A New Hc Core Transmitter of a Contactless Power Transfer System that is Compatible with Circular Core Receivers and H-shaped Core Receivers

Ryotaro Shimizu, Yasuyoshi Kaneko, and Shigeru Abe
Department of Electrical and Electronic Systems
Saitama University
Saitama, Japan

***Abstract*—Contactless power transfer systems for electric vehicles contain two types of transformers (a pair consisting of a transmitter and a receiver): a rectangular (H-shaped) core double-sided winding transformer and a circular core single-sided winding transformer. Since the magnetic field structures of these two transformers differ greatly, these two types of transformers have been incompatible in the past, although a number of compatible receivers have recently been proposed. This paper proposes a novel Hc core transmitter that is compatible with both types of receivers. The Hc core transmitter adds a central magnetic pole by dividing the winding coil of the H-shaped core transmitter. This transmitter can change the magnetic field structure by changing the connections of divided windings and can transfer power to both types of receivers. Compatibility tests at 3 kW are carried out, and the test results are presented.**

***Keywords*—electric vehicle; contactless transfer; compatibility; efficiency**

I. INTRODUCTION

The development and commercialization of plug-in hybrid electric vehicles (PHVs) and electric vehicles (EVs) are actively being realized, due to environmental concerns and increasing oil prices. Plug-in hybrid electric vehicles and EVs currently require connection to a power supply by electric cables for battery charging. A contactless power transfer system [1, 2] would have numerous advantages, such as safety, convenience, and wireless, maintenance-free, high-power charging. Therefore, contactless power transfer systems are being investigated worldwide.

Contactless power transfer system for electric vehicles contain two types of transformers: a rectangular (H-shaped) core double-sided winding transformer [1, 3] and a circular core single-sided winding transformer [4, 5]. The advantages of the H-shaped core transformer include compactness, light weight, and good tolerance to misalignment in the lateral direction. On the other hand, the circular core transformer has the advantages of lower leakage levels of the magnetic field and the electric field. Since each type of transformer has a different magnetic field structure, the compatibility between the types of transformers is an important issue. Covic *et al.* proposed new receivers (DDQP [6] and BPP [7]) that are compatible with both types of transmitters.

This paper proposes an Hc core transformer, a new transformer that is compatible with H-shaped core transformers and circular core transformers. The Hc core transformer is considered to be suitable as a transmitter for use in parking areas in the city because car owners want to use the same type of transmitter and receiver (H-shaped or circular) at home and smaller, lighter receivers should be incorporated into cars. On the other hand, there are various types of EVs and PHVs that use H-shaped or circular receivers in parking spaces in the city.

The Hc core transmitter is based on the H-shaped core transmitter. A central magnetic pole is added, and the winding coil is divided into two winding coils. This transmitter can be made compatible with both types of receivers by changing the connection of the divided winding coils.

Section II describes the difference in magnetic field structure between the H-shaped core transformer and the circular core transformer. Section III describes the structures of the Hc core transmitter and the methods of connecting the power supply to the divided winding coils in the case of using the H-shaped core receiver or the circular core receiver. Section IV presents the experimental results for a 3-kW power supply, and Section V presents the conclusions.

II. DIFFERENCE IN MAGNETIC FIELD STRUCTURE BETWEEN THE H-SHAPED CORE AND THE CIRCULAR CORE

A. *Contactless Power Transfer System for EVs*

Fig. 1 shows a schematic diagram of a contactless power transfer system with series and parallel resonant capacitors [8]. 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. 2 shows a detailed equivalent circuit, which 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 reactance at the resonant frequency, the winding resistances (r'_1 and r'_2) and the ferrite-core loss r'_0 can be ignored.

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

$$\frac{1}{\omega_0 C_P} = \omega_0 L_2 = x_P = x'_0 + x_2$$
$$\frac{1}{\omega_0 C'_S} = x'_S = x'_1 + \frac{x'_0 x_2}{x'_0 + x_2} x_2 \tag{1}$$

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

$$V_{IN} = abV_2, \quad I_{IN} = I_D/(ab), \quad b = \frac{x'_0}{x'_0 + x_2} \tag{2}$$

Equation (2) indicates that the equivalent circuit for a transformer with these capacitors is the same as that for an ideal transformer with a turn ratio of ab at the resonant frequency. Without a rectifier circuit, the efficiency can be approximated as follows:

$$\eta = \frac{R_L I_L^2}{R_L I_L^2 + r'_1 I'^2_1 + r_2 I_2^2} = \frac{R_L}{R_L + \frac{r'_1}{b^2} + r_2\left\{1 + \left(\frac{R_L}{x_P}\right)^2\right\}} \tag{3}$$

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

$$R_{L\,max} = x_P \sqrt{\frac{1}{b^2}\frac{r'_1}{r_2} + 1}$$
$$\eta_{max} = \frac{1}{1 + \frac{2r_2}{x_P}\sqrt{\frac{1}{b^2}\frac{r'_1}{r_2} + 1}} \tag{4}$$

B. *Difference in Magnetic Field Structure between the H-shaped Core Transformer and the Circular Core Transformer*

Fig. 3 shows the difference in the magnetic field structures between the rectangular (H-shaped) core transformer and the circular core transformer. The circular core transformer has two magnetic flux loops in its vertical cross section, as shown in Fig. 3(b). The flux coupling between the primary winding and the secondary winding varies according to the misalignment of these windings. If the secondary winding is placed in the center of the positions (A) and (B), then the total flux penetrating the secondary winding becomes zero. This means that the coupling factor k becomes zero.

In the rectangular (H-shaped) core transformer, there is one magnetic flux loop in the vertical cross section. If the position of the secondary winding changes as shown in Fig. 3(a), the total flux penetrating the secondary winding decreases only slightly, and the decrease in the coupling factor k is small. Therefore, the rectangular core transformer has good tolerance to lateral misalignment.

The difference in the magnetic field structure has made the realization of compatibility between the two transformers difficult.

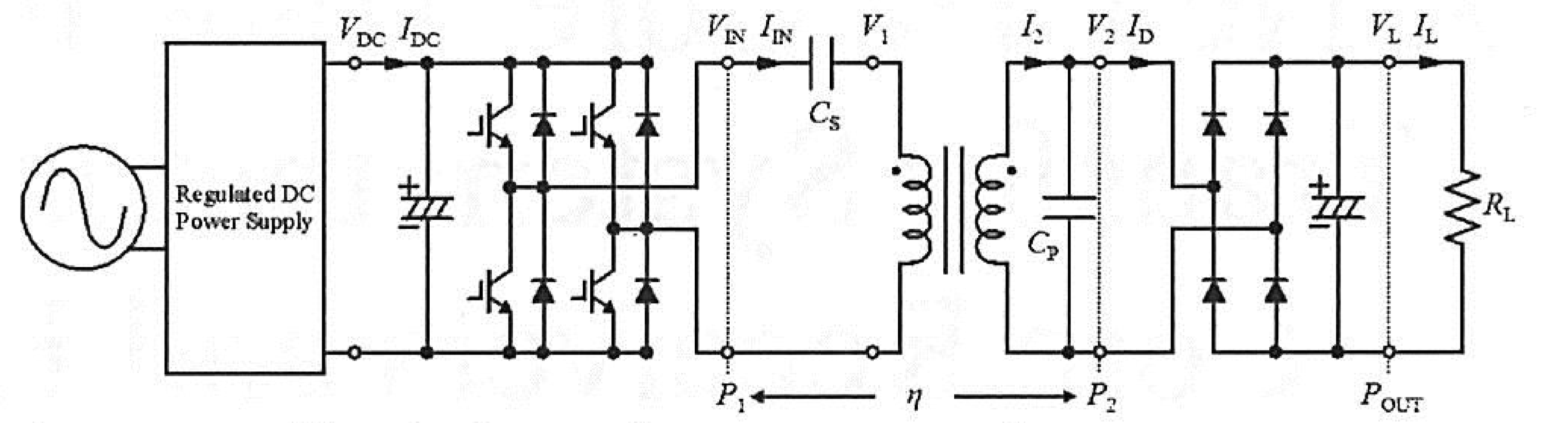


Fig. 1. Contactless power transfer system.

