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10 kW Contactless Power Transfer System for Rapid Charger of Electric Vehicle

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Abstract

A contactless power transfer system for charging electric vehicles requires a high efficiency, a large air gap, and a good tolerance to lateral misalignment and needs to be compact and lightweight. A double-sided winding 10 kW transformer based on a 1.5 kW H-shaped core transformer was developed for a rapid charger. Even though the transformer capacity was increased, the dimensions of the 10 kW transformer were almost the same as those of the 1.5 kW transformer. In this paper, the design concept for this 10 kW transformer and the results of experimental are described. The transformer was found to exhibit more than 94% efficiency with a mechanical gap of 70mm. Even for gap change and position change, an efficiency of over 92% was maintained.

In a contactless power transfer system with a series resonant capacitor, the primary terminal voltage increases with increasing power. This overvoltage may lead to the problem of breakdown voltage of capacitor and the breakdown of winding insulation. To prevent such an overvoltage occurring, it is suggested that the primary winding and the series capacitor are split into two pieces or more respectively, and the split windings and capacitors are alternately connected in a series. Electric vehicles using a contactless power transformer for rapid charging would also uses normal charging. Therefore, the 10 kW transformer was designed to be compatible with the 1.5 kW transformer. Consequently, electric vehicles equipped with the 10 kW transformer can charge even using a 1.5 kW ground transformer, without decrease efficiency.

Keywords: wireless charging, fast charge, efficiency, charging

1 Introduction

Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are actively being developed and commercialized in response to environmental concerns[1]. PHEVs and EVs

currently need to be connected to a power supply by electrical cables to charge their batteries. A contactless power transfer system would have many advantages such as having the convenience of being cordless and enabling high-power charging to be performed safely. Therefore, contactless power transfer systems are being

studied around the world.

A contactless power transfer system for EVs must have a high efficiency, a large air gap, and a good tolerance to lateral misalignment and be compact and lightweight. We have demonstrated these requirements can be met by using a double-sided winding.

In previous studies, we developed a 1.5–3 kW transformer for normal charging[2]. It had a novel H-shaped core. We newly developed a 10 kW transformer for rapid charging. This paper describes the characteristics of this transformer.

The 10 kW transformer should be compatible with a 1.5 kW transformer for normal charging. To design a 10 kW transformer with the same number of turns on the primary and secondary windings as the 1.5 kW transformer, the distance between the poles has to be nearly the same. Consequently, both transformers have similar parameters, including the load resistance R_L at maximum efficiency. Therefore, in the 10 kW system, the inverter output voltage V_{IN} and the load voltage V_L are designed to be 2.6 (the square root of power ratio 10 kW/1.5 kW) times larger compared to the 1.5kW system. The cross-sectional area of the ferrite core and the number of parallel windings of the 10 kW transformer are increased relative to those of the 1.5 kW transformer because the flux density and current are 2.6 times greater. As a result, the 10 kW transformer had an equivalent performance to the 1.5 kW transformer and realized an efficiency of 94.7% when the mechanical gap was 70 mm.

In addition, even when either the primary or secondary transformer is replaced with the 1.5 kW transformer, it is still possible to transfer 1.5 kW with an efficiency of 94% or more. This ability to interoperate between normal charging and rapid charging is a novel characteristic of contactless power transfer systems with double-sided windings, which conventional chargers do not possess.

2 Contactless Power Transfer System for EVs

2.1 Contactless Power Transfer System

Figure 1 shows a schematic diagram of the contactless power transfer system with series and parallel resonant capacitors[3]. A full-bridge inverter is used as a high-frequency power supply. The cores are made of ferrite and the windings are litz wires.

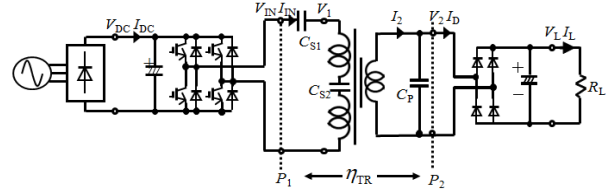


Fig. 1. Contactless power transfer system.

