for the 10kW transfer at the normal position, with misalignments (±60mm in the forward direction x and ±150mm in the lateral direction y), and with a +30mm change in the gap length. The operating frequency f_0 was 30kHz, and it was constant during the experiments. A full-bridge rectifier circuit and a load resistance R_L were connected to a secondary transformer. The new transformer efficiency at the normal position was 95.1%, even with misalignments, and when a change in the gap length occurred, the efficiency was 93.7% or more.

IV. TEMPERATURE RISE TEST RESULTS

A. Simulation Results

Figure 7 shows a 10kW simulation result for heat conduction, given that the heat generation of the ferrite core, the coil, the aluminum plate, and the aluminum bars with the loss values are uniform. The loss values in Table II were used in this simulation. Three hours later, the ferrite-core average temperature for the new transformer was more than 30°C lower than the conventional one. This result indicates that the aluminum cooling structure is able to improve cooling performance.

B. 10kW Temperature Rise Test

A 10kW temperature rise test at the normal position was performed in the circuit shown in Fig. 1. In this test, the transformer temperature was measured with thermocouples.

Figure 8 shows the results for the temperature rise of the secondary ferrite core and the aluminum plate. The conventional 10kW transformer without the cooling structure is shown in Fig. 8 with dashed lines. The new 10kW transformer is shown with it in Fig. 8 with solid lines. The conventional transformer temperature showed an upward trend over about 100°C. On the other hand, the new 10kW transformer's secondary ferrite core reached a temperature of 80°C in 60 minutes. One hundred and fifty minutes later, the temperature rose up to about 100°C. Then, the new transformer was at thermal equilibrium. This new transformer was able to maintain a high efficiency of more than 95%. Additionally, the temperature of the new transformer’s aluminum plate was higher than the transformer without the cooling structure because the aluminum bars and the aluminum junctions were able to transfer the heat generated at the ferrite core to the

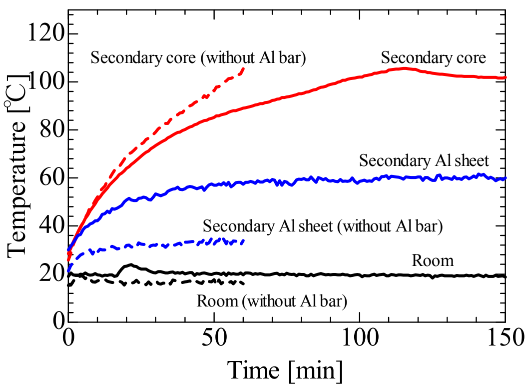


Figure 8. Experimental results for temperature rise.

aluminum plate. Therefore, these results show that the novel cooling structure provides heat dissipation for a transformer with a double-sided winding.

In this study, aluminum bars are used as a heat sink. However, it is possible to improve the cooling performance by modifying the metallic material or changing the heat sink to something such as a heat pipe.

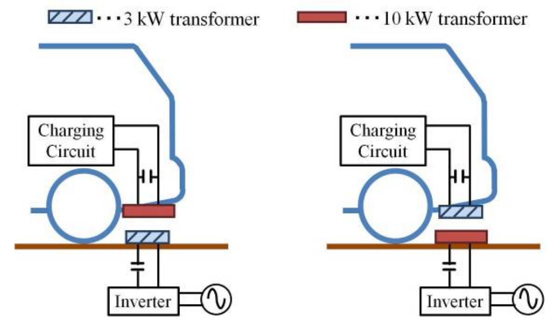
V. Interoperability Between 10kW Fast Charging and 3kW Normal Charging Transformers

A. *Transformer Design for Interoperability*

A contactless power transformer is desirable to have interoperability between fast charging and normal charging, as shown in Fig. 9. When designing the 10kW transformer for fast charging, the number of winding turns had to be the same and the distance between the magnetic poles had to be nearly the same to ensure interoperability with the 3kW transformer for normal charging. When there is nearly the same distance between poles in the 10kW and 3kW transformers, the inductances and load resistance that maximize the efficiency ($=R_{Lmax}$) are the same [3]. The characteristics of the 3kW, conventional 10kW, and the new 10kW (aluminum structure) transformers were compared in terms of interoperability. Table I lists the transformer parameters. Table I indicates that these transformers have similar inductances and values for R_{Lmax}, even when aluminum bars are inserted.