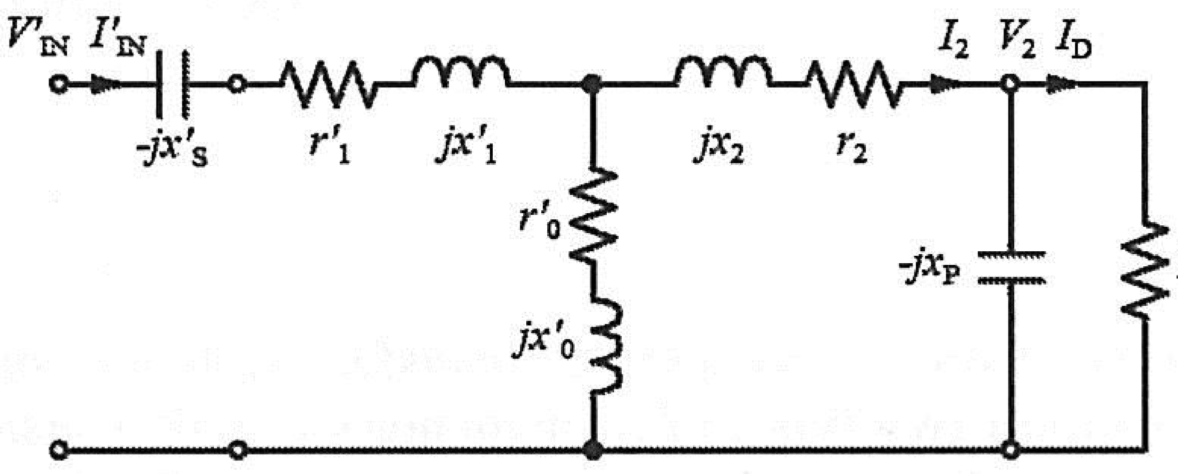
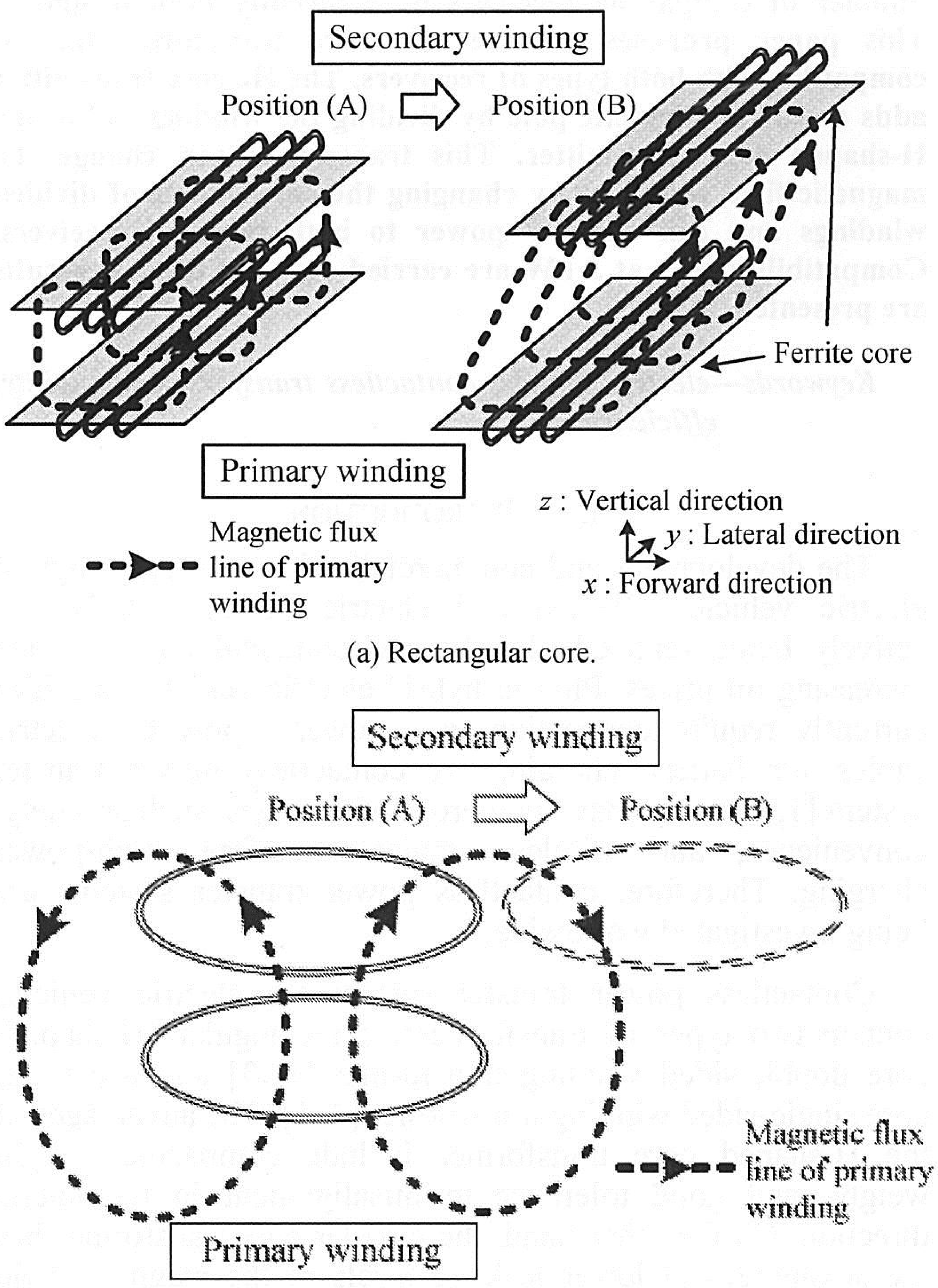


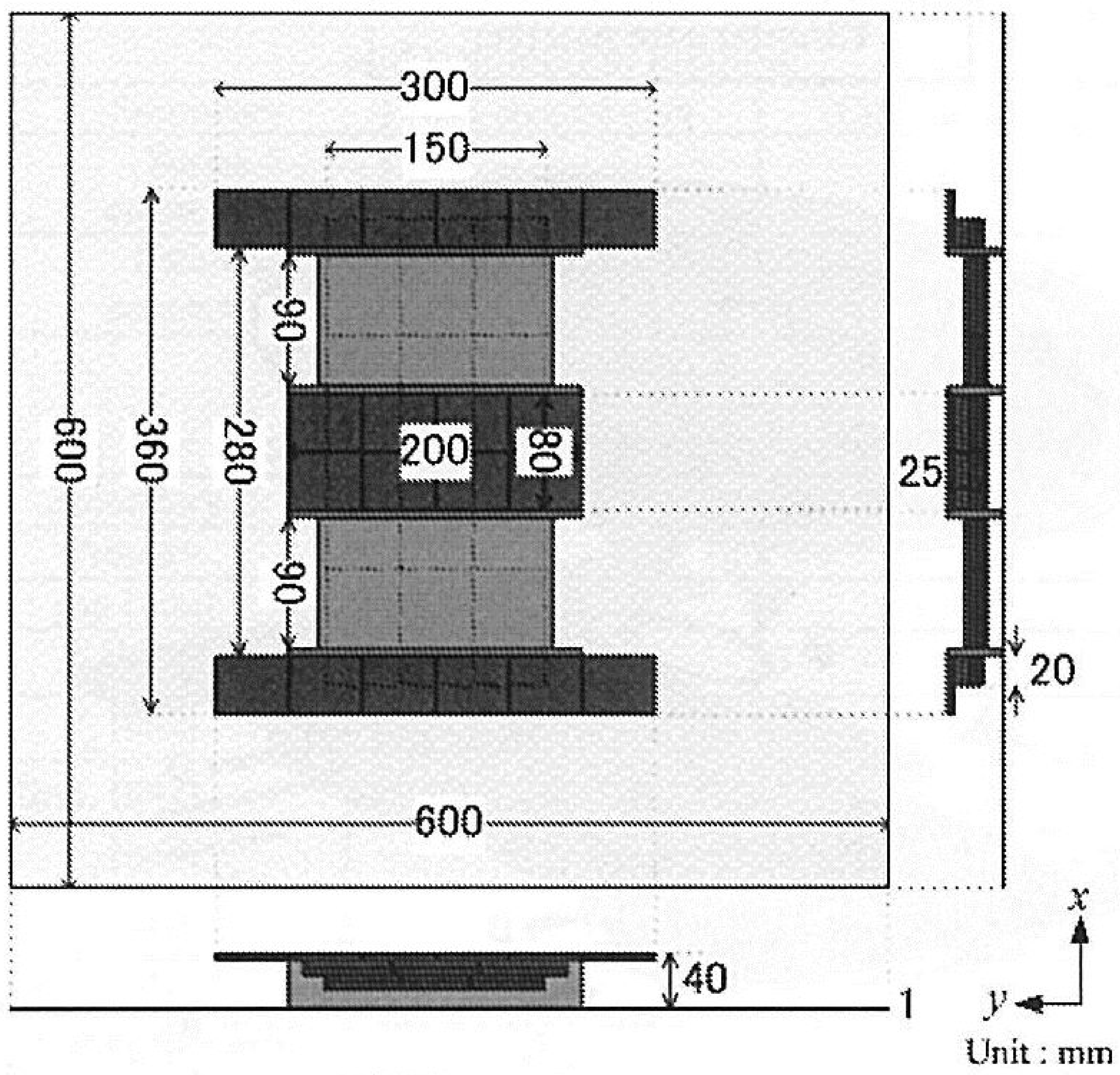
Fig. 2. Detailed equivalent circuit.