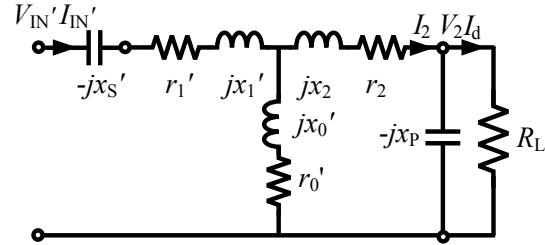


Fig. 2. Detailed equivalent circuit.

2.2 Equivalent Circuit

Figure 2 shows a detailed equivalent circuit. It consists of a T-shaped equivalent circuit to which resonant capacitors C_S and C_P and a load resistance R_L have been added. Primary values are converted into secondary equivalent values using the turn ratio $a = N_1/N_2$. Since the winding resistances and the ferrite-core loss are considerably lower than the mutual and leakage reactances r_2 at the resonant frequency, the winding resistances (r_1' and r_2') and the ferrite-core loss r_0' , can be ignored.

2.3 Characteristics of Series and Parallel Resonant Capacitor System

The secondary parallel capacitor C_P and the primary series capacitor C_S can be expressed by:

$$\frac{1}{\omega_0 C_P} = x_p = x_0' + x_2, \quad (1)$$

$$\frac{1}{\omega_0 C_S} = x_s' = \frac{x_0' x_2}{x_0' + x_2} + x_1'$$

The input voltage V_{IN}' and the input current I_{IN}' can be expressed by:

$$V_{IN}' = b V_2,$$

$$I_{IN}' = I_D / b,$$

$$b = \frac{x_0'}{x_0' + x_2} \quad (2)$$

Equation (2) represents that the equivalent circuit of a transformer with these capacitors is the same as an ideal transformer with a turn ratio of b at the resonant frequency.

Without a rectifier circuit, the efficiency can be approximated by:

$$\eta = \frac{R_L I_L^2}{R_L I_L^2 + r_1' I_1'^2 + r_2 I_2^2} = \frac{R_L}{R_L + \frac{r_1'}{b^2} + r_2 \left\{ 1 + \left(\frac{R_L}{x_p} \right)^2 \right\}} \quad (3)$$

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

$$R_{L\max} = x_p \sqrt{\frac{1}{b^2} \frac{r_1'}{r_2} + 1} \quad (4)$$

$$\eta_{\max} = \frac{1}{1 + \frac{2r_2}{x_p} \sqrt{\frac{1}{b^2} \frac{r_1'}{r_2} + 1}}$$

2.4 Efficient Transformer Design

The primary winding Q_1 and the secondary winding Q_2 are represented by:

$$Q_1 = \frac{\omega_0 L_1}{r_1}, \quad (5)$$

$$Q_2 = \frac{\omega_0 L_2}{r_2}$$

Here, L_1 and L_2 are respectively the primary and secondary self-inductances and ω_0 is the resonant angular frequency.

From equation (4), when:

$$\frac{1}{k^2} \frac{Q_1}{Q_2} \gg 1 \quad (6)$$

η_{\max} and $R_{L\max}$ are represented by:

$$R_{L\max} \cong \frac{r_2 Q_2}{k} \sqrt{\frac{Q_1}{Q_2}}, \quad (7)$$

$$\eta_{\max} \cong \frac{1}{1 + \frac{2}{k \sqrt{Q_1 Q_2}}} \quad (8)$$

Equation (8) indicates that the maximum efficiency η_{\max} depends solely on the quality factor Q and the coupling factor k , if core loss can be ignored.

2.5 Double-sided Winding Transformer

Contactless power transformers can have two different structures: circular cores with single-sided winding[4][5] and rectangular cores with double-sided winding[2][6]. Double-sided winding transformers have a leakage flux at the back of the core and consequently they have low coupling factors k . To overcome this problem, an aluminum sheet is attached to the back of the

core. Since the leakage flux is shielded by the aluminum sheet, the coupling factor k can be large. For the same coupling factor 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 factor k of a single-sided winding transformer becomes zero when the lateral misalignment is approximately 40% of the core diameter[3]. For the double-sided winding transformer, if the secondary winding is moved laterally, the total flux penetrating the secondary winding will decrease only slightly and the reduction in the coupling factor 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 its core because the core is covered by the winding. In addition, the double-sided winding transformer has a low heat capacity due its small volume. Moreover the 10 kW transformer will produce greater heat compared to the 1.5 kW transformer, thermal problems are unavoidable for large-capacity transformers.

