Compact Contactless Power Transfer System for Electric Vehicles

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***Abstract*--Electric vehicles (EVs) have been attracting considerable interest recently. A contactless power transfer system is required for EVs. Transformers can have single-sided or double-sided windings. Transformers with double-sided windings are expected to be more compact and lightweight than transformers with single-sided windings. A contactless power transfer system for EVs needs to have a high efficiency, a large air gap, good tolerance to misalignment and be compact and lightweight. In this paper, a novel transformer using series and parallel capacitors with rectangular cores and double-sided windings that satisfies these criteria has been developed, and its characteristics are described. It has an output power of 1.5 kW and an efficiency of 95% in the normal position. To reduce the cost of expensive ferrite cores, a transformer with split cores is also proposed.**

***Index Terms*--Contactless power transfer system, Efficiency, Electric vehicle, Plug-in hybrid electric vehicle**

I. INTRODUCTION

Plug-in hybrid electric vehicles (PHVs) and electric vehicles (EVs) are increasingly becoming realities because of environmental concerns and rising oil prices. PHVs and EVs currently need to be connected to a power supply by electric cables to charge their batteries. A contactless power transfer system (such as that depicted in Fig. 1) has many advantages, including the convenience of being cordless (so that there is no need to unplug the cable) and safety during high-power charging.

The following specifications are very important for a contactless power transfer system for PHVs and EVs:

1. An efficiency of at least 95%.
2. An air gap of at least 70 mm.
3. Good tolerance to misalignment in the lateral direction (e.g., ±125 mm).
4. Compact and lightweight.

We used two technologies to satisfy these specifications. The first technology is a resonant capacitor configuration in which the primary capacitor is in series and the secondary capacitor is in parallel to each winding. The second technology is a transformer with a novel structure in which double-sided windings are wrapped around rectangular cores.

Because transformers have a large air gap, they have low coupling factors (0.1-0.5). Hence, a high-frequency (10-50 kHz) inverter is used as the power supply and resonant capacitors are connected to the terminals.

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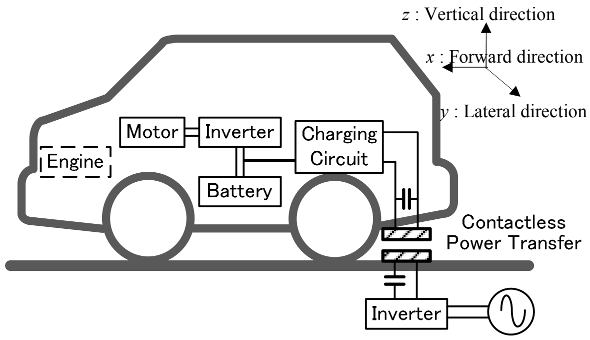

Fig. 1. Contactless power transfer system for an EV

Various resonant capacitor configurations have been proposed [1]. Among them, a configuration in which the primary capacitor is in series and the secondary capacitor is in parallel has an interesting characteristic [2]: if the capacitors are chosen correctly and the winding resistances are ignored, the equivalent circuit of a transformer with these capacitors is the same as an ideal transformer at the resonant frequency, which is equal to the inverter frequency.

From this characteristic, the following benefits are obtained:

1. When there is a resistance load, the power factor of the inverter output is always 1 and soft switching is performed.
2. The capacitances of the resonant capacitors are independent of the output power.
3. If the primary voltage/current is constant, the secondary voltage/current will also be constant regardless of the load change.
4. The theoretical equation for the efficiency can be easily derived. This enables the optimum transformer design to be determined and the transformer to be operated at its maximum efficiency [3].

Transformers with circular cores and single-sided windings have commonly been used. As they have two flux loops in their cross section, the core width is large and the coupling factor between the windings will be zero when the horizontal misalignment is about half the core diameter [4]. The proposed transformer has rectangular cores with double-sided windings and has a single flux loop in its cross section. Consequently, it has a small core width and there is only a moderate reduction in the coupling factor when there is lateral misalignment.

A 1.5 kW transformer with double-sided windings that satisfies the above specifications has been constructed. Furthermore, to reduce the cost and the weight of ferrite

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cores, a transformer with split cores has also been developed. The following sections describe the characteristics of these transformers and present various test results.