(a) Rectangular core.

(b) Circular core.

Fig. 3. Magnetic field.



(a) Dimensions.

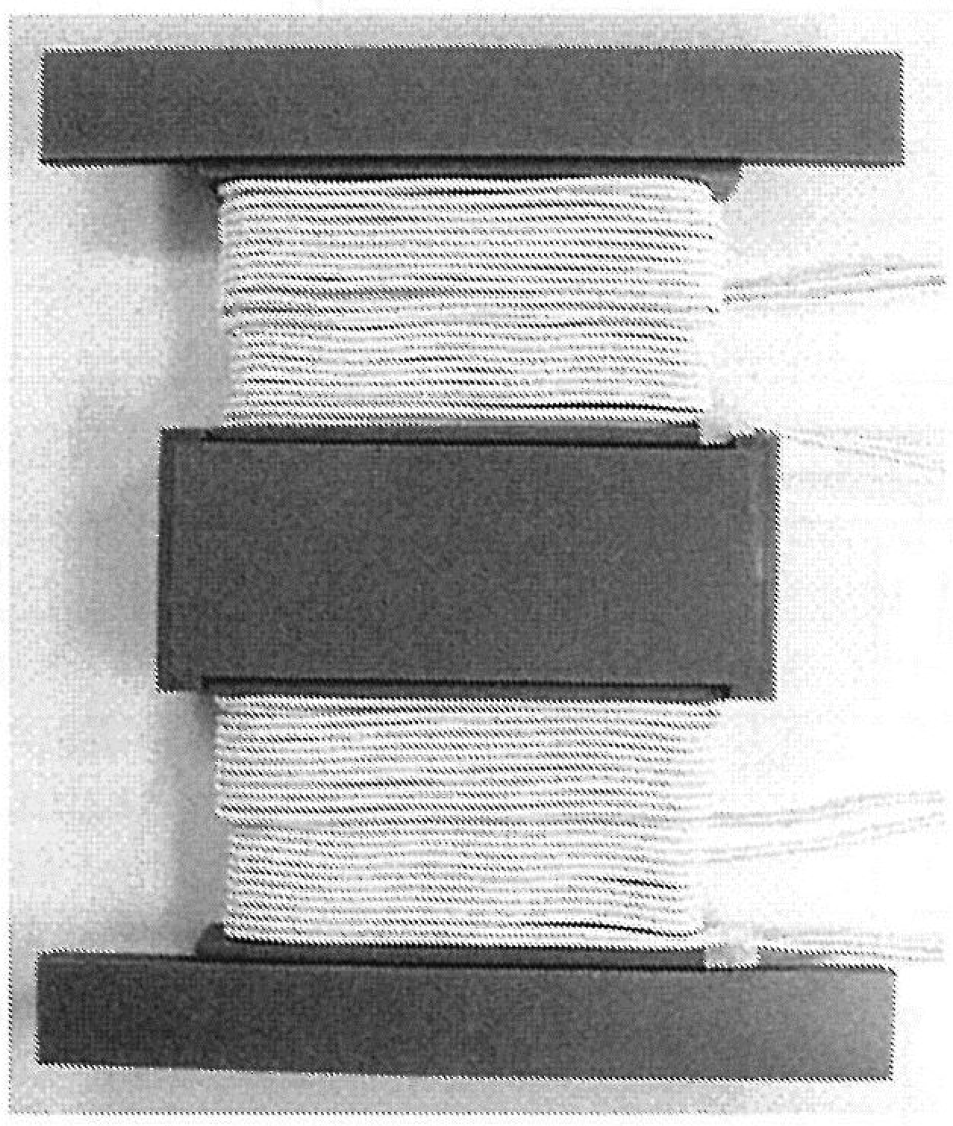

(b) Photograph.

Fig. 4. Dimensions and photograph of Hc core transmitter.

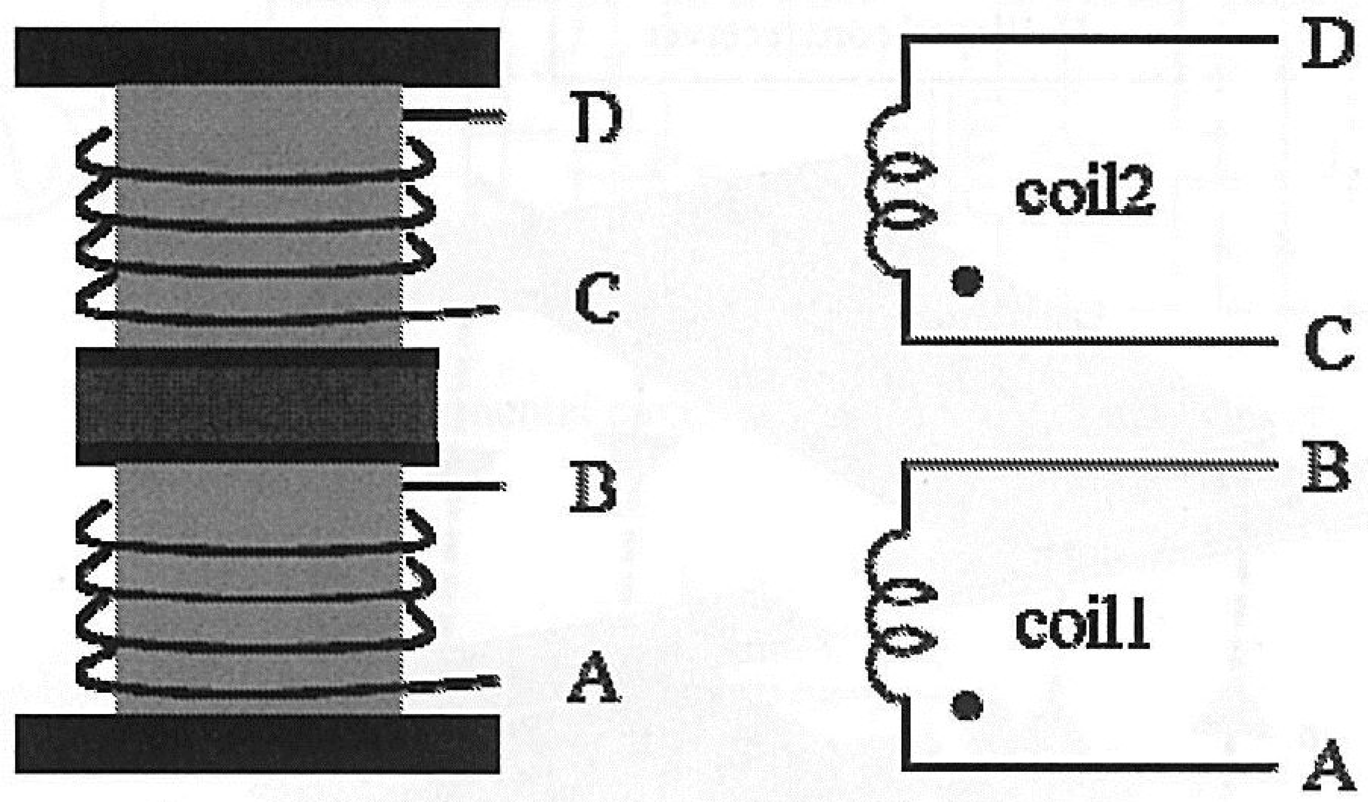


Fig. 5. Hc core transmitter winding.