2.6 Interoperability between Normal Charging and Rapid Charging

When an EVs is equipped with a contactless power transfer system for rapid charging, its secondary transformer is desirable to be interoperable with a primary transformer for normal charging. If the turns of primary and secondary windings and the operational frequencies are the same and the distances between the poles are nearly the same between two transformers, each primary transformer is interoperable with another secondary transformer. In this case, the transfer power is limited to the lower rated power in two transformers. Thus, the compatibility can be realized between rapid charging and normal charging.

Usually, a conventional rapid charging that uses a cable connection requires a different connector and circuit to those used for normal charging. In contrast, a contactless power transfer system can use the same charging circuit when a transformer that can be used for both rapid and normal charging is employed.

Table 1. Specifications of transformers.

Transformer		1.5 kW	10 kW
Voltage		1 ϕ AC 100 V	3 ϕ AC 200 V
Litz wire		0.1 mm ϕ ×800	
Winding	Primary	20 T (3p)	20 T (4p)
	Secondary	6 T (9p)	6 T (12p)
Weight of secondary		3.9 kg	5.74 kg
Shielding Al sheet		600×400×1 mm (0.6 kg)	

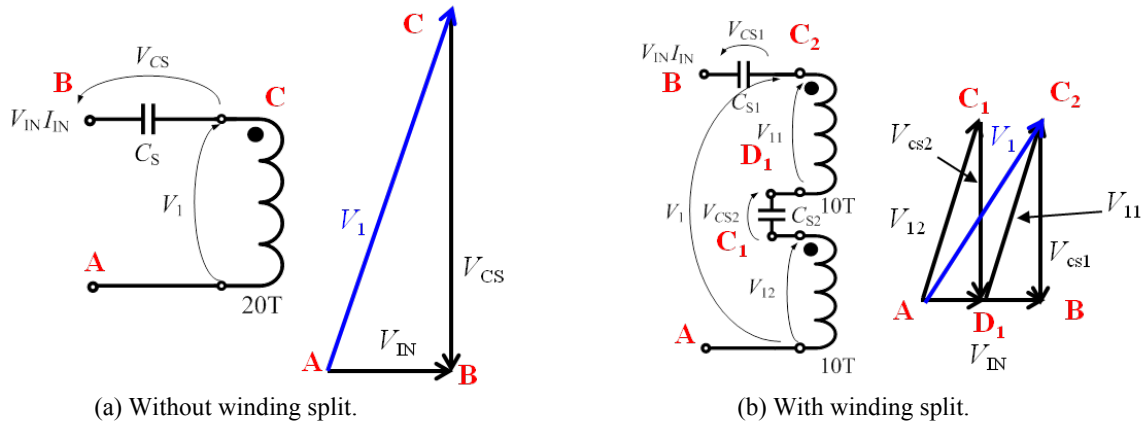
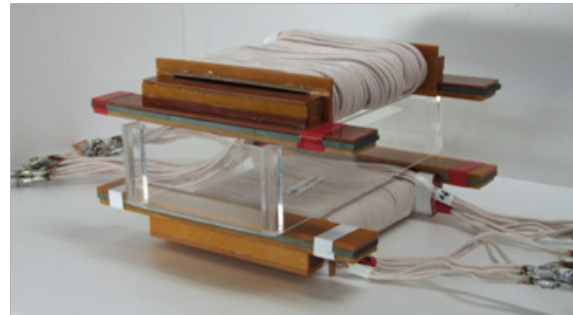


Fig. 3. Split winding voltage vector.

