Small-Size Light-Weight Transformer with New Core Structure for Contactless Electric Vehicle Power Transfer System

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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 be compact and lightweight. A new 1.5 kW transformer has been developed to satisfy these criteria using novel H-shaped cores, which is more efficient, more robust to misalignment, and lighter than previously employed rectangular cores, and its characteristics are described. An efficiency of 95% was achieved across a 70 mm air gap. The results of test at wide air gap of 100mm, temperature rise test and 3kW operation test are also presented.**

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 rise in oil prices. PHVs and EVs currently require connection to a power supply by electric cables for battery charging. A contactless power transfer system (cf. Fig. 1) would have many advantages, including the convenience of being cordless and safety during high-power charging. A contactless power transfer system for electric vehicles must have high efficiency, a large air gap, good tolerance to misalignment in the lateral direction and be compact and lightweight.

Transformers with circular cores and single-sided windings have commonly been used [1, 2]; however, we have revealed that a transformer with rectangular cores and double-sided winding has advantages of good tolerance to misalignment in the lateral direction, compactness and lightweight property [3, 4]. Boys and his group, pioneering researchers and developers of the inductive power transfer systems, have presented that the weak point of a transformer with circular cores for electric vehicles is small air gap and tolerance to misalignment [2]. They have also developed a transformer with double-sided winding of Flux pipe type to solve this weak point[5, 6]. It is expected that a transformer with double-sided winding for electric vehicles will be a main stream in the near future.

We have developed a new 1.5kW transformer using a novel H-shaped core, which is more efficient, more robust to misalignment, and lighter than previously employed rectangular cores, and thus, satisfies above mentioned criteria. The specification and characteristics of this new transformer are described here. This transformer at normal air gap 70mm has high average efficiency of 94% within misalignment of ±150mm in the lateral direction. This transformer is also small size, 240×300×40mm, and light weight of 3.9kg in-vehicle side. The results of test at wide air gap of 100mm, temperature rise test and 3kW operation test are also presented.

II. Contactless Power Transfer System for EVs

A. Contactless Power Transfer System

Fig. 2 shows a schematic diagram of the contactless power transfer system with series and parallel resonant capacitors [7]. A full-bridge inverter is used as a high-frequency power supply. A double-voltage rectifier is used as a rectifier circuit on the second side to raise efficiency.

B. Equivalent Circuit

Fig. 3 shows a detailed equivalent circuit of the system, with resonant capacitors C_S and C_P, rectifier, and a resistance load R_L. Primary values are converted into secondary equivalent values by the turn ratio, $a = N_1/N_2$. Here, primes are used to indicate converted values. The winding resistances and the ferrite-core loss are considerably lower

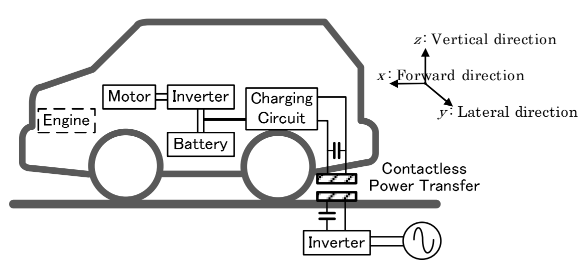


Figure 1. Contactless power transfer system for an EV.

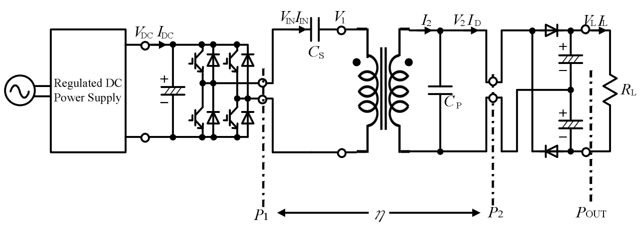


Figure 2. Contactless power transfer system.