Table 1. Hc core transmitter specifications.

Coil winding	90 mm × 2
Litz wire	0.1 mm φ × 800
Weight without aluminum sheet	6.92 kg
Size	360 × 300 × 40 mm
Winding	16 T (2 parallel) × 2
Aluminum sheet (weight)	600 × 600 × 1 mm (1.06 kg)

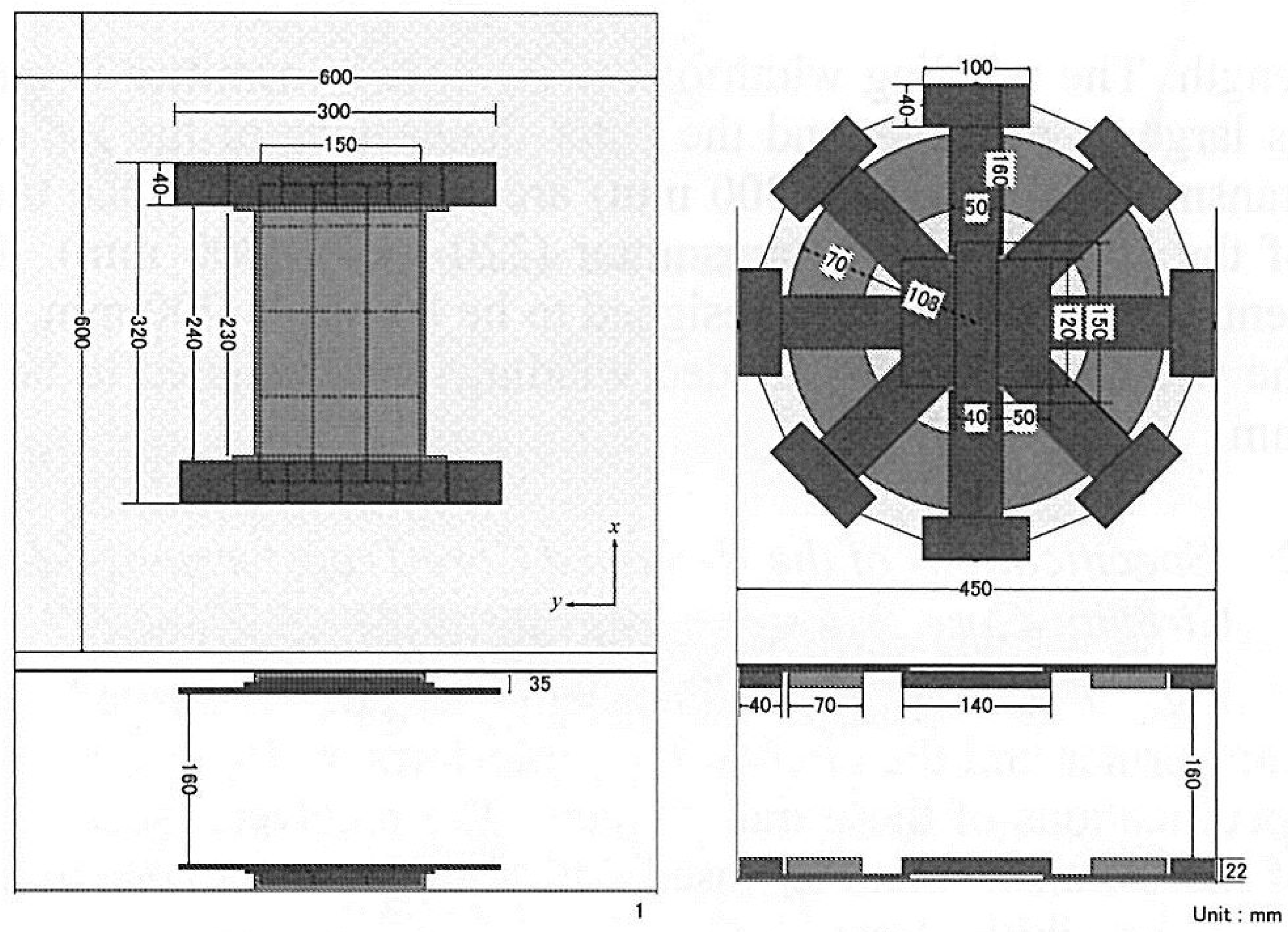

(a) H-shaped core. (b) Circular core.

Fig. 7. Transformer dimensions.

III. New Hc Core Transmitter with a Central Magnetic Pole

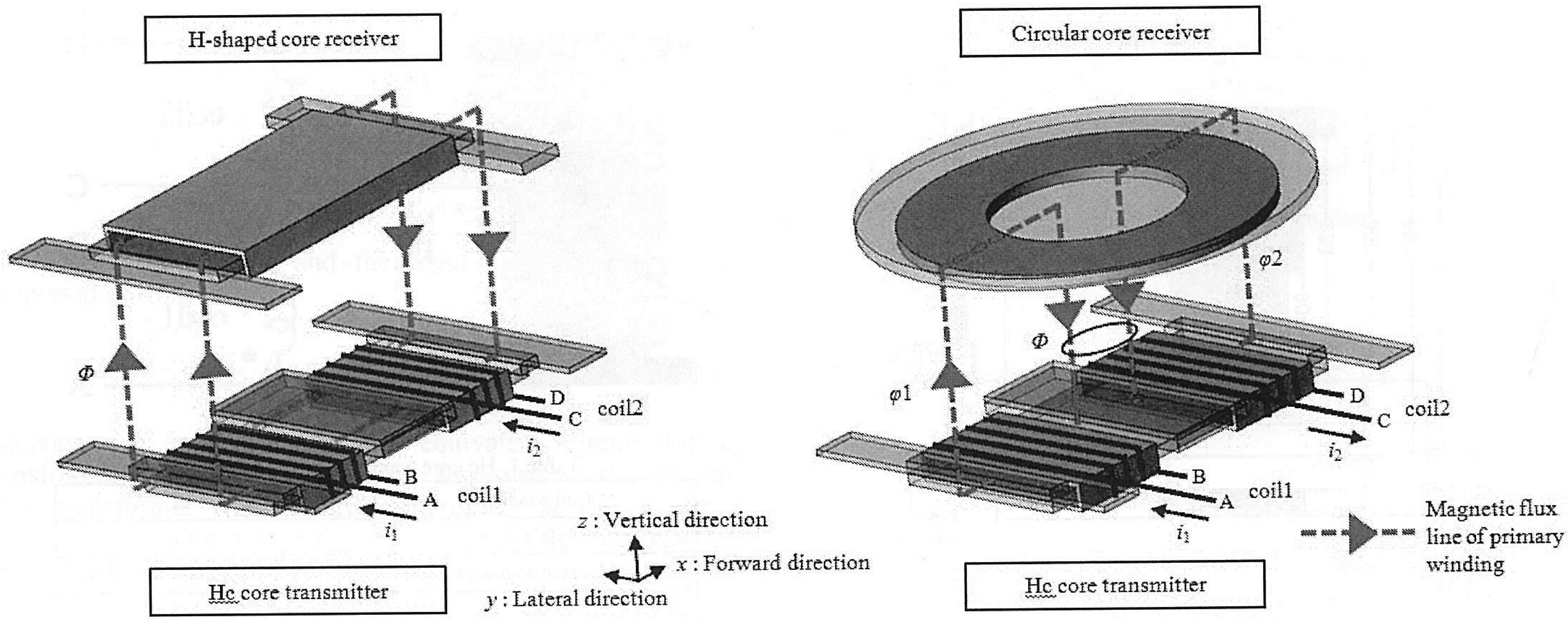
A. Design and Specifications of the Hc Core Transmitter

We herein propose a new Hc core transmitter that is based on the H-shaped core transmitter [3] and is compatible with both H-shaped core receivers and circular core receivers. Fig. 4 shows a photograph and the dimensions of the Hc core transmitter. Fig. 5 shows the winding coils of the transmitter. Table 1 lists the specifications of the Hc core transmitter.