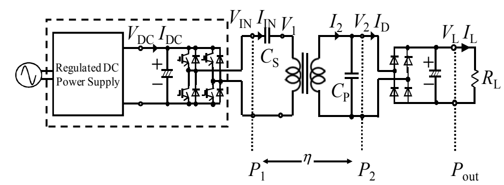
B. *3kW Interoperability Test Results*

Interoperability tests were performed assuming the following: For case A, a fast-type (10kW) transformer is installed on the EVs, and a normal-type (3kW) transformer is laid on the ground, as shown in Fig. 9(a); for case B, a normal-type (3kW) transformer is installed on the EVs, and a fast-type (10kW) transformer is laid on the ground, as shown in Fig. 9(b). The 3kW transformer and the new 10kW transformer were used. The normal position is taken

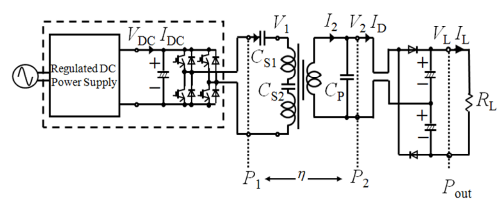


(a) Case A: normal to fast (b) Case B: fast to normal

Figure 9. Interoperability between normal and fast.



(a) Circuit in Case A



(b) Circuit in Case B

Figure 10. Contactless power transfer system.

to have a mechanical gap length of 70mm with no misalignment. The transformer characteristics were measured for a gap length of 70±30mm, misalignments in the forward direction x of ±60mm, and misalignments in the lateral direction y of ±150mm.

The operating frequency f_0 was constant at 30kHz throughout the tests. Figure 10(a) shows the schematic diagram for case A; a full-bridge rectifier circuit and a load resistance R_L=15 Ω are connected to the secondary transformer. Figure 10(b) shows a schematic diagram for case B; a double-voltage rectifier circuit and load resistance R_L=80 Ω are connected to the secondary transformer. In this test, the transfer power is limited to the lower rated power of the two transformers. Therefore, the transfer power was 3kW.

Figures 11 and 12 show the parameters and characteristics for cases A and B, respectively. These

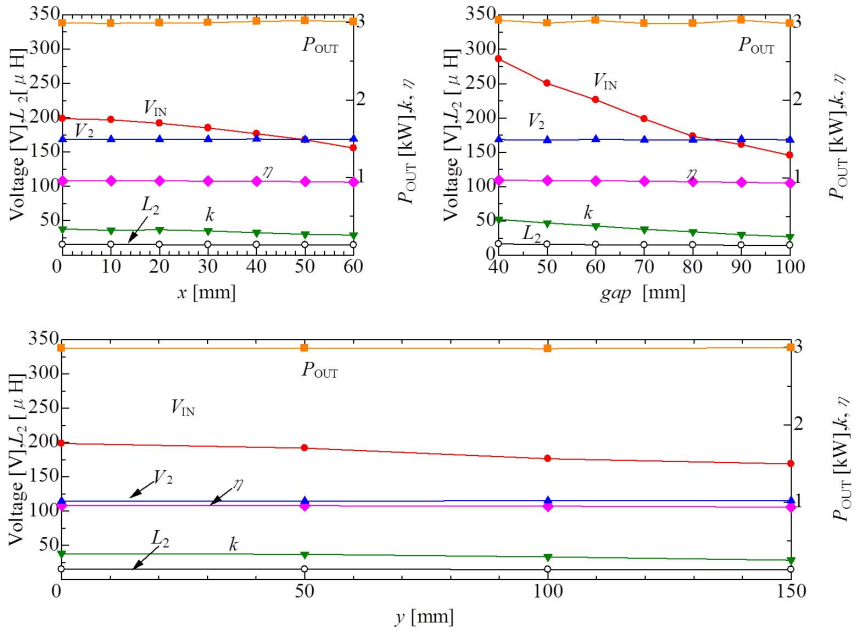


Figure 11. Experimental results in case A.