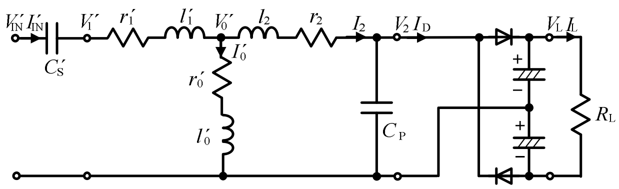
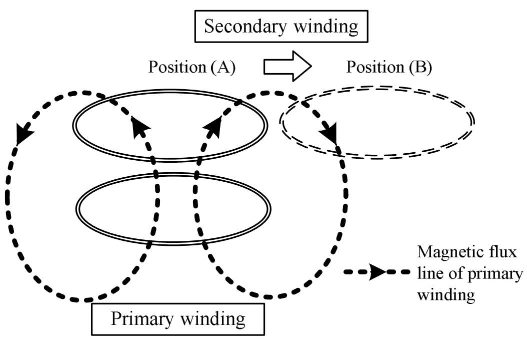
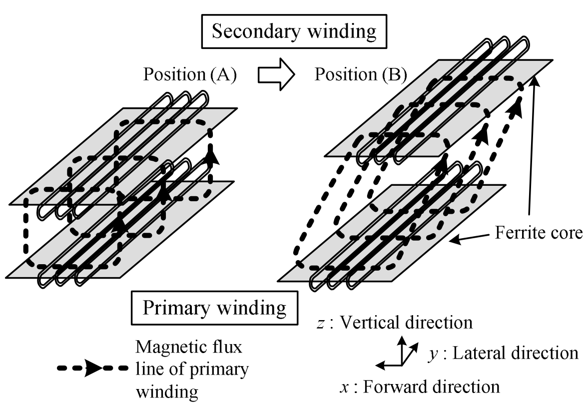


Figure 3. Detailed equivalent circuit.



(a)



(b)

Figure 4. Single and double-sided winding transformers. (a) Single-sided winding transformer. (b) Double-sided winding transformer.

than the leakage and mutual reactance at the resonant frequency. Therefore, the winding resistances (r'_1 and r_2) and the ferrite-core loss r'_0 are omitted in the circuit for analysis. The rectifier is also omitted, and a secondary circuit for analysis consists of C_P and load resistance R_L.

C. 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 ($=\omega_0 l'_0$) and a leakage reactance x_2 ($=\omega_0 l_2$), the secondary parallel capacitor 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 determined as:

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

This implied the power factor of the inverter output is 1, and the efficiency of inverter becomes high with soft switching.

D. Characteristics of an Ideal Transformer

The input voltage V'_{IN} and the input current I'_{IN} can be expressed as follows [8]:

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

This equation represents the equivalent circuit of a transformer with these capacitors, which is the same as an ideal transformer with a turn ratio of b at the resonant frequency.

E. Efficiency

Without rectifier circuit, the efficiency is approximated by [6]:

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

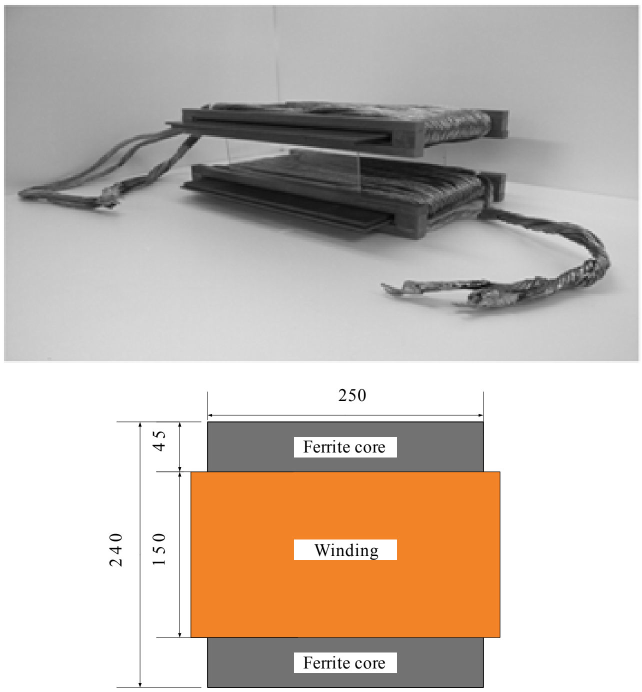
The maximum efficiency η_{max} is obtained when $R_L = R_{Lmax}$.