This Hc core transmitter adds a central magnetic pole by dividing a coil of the H-shaped core transmitter (H-shaped core with central magnetic pole). When the power is transferred to the H-shaped core receiver, the central magnetic pole is not used (Fig. 6(a)). This central magnetic pole is used when the power is transferred to the circular core receiver (Fig. 6(b)). The magnetic field structure can be changed depending on whether the central magnetic pole is used. In the case shown in Fig. 6(a), an increase in the leakage flux and a decrease in the coupling factor k due to this central pole occur. However, the adverse effect is very small. Similarly, in the case shown in Fig. 6(b), the circular core is not used fully for the main flux, and a decrease in the coupling factor k occurs.

The central magnetic pole was designed with three goals: (1) better coupling with the circular core transformer, (2) high tolerance to horizontal misalignment, and (3) avoiding saturation of the main flux. Therefore, in order to ensure a sufficient area, the central magnetic pole was designed such that the x direction is longer and the y direction is shorter than the magnetic poles of both ends.

As described above, the circular core transformer produces magnetic flux from the center pole to the outer pole in all directions. On the other hand, the Hc core transformer produces magnetic flux in only one direction (the x-direction). Therefore, the coupling factor k is inevitably reduced when power is transferred to the circular core receiver. The coupling factor depends on the ratio of the winding width to the gap



(a) Hc core transmitter and H-shaped core receiver.

(b) Hc core transmitter and circular core receiver.

Fig. 6. Magnetic field.

length. The winding width of the Hc core transmitter is made as large as possible, and the outer dimensions of the Hc core transmitter (360 mm × 300 mm) are slightly larger than those of the H-shaped core transmitter (320 mm × 300 mm). The central magnetic pole is designed to be 80 mm × 200 mm, and the widths of the two divided windings are designed to be 90 mm.

B. *Specifications of the H-shaped Core Transformer and the Circular Core Transformer*

Fig. 7 shows the dimensions of the H-shaped core transformer and the circular core transformer. Table 2 lists the specifications of these transformers. The receivers (secondary) of these transformers are used with the Hc core transmitter in the compatibility tests.

C. *Change in Magnetic Field Structure in the Hc Core Transmitter*

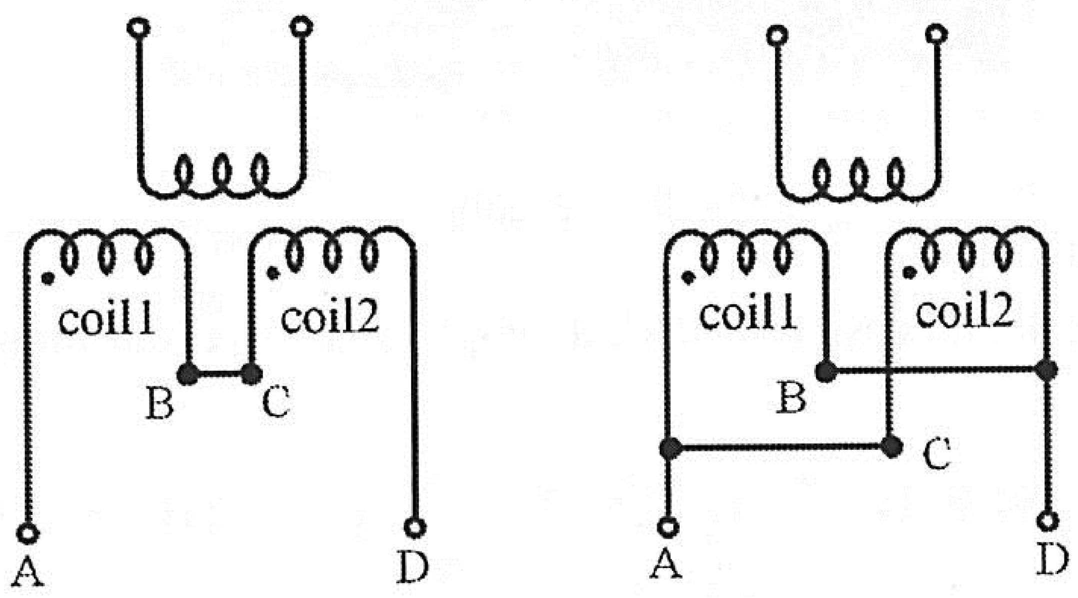
The Hc core transmitter can change the magnetic structure by changing the direction of the current through the divided winding coils (coil 1 and coil 2). When power is transferred from the Hc core transmitter to the H-shaped core receiver, the direction of current i_1 through coil 1 and the direction of current i_2 through coil 2 must be the same (Fig. 6(a)). On the other hand, when power is transferred to the circular core receiver, the directions of currents i_1 and i_2 must be opposite (Fig. 6(b)).

D. *Relationship between the Connection Method of Two Divided Coil Windings and the Number of Winding Turns*

Both the directions of the currents and the connection method (series or parallel) for the two divided windings are important. Fig. 8 shows the series and parallel connection methods for Hc core windings powering an H-shaped core receiver. Fig. 9 shows the connection methods for Hc core windings powering a circular core receiver. By connecting the windings, the two divided windings can be considered to be a single winding. The numbers of turns of the connected windings vary according to the connection method.

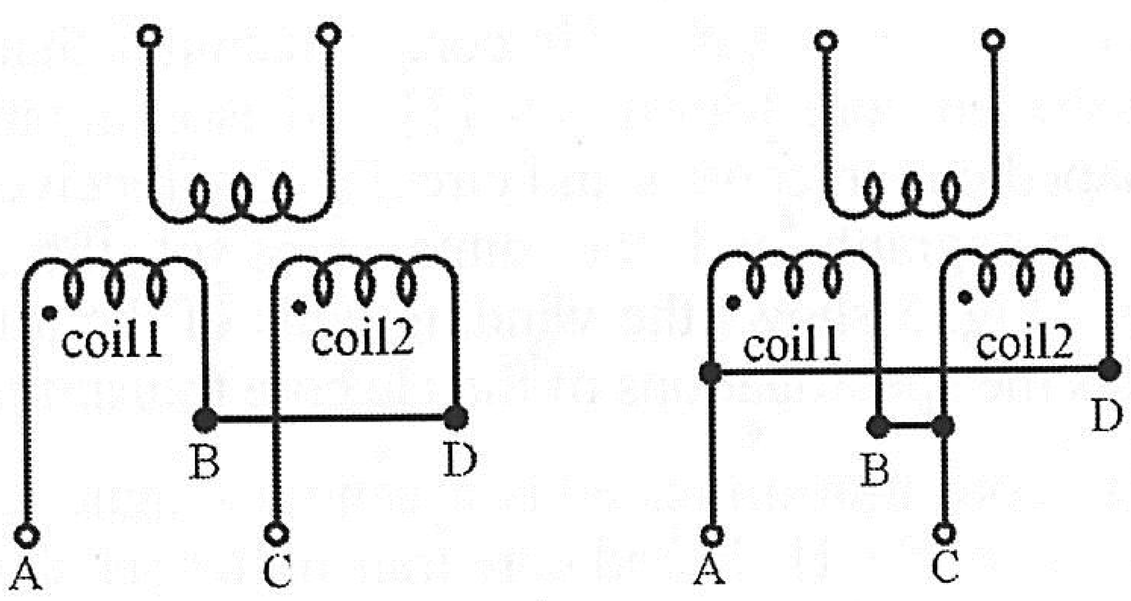
Table 2. Transformer specifications.

Type		H-shaped core	Circular core
Weight [kg]	Primary	6.06	9.82
	Secondary	6.43	10.54
Winding	Primary	16 T (2 parallel)	16 T (2 parallel)
	Secondary	4 T (15 parallel)	4 T (8 parallel)



(a) Series. (b) Parallel.

Fig. 8. Connection methods to an H-shaped core.



(a) Series. (b) Parallel.

Fig. 9. Connection methods to a circular core.

Table 3. Relationship between winding number and connection method.

Secondary	H-shaped core	Circular core
Series connection	$2N$	N
Parallel connection	N	$N/2$

Table 4. Transformer parameters.