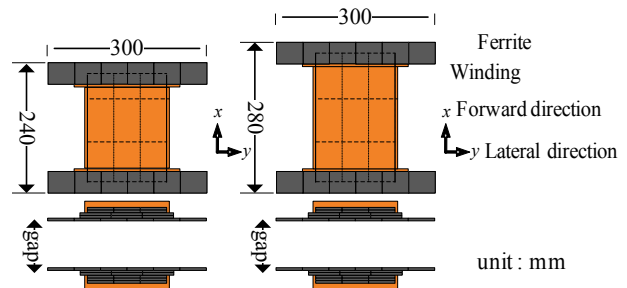
3 10 kW contactless power transfer system

3.1 Countermeasure for Overvoltage of Primary Winding

In the 10 kW contactless power transfer system, the primary current I_{IN} increases compared to 1.5 kW system, and consequently the primary terminal voltage V_1 (i.e., the voltage after C_S in Figure 1) increases in proportion to I_{IN} . Increasing V_1 may cause problems such as overvoltage of the capacitor and the winding. To prevent overvoltage, the primary winding and series resonant capacitors are split and the split windings and capacitors are alternately connected in a series (circuit is depicted in Figure 1). Figure 3 depicts the voltage vectors when the primary winding and the series capacitor are split (Figure 3(b)); it shows that reducing the capacitor voltage reduces the primary terminal overvoltage.



(a) Photograph of 10 kW transformer.



(b) 1.5 kW transformer. (c) 10 kW transformer.

Fig. 4. (a) Photograph and (b), (c) dimensions of transformer.

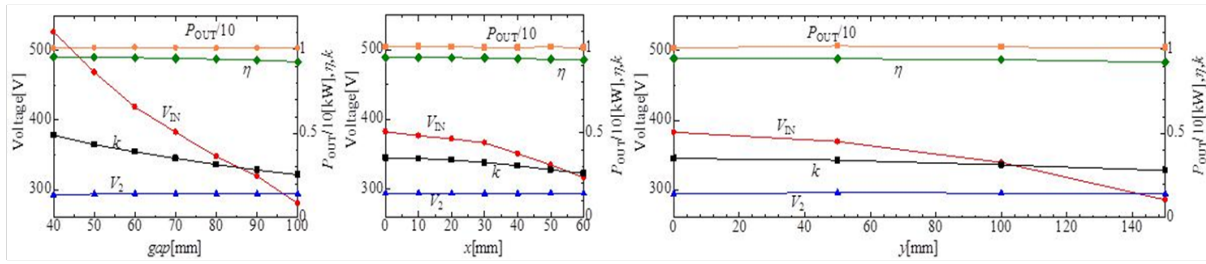


Fig. 5. Experimental results for 10 kW transformer.

3.2 10 kW Transformer

The 10 kW contactless power transformer was designed and made based on the 1.5 kW transformer. It has an H-shaped ferrite core and double-sided winding. An aluminum sheet is attached to the back of the transformer. Table 1 lists the transformer specifications. Figure 4 shows a photograph and the dimensions of the transformer.

When designing the 10 kW transformer, the number of winding turns had to be same and the distance between the poles had to be nearly the same to ensure compatibility with the 1.5 kW transformer. When there is a nearly the same distance between the poles in the 10 kW and 1.5 kW transformers, the inductances and load resistance that maximize the efficiency are the same as those for the 1.5 kW transformer. Therefore, in the 10 kW system, V_{IN} and V_L will be increased 2.6 times and the flux density and current will be about 2.6 times greater.

To avoid the increase in the flux density, the cross-sectional area of the ferrite core was increased. To avoid the increase in the current density, the number of parallel windings was increased. In addition, the distance between the poles was increased by 40 mm so that more litz wire could be wound and to increase the coupling factor k by reducing the leakage flux.

3.3 Characteristics of 10 kW Power Transfer Tests

When using contactless power transfer systems for EVs, misalignment by the driver's skill and gap change due to the car weight cannot be avoided. A mechanical gap length of 70 mm with no misalignment is taken to be the normal position. The transformer characteristics were measured for gap lengths in the range ± 30 mm, a misalignment in the forward direction x of ± 60 mm, and a misalignment in the lateral direction y of ± 150 mm. Misalignment in the x direction can be made small by using a wheel stop, but a large misalignment tolerance in the y direction is required to allow for easy parking.