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

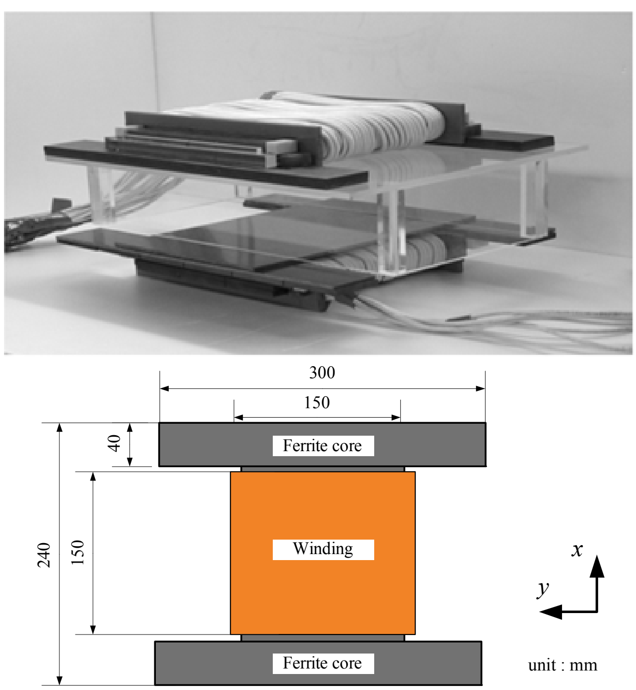
If these characteristics are used, it is possible to design a transformer that has a maximum efficiency when the output power is equal to the rated power.

F. Single and Double-sided Winding Transformers

The structure of contactless power transformers can be classified into two groups: one is circular cores with single-sided winding [1, 2] and the other is rectangular cores with double-sided winding [3, 4, 5, 6]. The 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. The leakage flux is shielded by the aluminum sheet and the coupling factor can be large [4]. The core width of the single-sided winding must be doubled (winding width + pole width), whereas the core width of the double-sided



(a)



(b)

Figure 5. Transformer's photographs and their dimensions. (a) with rectangular cores. (b) with H-shaped cores.

winding needs only half of it. 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 *k* of a single-sided winding transformer becomes zero when the horizontal misalignment is approximately about 40% of the core diameter [2]. As shown in Fig. 4(a) of the single-sided winding transformer, the magnetic flux of the primary winding penetrates upward in the secondary winding at position (A) of secondary winding. However, the magnetic flux penetrates downward in the secondary winding at position (B). Therefore, there is the position of secondary winding in which the total flux penetrating secondary winding and the coupling factor *k* become zero, between positions (A) and (B).

In the case of the double-sided winding transformer (Fig. 4(b)), if the position of secondary winding is moved laterally from (A) to (B), the total flux penetrating secondary winding only decrease a little, and the decrease of coupling factor *k* is small. Therefore, the double-sided winding transformer has good tolerance to lateral misalignment.

III. COMPARISON OF CHARACTERISTICS OF TRANSFORMERS

A. Transformers with Rectangular Cores and H-shaped Cores

A transformer with rectangular cores and double-sided winding has many advantages such as good tolerance to misalignment and compact and lightweight. We developed some transformers with rectangular cores. Fig. 5 (a) shows a 1.5kW transformer for EVs and its characteristics are presented in [4]. The gap length and misalignment characteristic of this transformer depends on size of the magnetic poles and winding width between magnetic poles. Even if the gap length and the winding width are kept the same values, the coupling factor *k* does not change. To reduce the resistance and the weight of windings, we designed a transformer with H-shaped cores shown in Fig. 5 (b).

The following effects can be expected from a transformer with H-shaped cores.

- Weight reduction by decreasing the length of windings and volume of ferrite cores.
- Copper loss reduction by decreasing the length of windings.
- Tolerance enhancement to misalignment in the lateral direction by increasing the length of magnetic poles in lateral direction.

The power supply frequency is increased at the same time to improve the transformer efficiency.

Table I lists the design goal of a transformer with H-shaped cores. The misalignment of the forward direction is easily limited by the use of wheel stopper, which help drivers to position the forward direction of the PHV/EV for charging.

TABLE I. DESIGN GOAL

Rated power		1.5kW
Weight		4.0kg
Gap length		70±30mm
Tolerance to Misalignment	*x*	±45mm
	y	±150mm

TABLE II. SPECIFICATION

Type		Rectangular	H-shaped core
Core		FDK 6H20	FDK 6H20 TDK PC40
Litz wire		0.25mmφ×24×16	0.1mmφ×800
Weight of the secondary		4.6kg	3.9kg
Size		240×250×40mm	240×300×40mm
Winding	Primary	1p×18T	3p×20T
	Secondary	2p×9T	9p×6T
Aluminum sheet		400×600×1mm	

TABLE III. PARAMETERS OF NORMAL POSITION

(gap=70mm)

