Large Air-Gap Coupler for Inductive Charger

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***Abstract*—A novel magnetic coupler with large air gap is presented. It is developed for the electric vehicle's automatic inductive charger. The new inductive coupler proposed here has sufficient exciting inductance even if it has a large air gap. Calculated exciting inductance is 40 μH at 2 turns of winding and 5 mm air gap, which agrees well with measured value. In order to assess the generation of heat caused by the eddy current, the magnetic flux densities in the inductive charger and also a flat iron plate, to which the inductive charger is attached, are calculated. The conversion efficiency with the coupler and a MOSFETs full-bridge inverter of 100 kHz, is 97% at 8.3 kW output.**

***Index Terms*—inductive charger, inductive coupler, large air gap coupler**

I. Introduction

Inductive charging is safe, efficient and easy to use for the electric vehicle (EV). Fig. 1 shows possible means of inductive charging for EV applications. Generally in the inductive charging, increasing of the air gap in the magnetic coupler, results is decreasing in the self-inductance, at the same time leakage inductance is increased. Therefore a conduction loss due to the proximately effect will not be negligible and a transferring power is limited by the leakage inductance. Presently, most of the inductive chargers for electric vehicle is of hand held insert-type as shown in Fig. 2 (A) [1]. Although in this type of charger, the air gap of the coupler is easy to make small, it will be troublesome to do inserting operations by hand. Further, if the power becomes large, it will be too heavy to carry it by hand. On the other hand, an automatic charging at parking site as shown in Fig. 2 (B) is more preferable and convenient because it has a mechanical carrying and adjusting tools [2][3]. In this system, however, it is necessary to have a small gap. In order to salve these problems, we examine a large ferrite pot core of a flat construction, by which the self-inductance becomes sufficiently large due to the short magnetic path and to the large cross sectional area of the core. With this construction, leakage inductance can be small at a long air gap, because the gap length is compensated effectively by a large cross sectional area. As results, inductive charging of high efficiency and large power is possible without any mechanical adjustment as shown in Fig. 2 (C).

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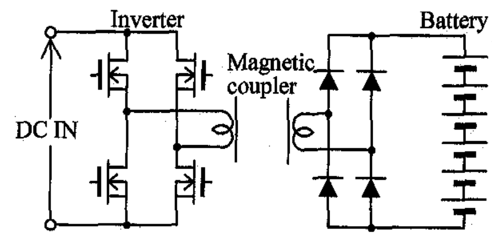

Fig. 1 Inductive charging for EV applications.

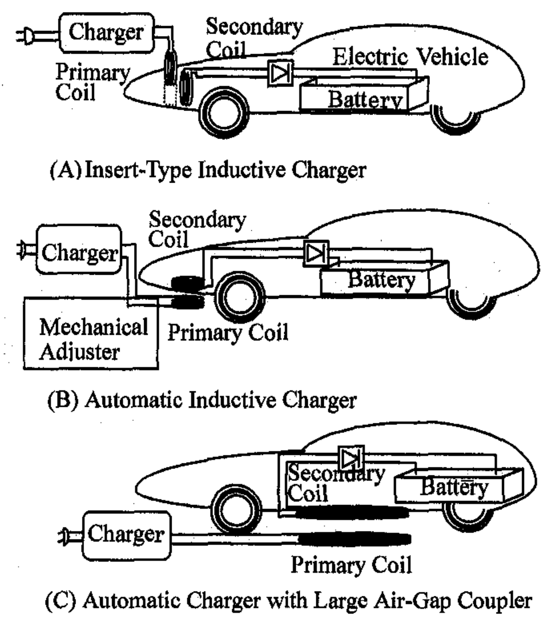

Fig. 2 Inductive charging system for electric vehicle.