The operating frequency f_0 is 30 kHz; it is

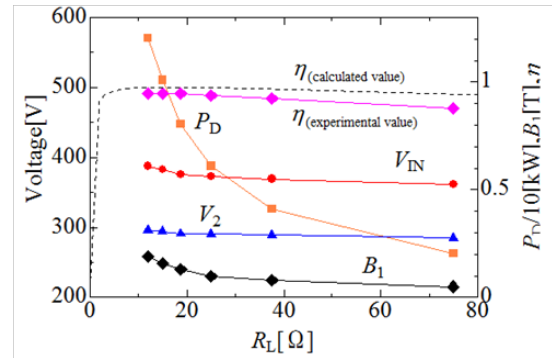


Fig. 6. Characteristics with change in the resistance load.

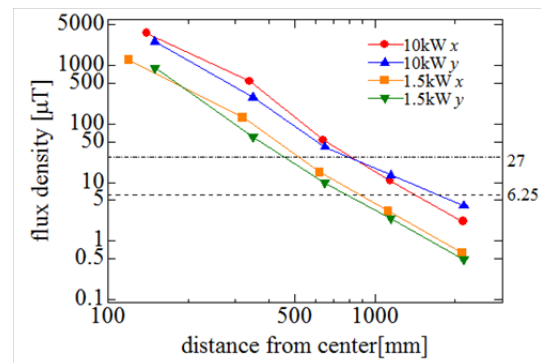


Fig. 7. Leakage flux measurement (30 kHz).

constant during the experiments. A full-bridge rectifier circuit and a load resistance R_L are connected to a secondary transformer. Figure 5 shows the transformer parameters for different gap lengths and positions. The mutual inductance l_0 and the coupling factor k decreased with increasing gap length or misalignment because the magnetic reluctance of the main flux path became larger. However, the secondary self-inductance L_2 was almost constant; consequently, the capacitance of the parallel capacitor C_p given by equation (1) can be constant. Therefore, in the experiment the capacitances of C_s and C_p remained constant during the experiment and the load resistance R_L was kept constant at 15 Ω . As shown in Figure 5, the coupling factor k decreased when the gap length or misalignment was increased and the ideal transformer turn ratio b also decreased and the voltage ratio

(V_2/V_{IN}) increased according to equation (2). The output power P_{OUT} remained constant at 10 kW when the input voltage V_{IN} was varied. The transformer efficiency η at the normal position was 94.7%; even when the mechanical gap was 100 mm, η was 92.6%. The transformer efficiency η was always greater than 92% during the experiments.

3.4 Characteristics of Varying Load Resistance

The charging power varies during charging. As a change in the charging power can be simulated by changing the resistance load R_L , it is important to know the characteristics when the resistance load R_L is changed. Figure 6 shows the transformer parameters when the resistance load R_L is increased from 12 to 75 Ω at the normal position and for constant output voltage V_L . While the transformer efficiency η decreased slightly, the voltage ratio (V_2/V_{IN}) remained almost constant. This demonstrates that this transformer has the characteristics of the ideal transformer.

3.5 Characteristics of Leakage Flux

As the contactless power transformer has small-coupling, the leakage flux is distributed around the transformer. Figure 7 shows the leakage flux densities of the 1.5 kW and 10 kW transformers at the normal position. The leakage flux density decreases according to the 2.7 power of the distance from the center of the transformer. Thus, when the distance is doubled, the leakage flux density decreases to 15%. As shown in Figure 7, the output power affects the leakage flux, but the reduction ratio is due to only the transformer structure.

In practical applications, the effect of leakage flux poses serious problem to human health. Figure 7 also shows criteria for exposure to electromagnetic lines; the 6.25 and 27 μ T lines represent reference levels for exposure to the general public given in ICNIRP1998 and ICNIRP2010[7], respectively. If

the transformer is attached to the center of the car, it might be safe on the vehicle side. In addition, charging must be stopped automatically when a person goes under the car.