Type	Rectangular	H-shaped core
f_0 [kHz]	20	30
r_0 [mΩ]	0.45	0
r_1 [mΩ]	82.5	106
r_2 [mΩ]	20.9	9.30
l_0 [μH]	40.2	55.4
l_1 [μH]	64.3	115
l_2 [μH]	17.2	9.70
L_1 [μH]	104	170
L_2 [μH]	27.3	14.7
k	0.38	0.33
b	0.37	0.34
R_{Lmax} [Ω]	9.85	8.69
η_{max} [%]	96.6	97.9

TABLE IV. EXPERIMENTAL RESULTS

(gap=70mm)

Type	Rectangular			H-shaped core			
f_0 [kHz]	20			30			
gap [mm]	70*			70			
x [mm]	0	45	0	0	45	0	0 ***
y [mm]	0	0	150	0	0	150	0
R_L [Ω]	23	50	23	80			
V_{IN} [V]	112	117	86.6	168	143	128	226
V_2 [V]	139	178	137	128	129	129	182
V_L [V]**	186	241	186	346	346	346	491
P_{OUT} [W]	1489	1166	1528	1507	1503	1506	3060
η [%]	95.3	91.9	93.1	94.9	93.7	93.0	94.7
B_2 [T]	0.14	0.18	0.14	0.21	0.21	0.22	0.29
C_S [μF]	0.696			0.189			
C_P [μF]	2.30			1.91			

* If the transformer covers are put up to rectangular cores, the gap length becomes 60mm.

** V_L is the output voltage value of either full-wave rectifier for Rectangular core or double-voltage rectifier for H-shaped core.

*** Values when 3kW feeding power.

Table II lists the specifications of both transformers with H-shaped cores and rectangular cores. Fig. 5 shows the photographs and dimensions of these transformers. The weight of a secondary transformer with H-shaped cores is 3.9kg and lighter than that with rectangular cores of 4.6kg. The weight of winding part in a transformer with H-shaped cores is 2.0kg and lighter than that with rectangular cores of 2.9kg.

In the contactless power transfer system for EVs, the misalignment of the transformer by the drivers' skill and the change of the gap length by the car weight can not be avoided. A mechanical gap length of 70 mm with no misalignment is taken to be the normal position. The characteristics of transformers were measured for gap lengths in the range ±30 mm, a misalignment in the forward direction x of ±45 mm, and a misalignment in the lateral direction y of ±150 mm.

The transformer parameters and the experimental results of the transformer with H-shaped cores compared with that with rectangular cores were shown in Table III and Table IV. The resistances R and the inductances L when either primary or secondary terminals of the transformer are opened or shorted were measured with LCR meters, and the transformer parameters were calculated from these values. The vales of the resonance capacitors C_S and C_P for the transformer with H-shaped cores and rectangular cores were determined by (1) and (2) respectively. An aluminum sheet with 1mm in thickness (400mm×600mm) was attached to the back of the transformer to shield the leakage flux.

B. *Characteristics of Normal Position*

Table III lists the transformer parameters of normal position (mechanical gap length of 70mm). The maximum efficiency η_{max} of the transformer with H-shaped cores calculated by (5) is higher than that with rectangular cores though the coupling factor k of the transformer with H-shaped cores is lower than that with rectangular cores. This is because the secondary winding resistance r_2 of the transformer with H-shaped cores is smaller than that with rectangular cores and the exciting reactance x_0 (=$2\pi f_0 l_0$) of the H-shaped cores is large by increasing the number of primary windings and the frequency f_0.

Table IV lists the experimental results at the normal position and Fig. 6 shows the primary and secondary waveforms of the transformer with H-shaped cores. The efficiency η (=P_2/P_1) of the transformer with rectangular cores was higher than that with H-shaped cores in Table IV. The efficiency of the transformer with rectangular cores became 94.6% when the transformer covers was attached, and the efficiency of the transformer with H-shaped cores of 94.9% was higher than that with rectangular cores. As shown in Fig.6, V_{IN} and I_{IN} and V_2 were coherent. This demonstrates that this transformer has the characteristics of an ideal transformer.