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II. New Inductive Coupler Dimension and Characteristics

The new inductive coupler is composed of two thin large ferrite pot cores and two windings as shown in Fig. 3. In this figure, the primary core is for primary coil of charger side, the secondary core is for secondary coil of the electric vehicle side, and the iron plate is the body of the electric vehicle shown in Fig. 2 (C). The primary and secondary cores have large cross sectional areas, as shown in plain D and plain E. On the other hand, the thickness of the bottom of the slot for winding seems to be thin. However, this portion being a periphery of the circle, the total cross sectional area of the core in plain C is not always small. Therefore, the magnetic reluctance of the flux path through the cores become small. So in this coupler, the self-inductance is large and the leakage-inductance is small even if air gap is of considerable length. Fig. 3 and table I show the dimension and design parameters of the core.

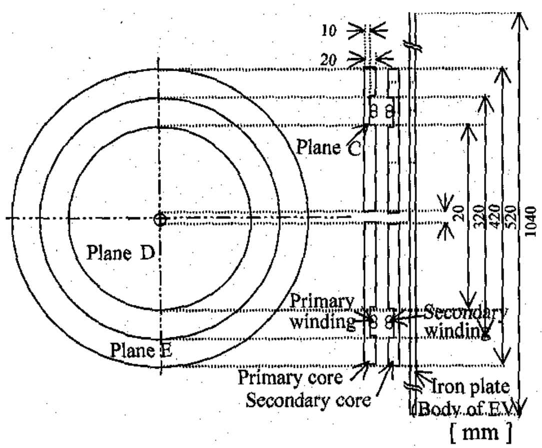

Fig. 3 Dimension of the magnetic coupler.

Table I Design parameters of the core

Core volume	366 cm^3
Core weight	17.2 kg
Core cross section C	100 cm^2
Core cross section D	801 cm^2
Core cross section E	738 cm^2
Flux path length	37 cm
Saturating flux density	0.5 T
Specific permeability	2300
Core loss	0.0035W/cm^2

III. Calculation and Measurement of Coupler Inductance

The self-inductance L and the leakage inductance L_l have been measured and calculated using the software package for magnetic field analysis ELF/MAGIC. The calculated values of the self-inductance L and the leakage inductance L_l are plotted as a function of the air gap. The calculated result and experimental result are shown in Fig. 4.

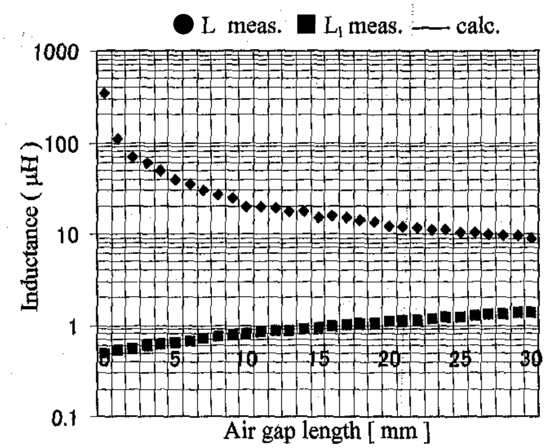

Fig. 4 Self-inductance and leakage-inductance.

Fig. 5 shows measured coupler self-inductance L and leakage inductance L_l when secondary side is shifted horizontally. L does not change almost but L_l increases from 1 μH to 10 μH when secondary side shifts horizontally from 0 mm to 50 mm.

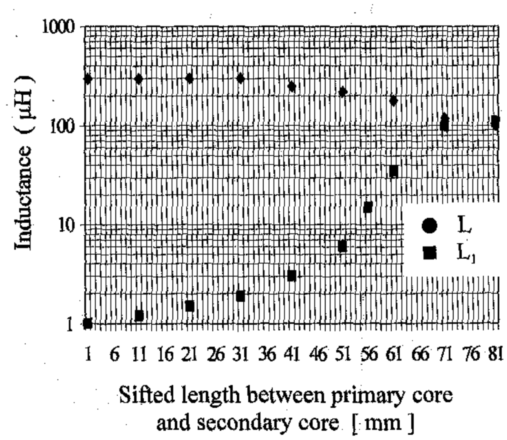

Fig. 5 Experimental result of L and L_l.