II. Primary Series Capacitor and Secondary Parallel Capacitor Configuration

A. Contactless Power Transfer System

Fig. 2 shows a schematic diagram of a contactless power transfer system with series and parallel resonant capacitors. 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. 3 shows a detailed equivalent circuit, which consists of a T-shaped equivalent circuit to which resonant capacitors C_S and C_P and a resistance load R_L have been added. Primary values are converted into secondary equivalent values using the turn ratio $a = N_1/N_2$ (primes are used to indicate converted values). As the winding resistances and the ferrite-core loss are much lower than the mutual and leakage reactances at the resonant frequency, the simplified equivalent circuit shown in Fig. 4(a), which ignores the winding resistances (r'_1 and r'_2) and the ferrite-core loss r'_0, is used.

B. Resonant Capacitors

To achieve resonance with the self-reactance of the secondary winding $\omega_0 L_2$, which is equivalent to adding a mutual reactance x'_0 and a leakage reactance x_2, the secondary parallel capacitor C_P is given by:

$$\frac{1}{\omega_0 C_P} = x_p = x'_0 + x_2 \tag{1}$$

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

$$\frac{1}{\omega_0 C'_S} = x'_s = \frac{x'_0 x_2}{x'_0 + x_2} + x'_1 \tag{2}$$

V'_{IN} and I'_{IN} can be expressed as:

$$V'_{IN} = bV_2 = bV_L, \quad I'_{IN} = I_L/b, \quad b = \frac{x'_0}{x'_0 + x_2} \tag{3}$$

Equation (3) stands for the equivalent circuit of a transformer with these capacitors is the same as an ideal transformer (Fig. 4(b)) at the resonant frequency.

C. Efficiency

The efficiency is approximated by:

$$\eta = \frac{R_L I_L^2}{R_L I_L^2 + r'_1 I'^2_1 + r_2 I_2^2} = \frac{R_L}{R_L + \dfrac{r'_1}{b^2} + r_2\left\{1 + \left(\dfrac{R_L}{x_P}\right)^2\right\}} \tag{4}$$

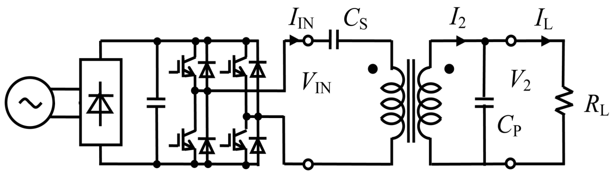


Fig. 2. Contactless power transfer system for an EV

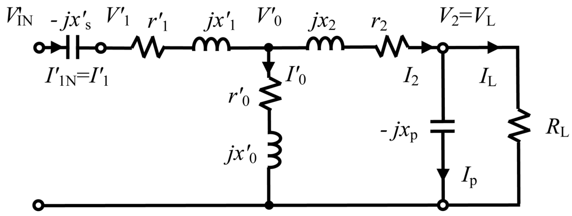
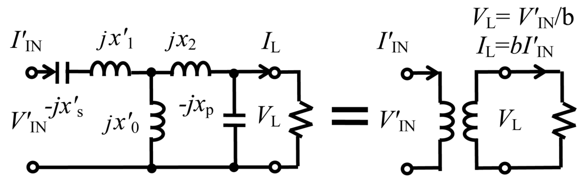


Fig. 3. Detailed equivalent circuit



(a) Simplified equivalent circuit (b) Ideal transformer

Fig. 4. Simplified equivalent circuit and ideal transformer

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

$$R_{L\max} = x_p \sqrt{\frac{1}{b^2}\frac{r'_1}{r_2} + 1} \qquad \eta_{\max} = \frac{1}{1 + \dfrac{2r_2}{x_p}\sqrt{\dfrac{1}{b^2}\dfrac{r'_1}{r_2} + 1}} \tag{5}$$

If these characteristics are used, it is possible to design a transformer that has a maximum efficiency when the output power is equal to the rated power.