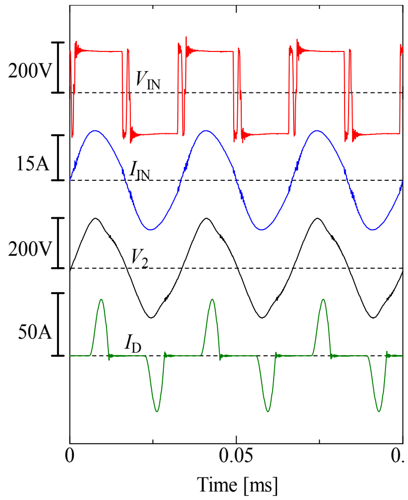


Figure 6. Wave forms of transformer with H-shaped core.

C. Characteristics with Change in Gap Length

Fig. 7 shows the transformer values of the transformer with H-shaped cores when the gap length or position is changed. The misalignment directions are shown in Fig. 5. The mutual inductance l_0 and the coupling factor k were decreased when the gap length or misalignment was increased because magnetic reluctance of main flux path became larger. In Fig. 7 (a), (b), and (c), the secondary self-inductance L_2 was almost constant. As the value of the parallel capacitor C_P determined by (1), the values of the resonant capacitors C_S and C_P remained constant during the experiment.

The coupling factor k and ideal transformer turn ratio b decreased when the gap length became larger, therefore, the voltage ratio (V_2 / V_{IN}) increased, as indicated by (3). The input voltage V_{IN} was adjusted to give an output power P_{OUT} of 1.5 kW. V_{IN} and V_2 roughly satisfied the relation of (3) though the gap length changed. The efficiency η decreased from 95.2% to 93.1% when the gap length increased from 40mm to 100mm. The average value of the efficiency was 94.5%.

D. Characteristics with Change in Positions

Fig. 7 (b) and (c) show the transformer values when the position (misalignment) is changed. The efficiency η of the transformer with rectangular cores and H-shaped cores were 93.1% and 93.0% respectively at maximum misalignment in the lateral direction y. The reduced efficiency of the transformer with H-shaped cores compared with efficiency of normal position was 1.9%, and smaller than that with rectangular cores of 2.2%. The transformer with H-shaped cores has good tolerance to misalignment in the lateral direction by increasing the length of magnetic poles.

E. Characteristics with Resistance-Load Change

Fig. 8 shows the transformer values of the transformer with H-shaped cores at normal position when the resistance-

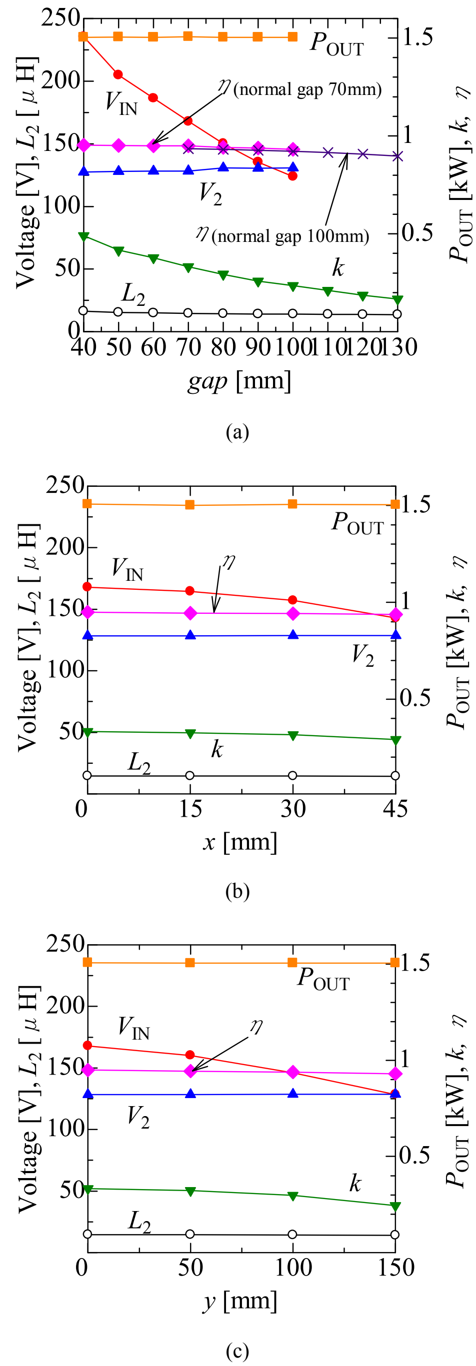


Figure 7. Experimental results for transformer with H-shaped core. (a)with change in gap length. (b)with change in position x. (c)with change in position y.