Fig. 6 shows measured coupler inductance when upper side is tilted vertically. The self-inductance L decreases when increasing tilt angle but the leakage inductance L_l does not change so much. L and L_l are 40 μH and 1.5 μH respectively at tilt angle of 1.6 degrees and tilt length of 14 mm. So it is important to keep low tilt angle for guaranteeing a sufficient inductance.

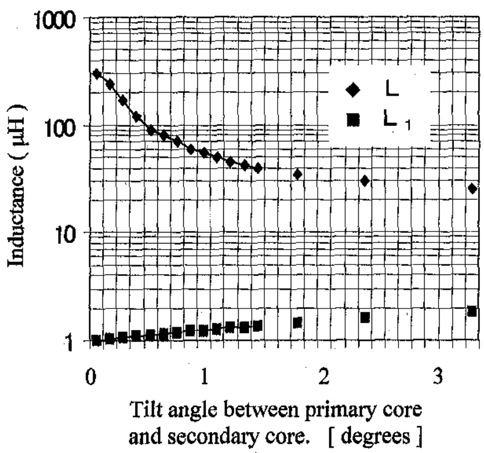

Fig. 6 Experimental result of L and L_l.

IV. Calculation of Flux Densities

In order to assess the generation of heat caused by the eddy current, the magnetic flux densities in the inductive charger and a flat iron plate, to which the inductive charger is attached, are calculated using the software package for magnetic field analysis ELF/MAGIC. In these calculations, the radius and thickness of the iron plate are 520 mm and 5 mm, respectively. Initial permeability of the ferrite pot core is 2300 and that of the iron plate is 5218. The coil of pot core has 2 turns and a constant current of 0.1 A flows in the coil. The magnetization is not saturated, therefore, Newton-Raphson iteration technique is not necessary. The air gap of the inductive charger is fixed to 2 mm. Fig. 7 shows the flux density plot of the coupler at the gap between the inductive charger and the iron plate is 1 mm. And the gap between the inductive charger and the iron plate is varied 0 mm to 30 mm. When the gaps are 0 mm and 5 mm, the calculated values of the flux densities at the plane H are 4.17×10^{-4} T and 4.29×10^{-5} T respectively. The calculated ratios of the magnetic flux densities at the plane F, G, H to those at the plane f, g, h shown in Fig. 7 respectively, are shown in Fig. 8. It may be concluded that the inductive charger is attached to the iron plate at few millimeters apart, in order to prevent the generation of heat caused by the eddy current.

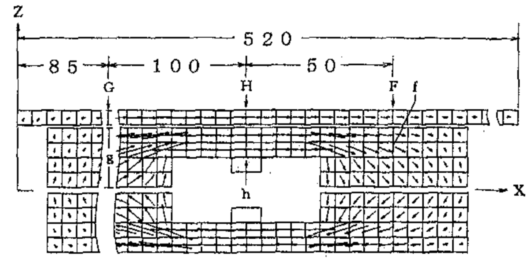

Fig. 7 Flux density plot of the coupler.

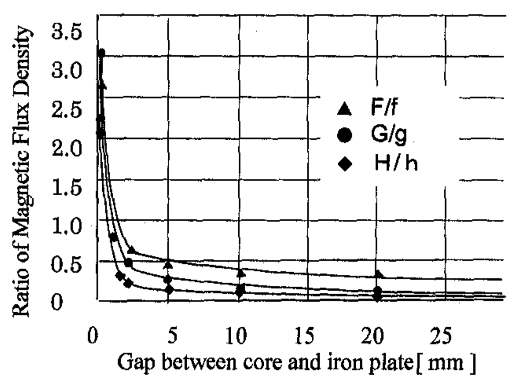

Fig. 8 Magnetic flux densities retio.

V. Conclusion

A new inductive coupler is proposed which has sufficient exciting inductance and low leakage inductance at large air gap length. The coupler is tested as an inductive charger, and high conversion efficiency is measured namely 97 % at 8.3 kW output when gap length is 3 mm and switching frequency is 100 kHz. It proves that this coupler can be used in large air gapped application such as automatic charging EV at parking area.

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