III. Comparison of Transformer Structure

Fig. 5 shows a comparison of a single-sided winding transformer and the proposed double-sided winding transformer. The winding width must equal or exceed the gap length for the coupling factor to be greater than 0.2. The core width of the single-sided winding must be 2× (winding width + 2×pole width), whereas the core width of the double-sided winding need only be 1× (winding width + 2×pole width). When a double-sided winding is used, the transformer can be made smaller than a transformer with a single-sided winding. Furthermore, the coupling factor of a single-sided winding transformer becomes zero when the horizontal misalignment is about half the core diameter.

However, double-sided winding transformers have a leakage flux at the back of the core and consequently they have low coupling factors. To overcome this problem, an aluminum sheet is attached to the back of the core, as shown in Fig. 5. The leakage flux is shielded by the aluminum sheet and the coupling factor becomes 50% larger than when no aluminum sheet is present. The reduction in the efficiency due to eddy current losses in the aluminum sheet is small (1-2%).

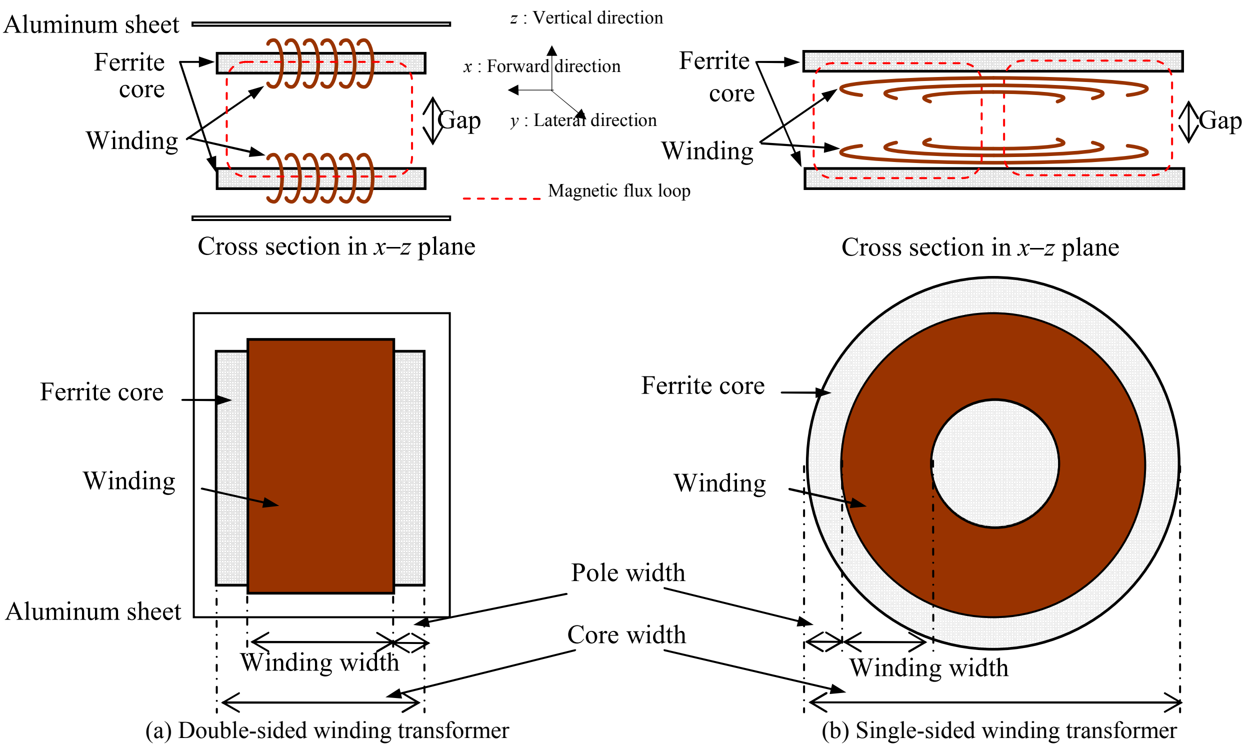


Fig. 5. Structures of transformers

IV. Characteristics of Transformer with Rectangular Cores

A. Specification

Table I lists the specifications of a 1.5 kW double-sided winding transformer and Fig. 6 shows a photograph of the transformer. A gap length of 70 mm with no misalignment is taken to be the normal position of the transformer. Characteristics were measured for gap lengths in the range ±20 mm, a misalignment in the forward direction of ±45 mm, and a misalignment in the lateral direction of ±125 mm.