4 Compatibility of 1.5 kW and 10 kW Transformers

4.1 Comparison of Characteristics

The characteristics of the 1.5 kW and 10 kW transformers were compared in terms of compatibility. Table 2 lists the transformer parameters. Table 2 shows that the two transformers have similar inductances and load resistance at the maximum efficiency.

Table 3 compares the efficiencies of the 1.5 kW and 10 kW transformers for different gap lengths and misalignments. In Table 3, the gap length of 70 \pm 30 mm and misalignments of 0–40 mm in the x direction and 0–150 mm in the y direction represent average ranges. Tables 2 and 3 show that both transformers have approximately the same specifications and characteristics.

Table 2. Transformer parameters.

Transformer	1.5 kW	10 kW
r_1 [m Ω]	106	107
r_2 [m Ω]	9.30	12.7
l_0 [μ H]	55.4	57.1
l_1 [μ H]	115	111
l_2 [μ H]	9.70	10.18
k	0.333	0.338
b	0.340	0.335
R_{Lmax} [Ω]	8.69	8.03
η_{max} [%]	97.9	97.6

Table 3. Transformer efficiencies.

Transformer			1.5 kW	10 kW	
η [%]	Normal position		94.9	94.7	
	Gap length		Average (30–100 mm)	94.5	94.5
			100 mm	93.1	92.6
	Tolerance to misalignment	x	Average (0–60 mm)	94.0	94.2
			60 mm	92.6	93.2
		y	Average (0–150 mm)	94.0	93.9
			150 mm	93.0	92.4

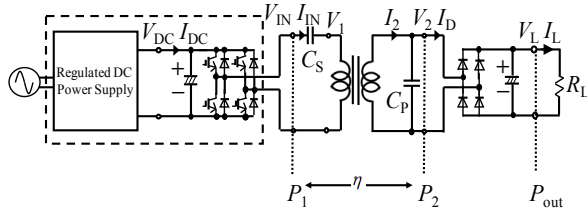


Fig. 8. Contactless power transfer system for case A (primary: 1.5 kW; secondary: 10 kW).

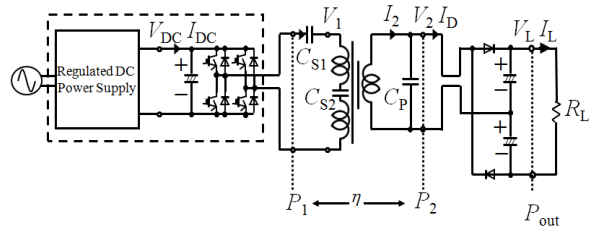


Fig. 9. Contactless power transfer system for case B (primary: 10 kW; secondary: 1.5 kW).

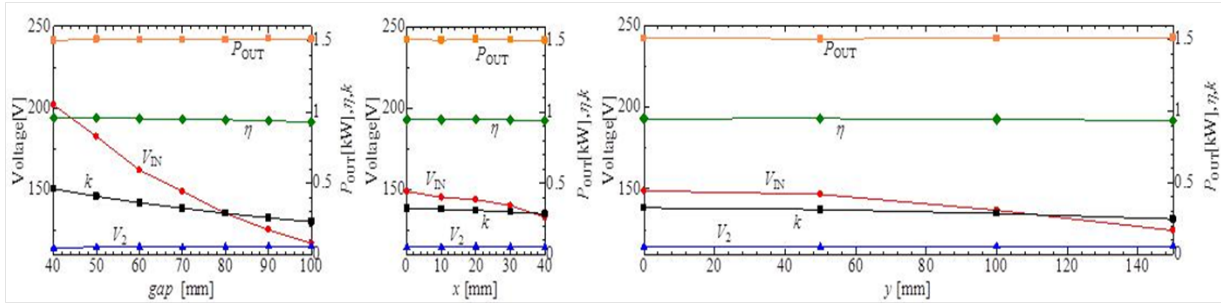


Fig. 10. Experimental results for case A (primary: 1.5 kW; secondary: 10 kW).