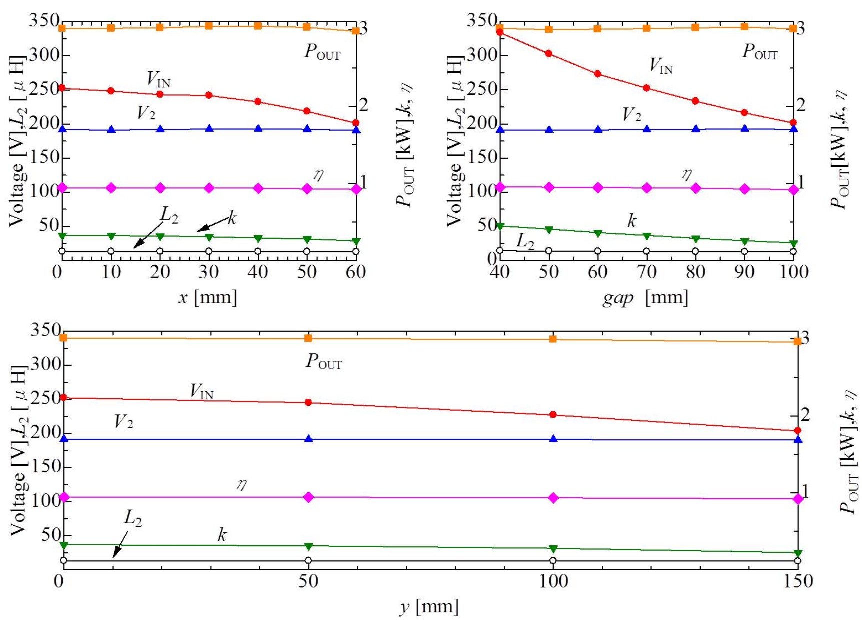


Figure 12. Experimental results in case B.

experimental results show that both transformers have approximately the same characteristics.

Table IV lists the transformer parameters for different gap lengths and positions of misalignment. In case A, the transformer efficiency was 95.8% at the normal position; even when the mechanical gap was increased to 100mm, the efficiency was 93.1%. In the misalignment experiments, the transformer efficiency was always more than 93.6%. On the other hand, in case B, the transformer efficiency was 94.4% at the normal position; even when the mechanical gap was increased to 100mm, the efficiency was 91.9%. In the misalignment experiments, the transformer efficiency was always more than 92.1%.

These results show that even if a transformer with double-sided windings has an aluminum cooling structure, having the same number of winding turns and nearly the same distance between the magnetic poles ensures interoperability between the normal charging and fast charging transformers.

TABLE IV. EXPERIMENTAL RESULTS.

Case				Case A	Case B
Transformer			Primary	3kW-type	10kW-type
			Secondary	10kW-type	3kW-type
Power (kW)				3.0	3.0
η[%]	Normal position			95.8	94.4
	Gap length		Average (40-100mm)	95.3	94.0
			100mm	93.1	91.9
	Tolerance to misalignment	x	Average (0-60mm)	95.2	93.7
			60mm	94.0	92.3
		y	Average (0-150mm)	95.0	93.5
			150mm	93.6	92.1

VI. CONCLUSION

A new 10kW transformer with a novel cooling structure for fast charging has been developed. The cooling structure is made of aluminum bars, aluminum junctions, and aluminum plate and can transfer the heat of the ferrite core without decreasing the transformer efficiency. The test results show that the transformer can transfer 10kW continuously for 150 minutes with a core temperature of 100°C.

This 10kW transformer is also designed to have interoperability with the 3kW transformer. It is required that the 10kW transformer and the 3kW transformer have the same number of turns and nearly the same distance between the poles. The 3kW interoperability test results show the high efficiency and good tolerance to misalignment in the lateral direction between the primary windings of the 3kW transformer and the secondary windings of the 10kW transformer as well as the inverse combination.

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