B. Experimental Results

In the experiment, the power supply voltage (V_{AC} = 100 V) and the inverter frequency (f_0 = 20 kHz) were kept constant. A full-bridge rectifier and a resistance load were connected to the secondary winding. Fig. 7 shows a schematic of the electric circuit.

Fig. 8 shows the transformer parameters when the gap length or position is varied. Fig. 9 shows the transformer values when the gap length or position is altered and they are also given in Table II. Fig. 5 depicts the misalignment direction. Fig. 10 shows the efficiency as a function of the resistance load and Fig. 11 shows the primary and secondary waveforms at 1.5 kW.

As shown in Fig. 8, the coupling factor k decreased when the gap length or misalignment was increased. The change in the value of the parallel capacitor C_P determined by Equation (1) was small because the secondary self-inductance L_2 was almost constant. The values of the resonant capacitors C_S and C_P remained constant when the various values were measured in Fig. 9.

TABLE I
TRANSFORMER SPECIFICATIONS

Rated power		1.5 kW
Gap length		70±20 mm
Core		FDK 6H40
Litz wire		0.25φ × 24 × 16
Size	Core	240 × 250 × 5 mm
	Winding width	150 mm
Weight	Primary	4.4 kg
	Secondary	4.6 kg
Winding	Primary	1p × 18 turns
	Secondary	2p × 9 turns
Aluminum sheet		400 × 600 × 1 mm

Fig. 6. Photograph of 1.5 kW transformer

The secondary voltage V_2 (determined by Equation (3)) increased because the coupling factor k and the ideal transformer turn ratio b decreased when the gap length was increased. The resistance load R_L was adjusted to the output power P_{OUT} = 1.5 kW when the transformer values were measured as a function of the gap length.