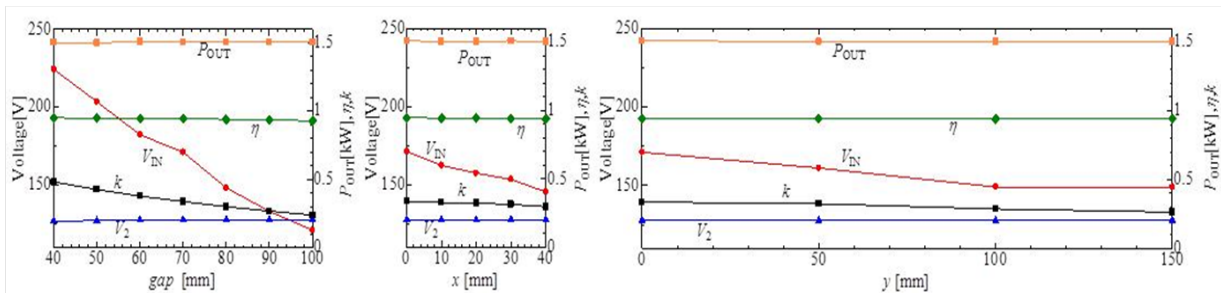


Fig. 11. Experimental results for case B (primary: 10 kW; secondary: 1.5 kW).

4.2 Characteristics of 1.5 kW Compatibility Tests

Two 1.5 kW tests were carried out in the compatibility test: case A in which an EVs is equipped with the rapid type(10 kW) and ground is the normal type(1.5kW), and case B in which an EVs is equipped with normal type and ground is the rapid type. The normal position is taken to have a mechanical gap length of 70 mm with no misalignment. The transformer characteristics were measured for gap lengths in the range ± 30 mm, a misalignment in the forward (x) direction of ± 40 mm, and a lateral (y) direction of ± 150 mm.

The operating frequency f_0 was constant at 30 kHz throughout the tests. Figure 8 shows a schematic diagram of case A; a full-bridge rectifier circuit and load resistance $R_L=15 \Omega$ are connected to the secondary transformer. Figure 9 shows a schematic diagram of case B; a double-voltage rectifier circuit and a load resistance $R_L=80 \Omega$ are connected to the secondary transformer.

Figure 10 and 11 show the parameters and

characteristics for cases A and B, respectively. Similar to the results for 10 kW operation, the mutual inductance l_0 and the coupling factor k decreased with increasing gap length or misalignment. The experimental results of case A and case B show both transformer has approximately the same characteristics.

Table 4 lists the transformer parameters for different gap lengths and positions. In case A, the transformer efficiency η at the normal position is 94.8%; even when the mechanical gap is 100mm η is 93.0%. In the misalignment experiment, the transformer efficiency η is always more than 93.4%. In case B, η at the normal position is 94.7%; even when the mechanical gap is 100mm η was 93.0%. In the misalignment experiment, the transformer efficiency η is always more than 93.9%. In contrast with the results in Table 3, even if the 1.5 kW transformer only replaces the primary or secondary side of the 10 kW transformer, the transformer efficiency η remains approximately the same.

Table 4. Experimental results for compatibility tests.

		Case A	Case B	
Transformer		Primary	1.5 kW	
		Secondary	10 kW	
η [%]	Normal position		94.8	
	Gap length	Average (30–100 mm)	94.8	
		100 mm	93.0	
	Tolerance to misalignment	x	Average (0–40 mm)	94.6
			40 mm	94.1
		y	Average (0–150 mm)	94.4
			150 mm	93.4

5 Conclusion

A novel 10 kW transformer that can be used for rapid charging was developed and its characteristics were investigated. It had a high efficiency and was compatible with a 1.5 kW transformer. To keep the compatibility, the 10 kW transformer was designed to have the same turns and the same distance between poles. To avoid high primary terminal voltage, the primary winding and the series capacitor are split into two severally, and split windings and capacitors are alternately connected in the series.

The interoperability tests between the 10 kW rapid charging transformer and the 1.5 kW normal charging transformer are carried out successfully.

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