Secondary	H-shaped core	Circular core
Primary	Hc core	
gap [mm]	150	100
f_0 [kHz]	50	
r_0 [mΩ]	0	14.6
r_1 [mΩ]	85.9	183
r_2 [mΩ]	5.99	12.3
l_0 [uH]	17.5	33.5
l_1 [uH]	73.6	125.
l_2 [uH]	4.67	9.54
C_S [uF]	0.115	0.064
C_P [uF]	1.758	0.871
k	0.191	0.195
b	0.189	0.180
R_{Lmax} [Ω]	9.22	20.0
η_{max} [%]	96.7	96.5
Q_1	333	275
Q_2	302	304

The number of turns can be examined based on the number of magnetic flux linkages between the current I and the main flux. In Fig. 6, coils 1 and 2 have N turns. The magnetic flux passing through coils 1 and 2 are $\varphi 1$ and $\varphi 2$, respectively, and there is no misalignment between transmitter and receiver. If the output current of the inverter is I, then the current through coils 1 and 2 becomes I in the series connection and $I/2$ in the parallel connection.

When power is transferred to the H-shaped core receiver, the number of magnetic flux linkages is $\lambda = 2N\Phi$ in Fig. 8(a) and $\lambda = N\Phi$ in Fig. 8(b). In the case of the series connection, the number of turns is $2N$. On the other hand, in the case of the parallel connection, the number of turns is N, and the number of parallel windings is doubled compared to the series connection.

When power is transferred to the circular core receiver, the number of magnetic flux linkages is $\lambda = N\Phi$ in Fig. 8(a) and $\lambda = N/2\Phi$ in Fig. 8(b). In the case of the series connection, the number of turns is N, and in the case of the parallel connection, the number of turns is $N/2$ and the number of parallel windings is doubled compared to the series connection.

Table 3 summarizes the number of turns of the Hc core transmitter. Depending on the type of receiver, coils 1 and 2 are connected either in parallel or in series in order to change the directions of currents i_1 and i_2 and equalize the turn ratio. The output voltage and current of the inverter then remain at the same level, even if the receiver type is changed.

In the present study, when power is transferred to the H-shaped core receiver, the connection method is the parallel connection, and when power is transferred to the circular core receiver, the connection method is the series connection.

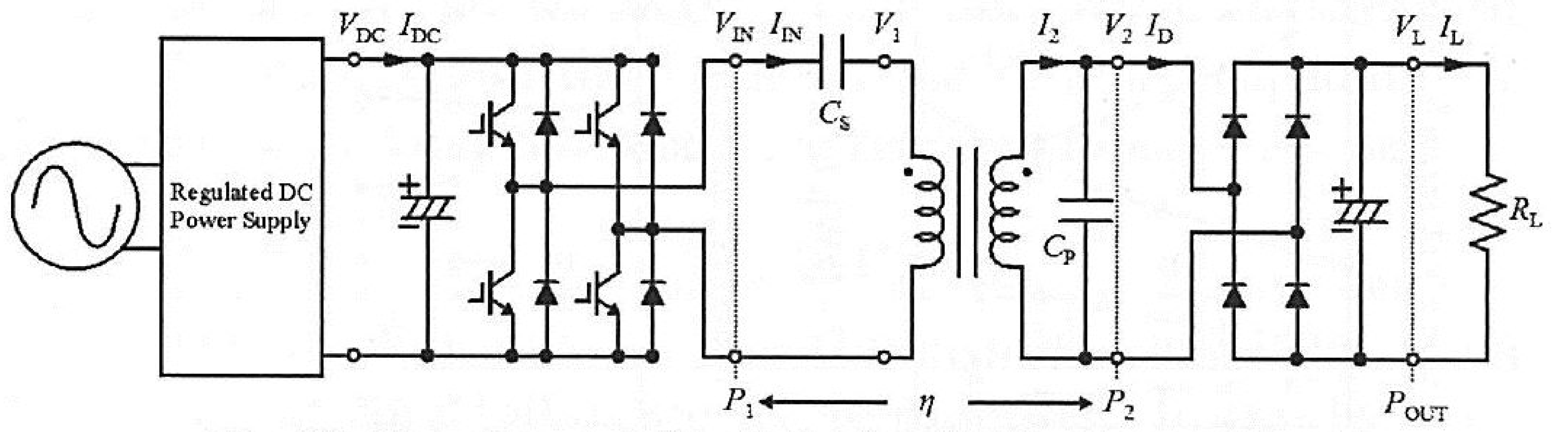
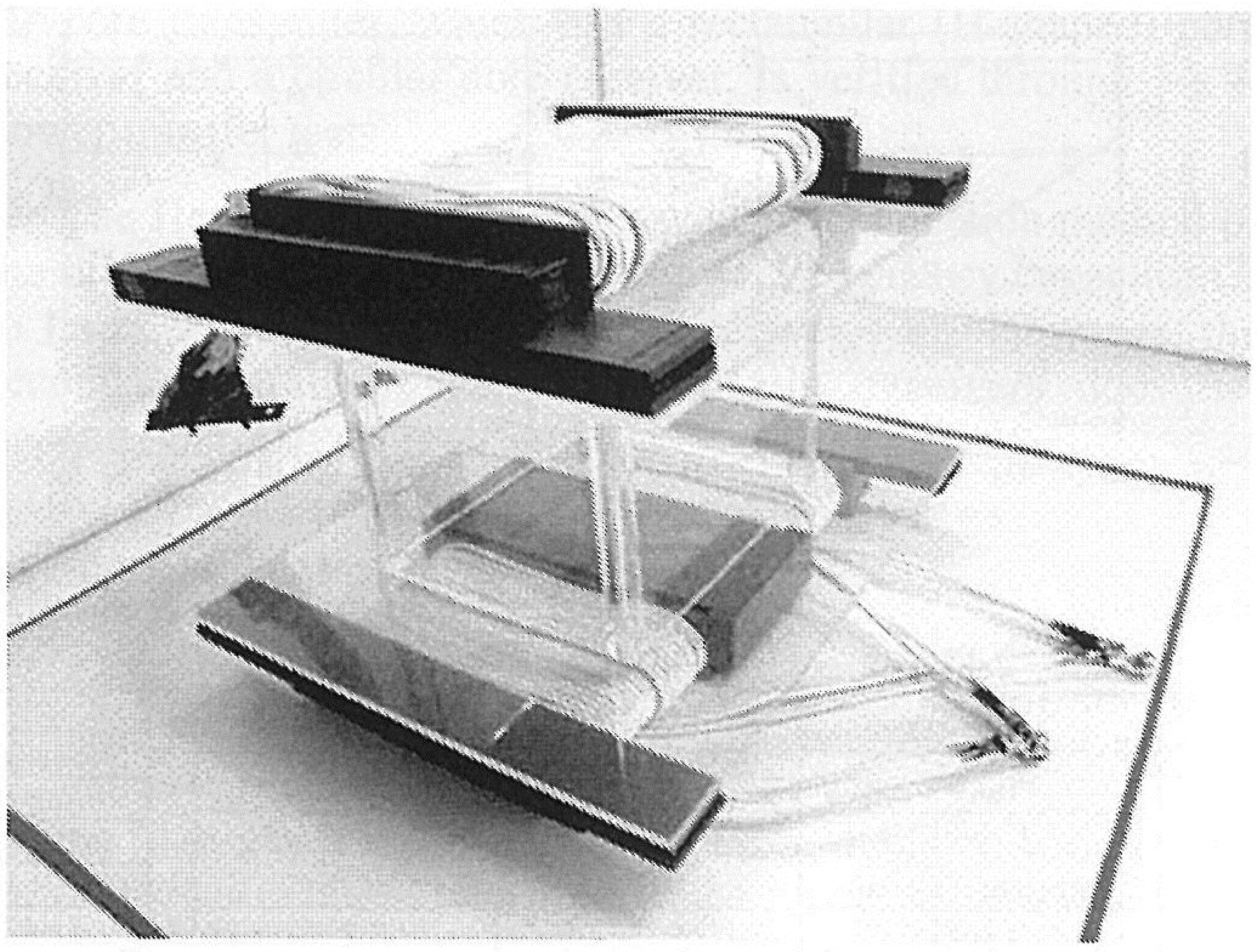


Fig. 10. Experimental circuit for the circular core receiver.