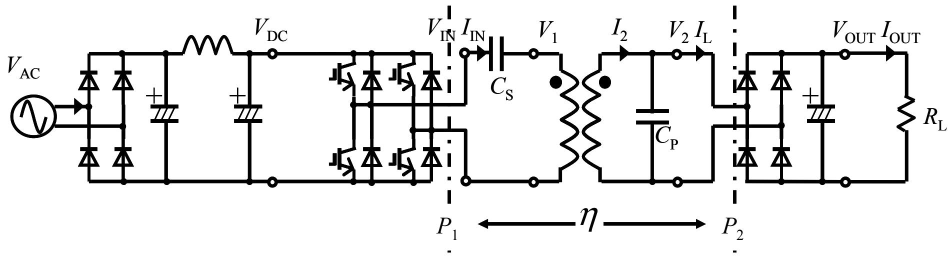


Fig. 7. Experimental circuit

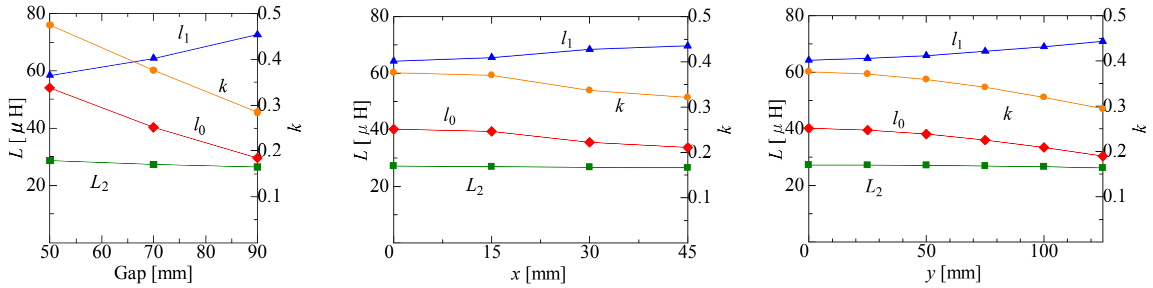


Fig. 8. Transformer parameters with change in gap length or position

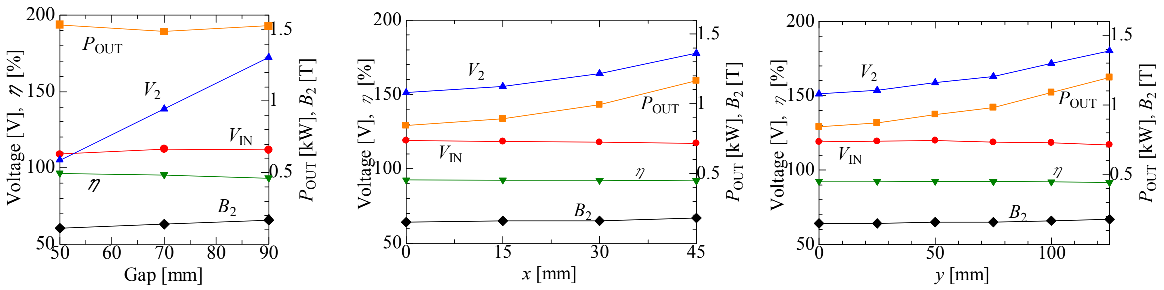


Fig. 9. Transformer values with change in gap length or position

TABLE II
TRANSFORMER SPECIFICATIONS

Frequency [kHz]	20	
Gap length [mm]	70	
x [mm]	0	45
y [mm]	0	125
R_L [Ω]	23.1	50.0
V_{IN} [V]*	112	110
V_2 [V]*	139	200
V_{OUT} [V]	186	281
P_{OUT} [kW]	1.49	1.57
η [%]	95.3	90.2
B_2 [T]	0.14	0.20
C_S [μF]	0.696	
C_P [μF]	2.30	

* rms value

The input voltage V_{IN} and the secondary voltage V_2 almost satisfy Equation (3), even when the gap length was varied. The efficiency η was 93.4% when the gap length was 90 mm.

The voltage ratio (V_{IN}/V_2) changed when the position or the gap length was varied. When the input voltage V_{IN} and the resistance load R_L were constant, the secondary voltage V_2 and the output power P_{OUT} increased when the misalignment increased.

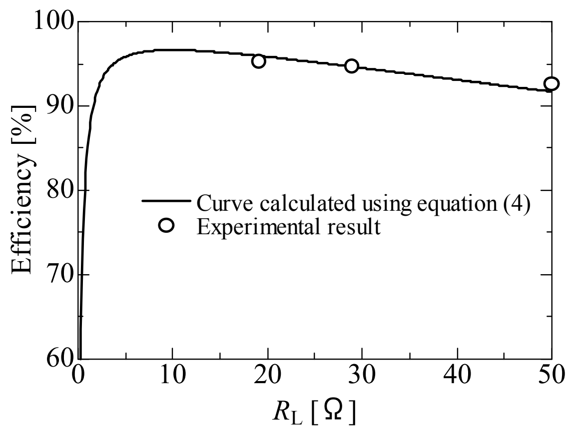
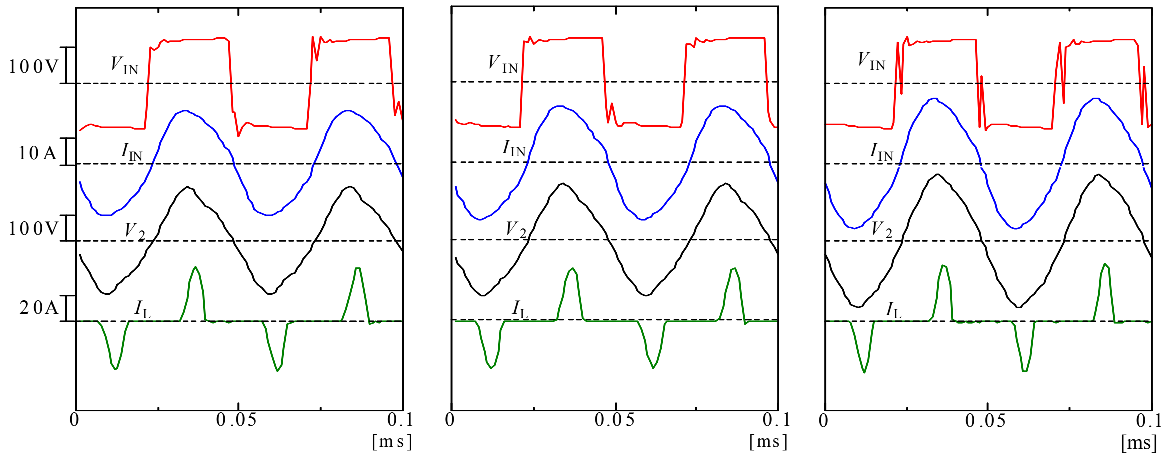