load changed. The output voltage V_L was kept constant during the test. In Fig. 8, dotted line shows the efficiency calculated with (4) by using the resistance load R_L corrected by voltage ratio (V_L / V_2) of the double-voltage rectifier [6]. There is good agreement between the measured efficiency and the calculated efficiency. The changes in the input voltage V_{IN} and the secondary voltage V_2 were small and the

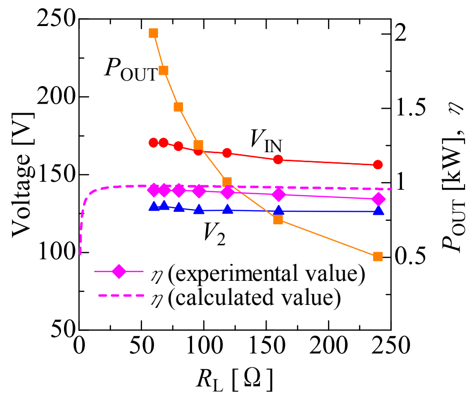


Figure 8. Characteristics with resistance-load change.

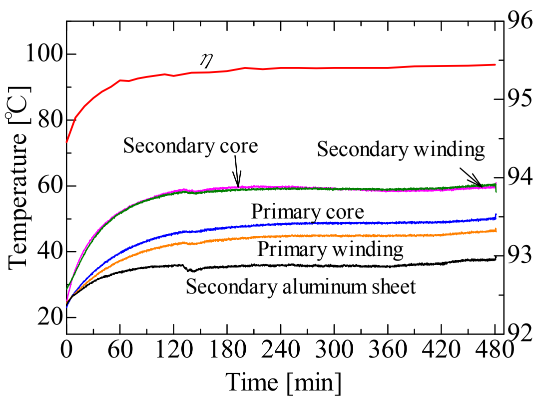


Figure 9. Temperature rise test.

voltage ratio (V_2/V_{IN}) was almost constant. This demonstrates that this transformer has the characteristics of an ideal transformer.

IV. The Other Characteristics of Transformer with H-shaped Cores

A. Characteristics in a Wide Gap

The characteristics of the transformer in a wide gap are of particular interest with respect to practical application of the transformer for contactless power transfer. The minimum ground clearance for PHVs and EVs is approximately 140 mm. The gap length was 100mm when the primary side transformer of 40mm in thickness was put directly on the ground in a parking lot. The characteristics of a transformer with normal gap length of 100mm were measured. The values of the resonant capacitors C_S and C_P decided by the parameters of the transformer with normal gap length of 100mm again. The input voltage V_{IN} was adjusted to give an output power P_{OUT} of 1.5 kW. The coupling factor k and the input voltage V_{IN} were decreased when the gap length became lager as shown in Fig. 7 (a). The efficiency η decreased from 93.5%, 92.1% to 89.7% when the gap length increased from 70mm, 100mm to 130mm. Although the average value of the efficiency decreased to 91.9%, it is possible to transfer 1.5 kW even at a gap length of 100 mm ±30 mm.

B. Temperature Rise Test

The full charging time of 1.5kW with AC 100V is assumed about 4 hours and 10 hours or more for PHVs and EVs, respectively. Therefore, the temperature rise of the core and the winding of the transformer with H-shaped cores become more severe because the size can be smaller than that of the circular cores with single-sided windings transformer. Fig. 9 shows the result of temperature rise test for the transformer with H-shaped cores. The temperature of the secondary core and winding became highest but were saturated 3 hours later because of the thermal equilibrium. The efficiency η has improved by about 1.0% compared to the beginning of experiment. This is because the loss of the ferrite has decreased with the temperature rise.

C. Characteristics of 3kW Charge

The 3kW charging can decrease the charging time about half compared to 1.5kW charging. As the current density of the winding and the flux density in the core are not high, the 3kW transfer test was performed. The efficiency η at normal position was 94.7% as shown in Table IV.

V. Conclusion

The novel H-shaped cores transformer suited for PHVs and EVs has been developed. A contactless power transfer system using this transformer can exhibit good performance such as high efficiency, a large air gap, good tolerance to misalignment in the lateral direction, and be compact and lightweight. A 1.5kW H-shaped cores transformer at normal air gap 70mm has high average efficiency of 94% within misalignment of ±150mm in the lateral direction. The transformer is small size (240×300×40mm) and light weight (3.9kg). The test results at wide air gap of 100mm and 3kW operation are also presented.

Acknowledgment

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