(a) Hc core transmitter and H-shaped core receiver.

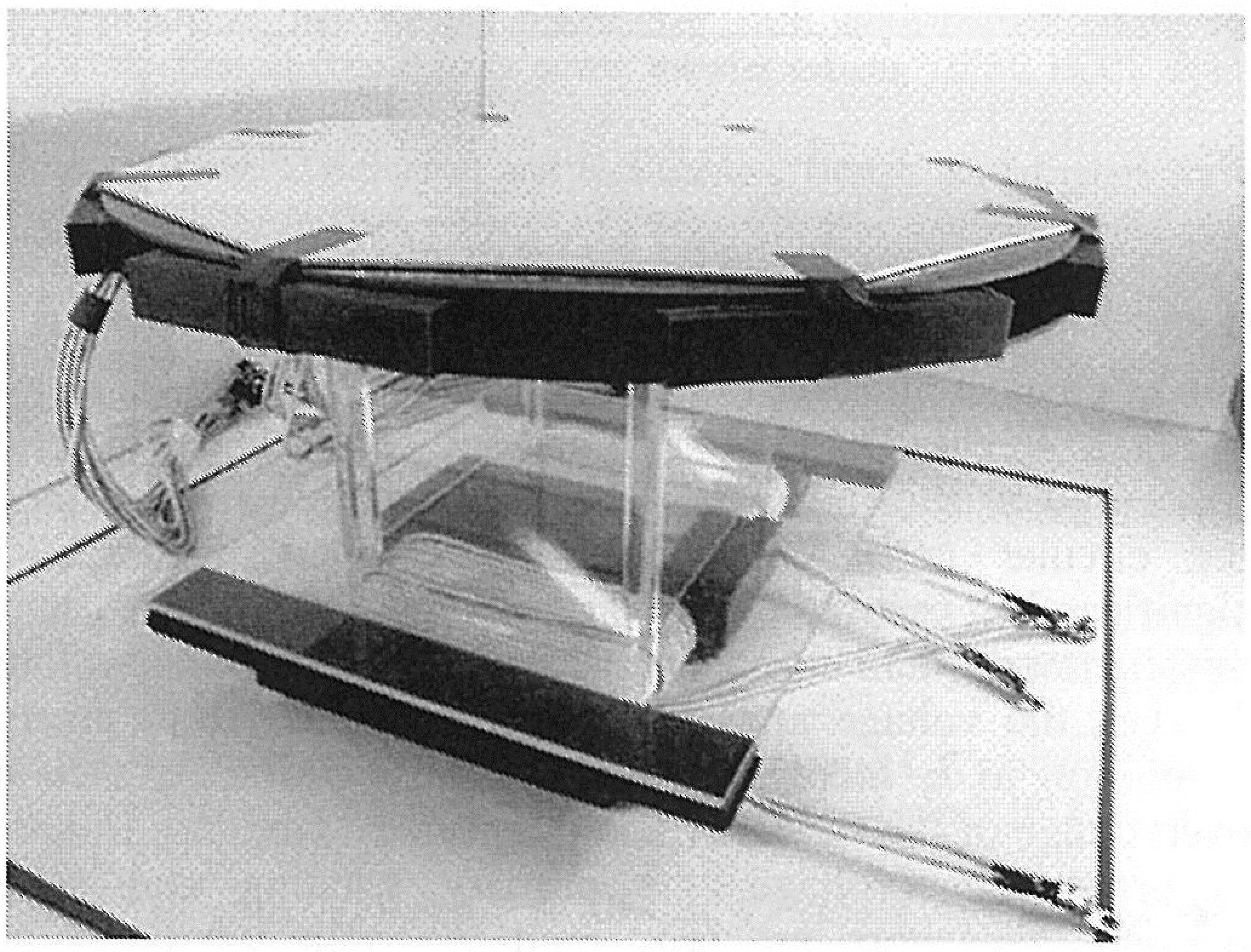

(b) Hc core transmitter and circular core receiver.

Fig. 11. Photographs of transformer.

IV. COMPATIBILITY TESTS AT 3 KW RESULTS

A. Summary of Compatibility Tests at 3 kW

Two compatibility tests at 3 kW were performed. Case A is a power transfer test from the Hc core transmitter to an H-shaped core receiver (Fig. 6(a)), and case B is a power transfer test from the Hc core transmitter to a circular core receiver (Fig. 6(b)). The operating frequency f_0 is 50 kHz and is constant during the experiments. A full bridge rectifier circuit and a load resistance R_L are connected to the receiver. In case A, the

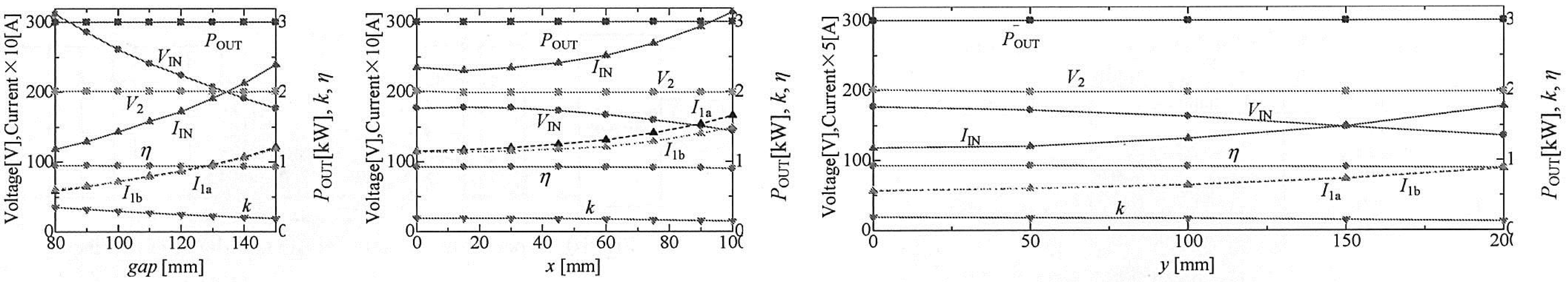


Fig. 12. Experimental results (primary: Hc core; secondary: H-shaped core).

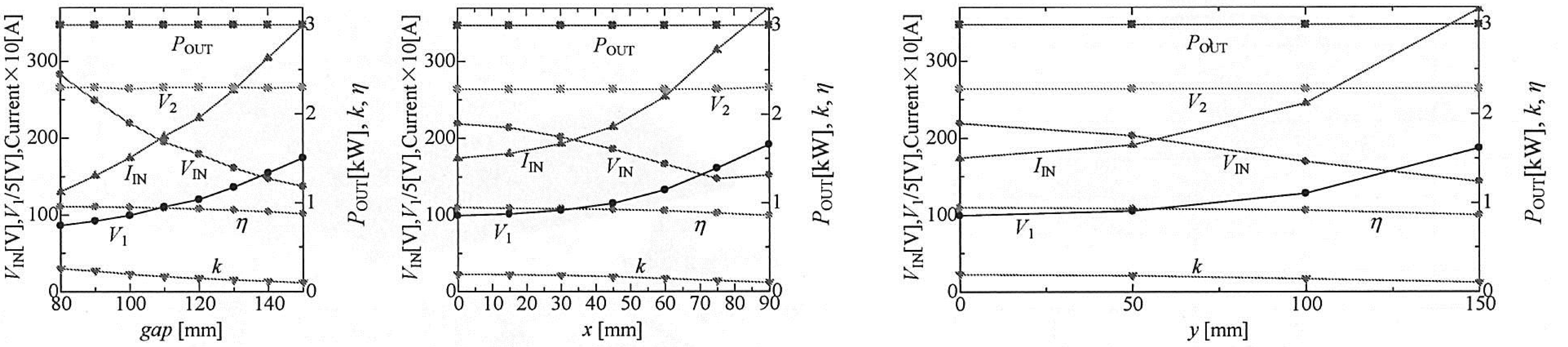


Fig. 13. Experimental results (primary: Hc core; secondary: Circular core).

Table 5. Values of resonant capacitors and a resistance load.

Secondary	H-shaped core	Circular core
Primary	Hc core	
C_S[uF] (corresponding gap)	0.116 (100mm)	0.0664, 0.0659 (100mm)
C_P[uF] (corresponding gap)	1.734 (150mm)	0.847 (100m)
R_L[Ω] (corresponding gap)	20 (150mm)	40 (100m)

Table 6. Parameters of experiments.