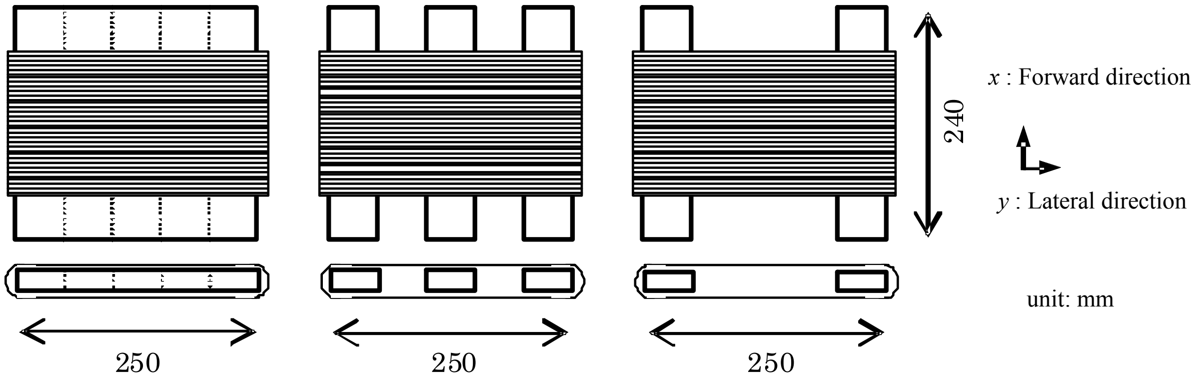
Fig. 10. Efficiency as a function of resistance load

In the misalignment test in the directions of x and y, the power supply voltage V_{AC} was 100 V, the resistance load R_L was 50 Ω, and the gap length was 70 mm; these parameters were kept constant. As shown in Fig. 9, the efficiency η was about 90% or higher. As Table 2 shows, it is possible to transfer 1.5 kW and maintain the transformer efficiency at over 90% even at the highest misalignment (x = 45 mm, y = 125 mm).



(a) Rectangular cores (b) Split cores #1 (c) Split cores #2

Fig. 11. Wave forms



(a) Rectangular cores (b) Split cores #1 (c) Split cores #2

Fig. 12. Transformers with various cores

The above results demonstrate that the rectangular double-sided winding transformer has good tolerance to misalignment. Fig. 10 reveals that there is good agreement between the measured efficiency and that calculated using Equation (4). As shown in Fig. 11, V_{IN} and V_2 and I_{IN} and I_L were coherent. This demonstrates that the transformer has the characteristics of an ideal transformer.

V. Characteristics of Transformer with Split Cores

To reduce the weight and cost of the transformer with rectangular cores, we developed a transformer with split cores. In the case of the transformer with rectangular cores, the flux density of the secondary core (B_2) is higher than that of the primary core and B_2 is much lower than the saturation flux density B_S (= 0.53 T), as shown in Fig. 9. Thus, it is possible to reduce the amount of ferrite core without reducing the power transfer performance.

A. Specifications

It is important when reducing the ferrite core to ensure that the transformer performance does not decrease when the gap length or position is varied. The external dimensions of the transformer must not be altered because the transformer performance depends on them. A transformer with split cores was developed by splitting the ferrite core into separate sections, as shown in Fig. 12(b) and (c). The same coils for the rectangular cores were used. Split core #1 is 40% (0.6 kg) and split core #2 is 60% (0.9 kg) lighter than the rectangular cores; the cross-sectional areas of these split cores were respectively 40% and 60% smaller than that of the rectangular core. The core flux densities of split cores #1 and #2 are expected to be 170% and 250% higher than that of the rectangular cores, respectively.

B. Experimental Results

Fig. 13 shows the variation in the parameters of the transformers with split cores when the gap length or position is changed. The coupling factor k was lower than that for the rectangular cores because the main flux path had a higher magnetic reluctance. The change in the value of the parallel capacitor C_P was small because the secondary self-inductance L_2 was almost constant even when the gap length or position was changed.

The same experiment was performed as that for the transformer with rectangular cores. When the transformer characteristics were measured as a function of the gap length, the power supply voltage V_{AC} was 100 V and the resistance load R_L was adjusted to give an output power P_{OUT} of 1.5 kW. In the misalignment test in the directions

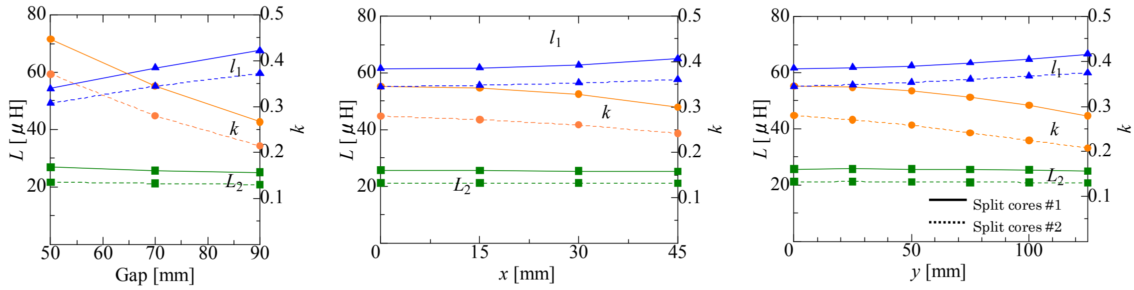


Fig. 13. Parameters of transformers with split cores

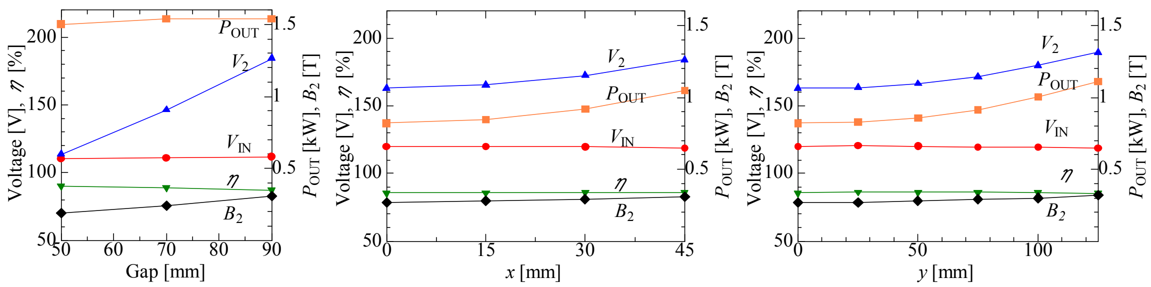


Fig. 14. Experimental results for transformer with split cores #1

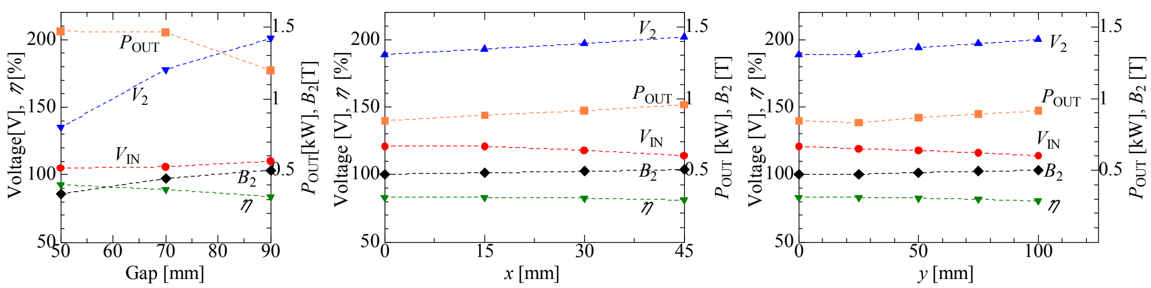


Fig. 15. Experimental results for transformer with split cores #2

of x and y, the power supply power voltage V_{AC} was 100 V, the resistance load R_L was 59.8 Ω (split cores #1) or 81.2 Ω (split cores #2), and the gap length was 70 mm; these parameters were kept constant. An experiment with the transformer with split cores #2 at y =125 mm was not performed since the required power exceeded the power supply capacity. Figs. 14 and 15 respectively show the parameters of the transformers with split cores #1 and #2 when the gap length or position was altered; the parameters are also given in Table III. Fig. 10 shows the primary and secondary waveforms at 1.5 kW.