	Case A				Case B					
Secondary	H-shaped core				Circular core					
Primary	Hc core									
f_0[kHz]	50									
gap[mm]	150				100					130
x[mm]	0	100	0	0	0	60	90	0	0	0
y[mm]	0	0	150	200	0	0	0	100	150	0
V_{IN}[V]	177	149	148	135	219	166	152	169	143	161
I_{IN}[A]	23.5	31.4	29.7	35.3	17.4	25.4	37.0	24.5	36.7	26.2
V_1[V]	686	908	864	1010	496	663	958	640	934	679
V_2[V]	201	199	198	198	264	264	264	264	264	266
I_{1a}[A]	12.1	14.9	14.8	17.6	-					
I_{1b}[A]	11.9	16.6	14.9	17.7						
P_{OUT}[kW]	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
η[%]	92.7	90.2	90.6	88.8	95.0	91.6	85.7	92.0	86.2	91.7
k	0.191	0.147	0.149	0.126	0.195	0.146	0.101	0.147	0.103	0.131

circuit connecting coils 1 and 2 in parallel was used, as shown in Fig. 1. In case B, a circuit connecting coils 1 and 2 in series [9] is used, as shown in Fig. 10. In the case of power transfer to the circular core transformer, the coupling factor k is significantly reduced for large gap lengths or large misalignments, and consequently the primary terminal voltage V_1 (i.e., the voltage after C_S in Fig. 1) increases in inverse proportion to k. Increasing V_1 may cause problems such as overvoltage of the capacitor and the primary winding. In order to prevent overvoltage, the primary winding and series resonant capacitors are split, and the split windings and capacitors are alternately connected in series (circuit shown in Fig. 10).

When using contactless power transfer systems for EVs, misalignment as a result of the driver's lack of skill and gap changes due to the vehicle weight cannot be avoided. The transformer characteristics were measured for gap lengths in the range of 80 to 150 mm, a misalignment in the forward direction x of ±100 mm, and a misalignment in the lateral direction y of ±200 mm. Misalignment in the x direction can be minimized by using a wheel stop, but a large misalignment tolerance in the y direction is required in order to allow for easy parking. The coupling factor k in case B is lower than that in case A. Therefore, the mechanical gap length of 150 mm in case A without misalignment and 100 mm in case B without misalignment are taken to be the normal position. Fig. 11 shows photographs of the Hc core transmitter, the H-shaped core receiver, and the circular core receiver. Table 4 lists the transformer parameters for the normal position. Table 5 lists the values of the capacitances of C_S and C_P and the load resistance R_L. These values remained constant during the experiments. The primary series capacitor C_S was set to the optimum value for a gap length of 100 mm in order to prevent the inverter load from becoming capacitive for small gap lengths.

As the number of at-home charge operations is greater than the number of charge operations in city parking areas, the secondary parallel capacitor C_P should be optimized for home charging. This means that C_P is set to the optimal value for transferring power between the same type of transmitter and receiver. Fortunately, the value of C_P is not affected by the specifications of the transmitters because C_P is determined by the input frequency f_0 and the self-inductance of the secondary winding L_2, as shown in Equation (1). Thus, the value of C_P can be constant, regardless of the specifications of the transmitters. In the compatibility tests, the value of C_P is set to the optimum value in order to achieve the maximum efficiency when power is transferred between the same type of transmitter and receiver.

B. Tests Results for the H-shaped Core Receiver

Fig. 12 and Table 6 show the test results for case A when the gap length and the forward/lateral position (misalignment) are changed. The transformer efficiency η for a gap of 80 to 150 mm exceeds 90%. In the misalignment test, the transformer efficiency η at $x \leq 100$ mm or $y \leq 150$mm exceeds 90%.

The coupling factor k is 0.191 for a gap of 150 mm without misalignment, and that for the case of the H-shaped core transformer (transmitter and receiver) under the same conditions is 0.197. The similar values of k indicate that the increase in the leakage flux due to the central magnetic pole is very small. Since the connection method is the parallel connection in case A, a current unbalance between the two windings may occur with the misalignment of the forward direction x. From Table 6, the current I_{1a} through coil 1 is 14.9 A, and the current I_{1b} through coil 1 is 19.6 A, so the current unbalance is ±11.4%. This indicates that there is no practical problem in designing the magnetic flux density of the core or the current density of the windings.

C. Tests Results for the Circular Core Receiver

Fig. 13 and Table 6 show the test results for case B for various gap lengths and positions. The transformer characteristics were measured for a misalignment in the forward direction x of ±90 mm and a misalignment in the lateral direction y of ±100 mm because the primary terminal voltage V_1 increases in the case of large misalignments. The transformer efficiency η at the normal position (gap: 100 mm) is 95.5%. In the misalignment experiment, the transformer efficiency η at $x \leq 60$ mm or $y \leq 100$ mm exceeds 90%. The transformer efficiency η decreases suddenly for a misalignment of x > 90 mm or y > 150 mm.

D. Results of the 3-kW Compatibility Tests

The test results verified that the Hc core transmitter can transfer power to the H-shaped core receiver and the circular core receiver, demonstrating the compatibility of Hc core transmitter. However, the coupling factor k for case B is smaller than that for case A, and the normal gap for case B must be smaller. Thus, a method by which to increase k is needed.

These tests confirmed that the value of C_P is not affected by the specifications of the transmitter, and the power can be transferred from the Hc core transmitter to the H-shaped core receiver and the circular core receiver.

However, in the Hc core transmitter, the connection of divided windings and the value of the primary capacitor C_S must be changed depending on the receiver type.

V. CONCLUSION

An Hc core transmitter, a novel transmitter that is based on the H-shaped core transmitter, was proposed. In the Hc core transmitter, the central magnetic pole is added, and the winding coil is divided into two winding coils. The compatibility of the Hc core transmitter, which has a rectangular (H-shaped) core receiver and a circular core receiver, is verified through 3-kW power transfer tests.

The Hc core transformer requires the connection method of the divided windings and the value of the primary capacitor C_S to be changed depending on the receiver type. However, the secondary parallel capacitor C_P of the receivers does not depend on the transmitter type.

REFERENCES

[1] M. Budhia, G. A. Covic, and J. T. Boys, "A new magnetic coupler for inductive power transfer electric vehicle charging systems," in proceedings of IEEE IECON 2010, pp. 2481–2486, 2010.

[2] M. Budhia, G. A. Covic, J. T. Boys and C. Y. Huang, "Development and evaluation of a single sided magnetic flux coupler for contactless electric vehicle charging," in proceedings of IEEE ECCE 2011, pp. 614-621, 2011.

[3] M. Chigira, Y. Nagatsuka, Y. Kaneko, S. Abe, T. Yasuda and A. Suzuki, "Small-size light-weight transformer with new core structure for contactless electric vehicle power transfer system," IEEE ECCE 2011, pp. 260–266 (2011).

[4] C.-S.Wang, O.H.Stielau, and G.A.Covic, "Design consideration for a contactless electric vehicle battery charger," IEEE Trans. Ind. Electronics, Vol.52, No.5, pp.1308-1314 (2005).

[5] R.Kluth and J.Ziegner, "Inductive charging – simplifying the charge to enable mass adoption," EVS26 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Los Angeles (2012).

[6] M.Budhia, G.A.Covic, J.T.Boys and C.Y.Huang, "Development and evaluation of single sided flux couplers for contactless electric vehicle charging," IEEE ECCE 2011, pp. 614-621 (2011).

[7] A. Zaheer, D. Kacprzak and G. A. Covic, "A Bipolar Receiver Pad in a lumped IPT System for Electric Vehicle Charging Applications", IEEE ECCE 2012, pp. 283-290 (2012).

[8] Y. Nagatsuka, N. Ehara, Y. Kaneko, S. Abe and T. Yasuda, "Compact contactless power transfer system for electric vehicles," IPEC Sapporo, pp. 807-813 (2012)

[9] T. Yamanaka, Y. Kaneko, S. Abe and T. Yasuda, "10kW Contactless Power Transfer System for Rapid Charger of Electric Vehicle," EVS26 Los Angeles, California (2012).