Fig. 11 shows that the waveforms of the transformers with split cores almost were the same as those of a transformer with rectangular cores. The flux densities of the secondary core B_2 for split cores #1 and #2 were higher than that of the rectangular cores, as shown in Figs. 14 and 15. The flux density B_2 of split cores #1 was lower than the saturation flux density B_S, whereas the flux density B_2 of split cores #2 was close to B_S. This indicates that that split cores #2 may have saturated.

C. Comparison of Performances of Transformers

The secondary voltage V_2 of transformers with split cores was higher than that of the transformer with rectangular cores because the coupling factor k was smaller. The efficiency η decreased since the copper loss at the secondary winding became larger. As Table 3 shows, the reduction in the efficiency η of the transformer with split cores #1 was small, whereas that of the transformer with split cores #2 decreased by 89% due to saturation of the secondary cores.

TABLE III
EXPERIMENTAL RESULTS

Core type	Rectangular	Split #1	Split #2
Frequency [kHz]	20		
Gap length [mm]	70		
x [mm]	0		
y [mm]	0		
k	0.38	0.34	0.28
R_L [Ω]	23.1	26.5	40.3
V_{IN} [V]*	112	111	106
V_2 [V]*	139	147	178
V_{OUT} [V]	186	195	245
P_{OUT} [kW]	1.49	1.54	1.47
η [%]	95.3	94.1	89.2
B_2 [T]	0.14	0.24	0.45
C_S [μF]	0.696	0.751	0.897
C_P [μF]	2.30	2.46	3.04

* rms value

The flux density of the secondary core B_2 was 170% (split cores #1) or 320% (split cores #2) higher than that of the rectangular cores. The reason why B_2 for split cores #2 is much higher than expected must be the high secondary voltage V_2 due to low coupling factor k.

These results demonstrate that split cores have equal performances as rectangular cores even when the gap length or position is changed, provided the cores are not saturated.

VI. Conclusions

A contactless power transfer system suited for PHVs and EVs is proposed. The configuration with capacitors in the primary winding being in series and those in the secondary winding being in parallel has an interesting characteristic: its equivalent circuit is the same as an ideal transformer. Consequently, it has simple efficiency equations. A transformer consisting of rectangular cores with double-sided windings is compact and insensitive to misalignment in the lateral direction. A 1.5 kW transformer was constructed and tested. Its dimensions are 240 mm×250 mm, its gap length is 70±20 mm, its misalignment tolerance in the lateral direction is ±125 mm, the mass of the secondary winding and core is 4.6 kg, and its efficiency is 95% in the normal position.

Using split cores reduces the size, weight, and cost without reducing the performance even when the gap length or the position is changed. In the future, we intend to improve the design of cores and windings to develop a transformer that is more lightweight and has a higher efficiency.

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References

[1] A.W. Green and J.T. Boys: "10 kHz Inductively Coupled Power Transfer – Concept and Control", *IEE Power Electronics and Variable Speed Drives Conference*, *PEVD*, No.399, pp.694-699 (1994)

[2] T. Fujita, Y. Kaneko, S. Abe: "Contactless Power Transfer Systems using Series and Parallel Resonant Capacitors", *IEEJ Trans. IA*, Vol.127, No.2, pp.174-180 (2007) (in Japanese)

[3] Y. Kaneko, S. Matsushita, Y. Oikawa, S. Abe: "Moving Pick-Up Type Contactless Power Transfer systems and their Efficiency Using Series and Parallel Resonant Capacitors", *IEEJ Trans. IA*, Vol.128, No.7, pp.919-925 (2008) (in Japanese)

[4] M. Budhia, G.A. Covic, J.T. Boys: "Design and Optimisation of Magnetic Structures for Lumped Inductive Power Transfer Systems", *IEEE Energy Conversion Congress & EXPO*, pp.2081-2088 (2009)