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Investigation of Wireless Power Transfer System with Spaced Arranged Primary H-shaped Core Coils for Moving EVs

Chihiro Kato
Graduate school of
Science and Engineering,
Saitama University,
Saitama, Japan
s14mm212@mail.saitama-u.ac.jp

Kazuma Tsuda
Graduate school of
Science and Engineering,
Saitama University,
Saitama, Japan
s15mm234@mail.saitama-u.ac.jp

Tsuyoshi Matsumura
Graduate school of
Science and Engineering,
Saitama University,
Saitama, Japan
s13mm233@mail.saitama-u.ac.jp

Yasuyoshi Kaneko
Graduate school of
Science and Engineering,
Saitama University,
Saitama, Japan
kaneko@ees.saitama-u.ac.jp

Toshiyuki Fujita
Technova Inc.,
Tokyo, Japan
t_fujita@technova.co.jp

Tomio Yasuda
Technova Inc.,
Tokyo, Japan
yasuda@technova.co.jp

***Abstract*— As a solution for long charging time and short running range of EVs, research on wireless power transfer systems for moving EVs have been getting attention. Although several power transfer systems with single or multiple grounded coils have been proposed, those systems have difficulties in maintenance, and require high system implementation and maintenance cost. In this paper, we evaluate the performance of a proposed wireless power transfer system for moving EVs, composed by a row of evenly spaced H-shaped core coils. With two types of resonance circuit, SP and SS topology, the performance of the system is evaluated under a constant voltage operation and a constant current operation. Comparison of the performance of the system with each resonance circuit in each operation is presented from the aspect of power output, efficiency and power factor. Among all experiment cases, power transfer with average transformer efficiency above 85% is achieved.**

I. INTRODUCTION

The development and commercialization of electric vehicles (EVs) and plug-in hybrid EVs (PHVs) are actively being realized because of environmental concerns and increasing oil prices. Current PHVs and EVs require a connection to a power source for battery charging using electric cables. A wireless power transfer system would have numerous advantages: it would be convenient, safe, and maintenance-free. Therefore, wireless power transfer systems are being investigated worldwide[1].

A wireless power transfer system for EVs must have a large air gap and good tolerance to misalignment. In addition, it must be compact and lightweight. Therefore we have developed the H-shaped core transformer to satisfy these requirements[2].

EVs have the issue of long charging time and short running range. A wireless power transfer system for moving EVs can solve these problems. The concept of the system is shown in Fig.1. This system allows the vehicle's battery to have less capacity, which leads to the lowering of the price of the vehicles and contributes to distribution of these vehicles. Showa Aircraft Industry Co. Ltd. proposed a system composed of a grounded loop coil and a pick up coil and Bombardier Inc. proposed a system composed of a primary S-shaped loop coil and a pick up coil[3][4]. However, these loop coil systems are not able to be expanded to the power transfer system for parked EVs which have been promoted standardization worldwide, and this limits the coevolution of two wireless power transfer

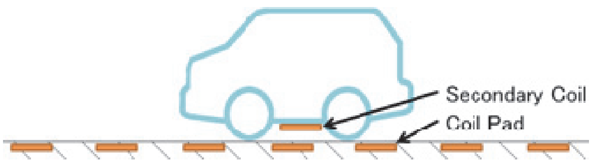


Fig. 1. Wireless power transfer system for Moving Vehicle.

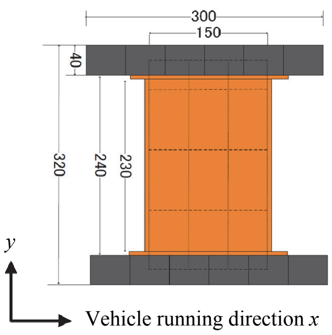


Fig. 2. Outline of an H-shaped solenoid coil.

systems (one for parked EVs/moving EVs). Moreover, all these systems with a grounded loop coil have difficulties in maintenance and extension of the system due to the inseparability of the grounded coil. KERI (The Korea Electro technology Research Institute) proposed a system composed of a number of grounded coils arranged to overlap slightly and a secondary pick up coil called receiver. Although it achieved around 80% of power transfer efficiency, the issue of the significantly low efficiency observed at the overlap point is reported[5]. Furthermore, the total cost of the system is considerable because the system needs to arrange many coils without any spaces, which leads to an increase in the number of the grounded coils. In response to the need of a system which is cheaper, easier to extend, and easier to maintain, Technova Inc. proposed a system with a row of evenly spaced H-shaped core coils which is relatively small, has a large air gap, and good tolerance to misalignment[6]. However, study of this system in terms of resonance circuit configuration and power source operation method has not been considered yet. In this research we evaluate the performance of the system with two types of resonance circuit (SP and SS circuit) along with two types of power source operation (constant voltage operation and constant current operation) in terms of power factor of power source output and transformer efficiency through experiments. Power transfer with above 85% transformer efficiency is achieved under those four different cases.

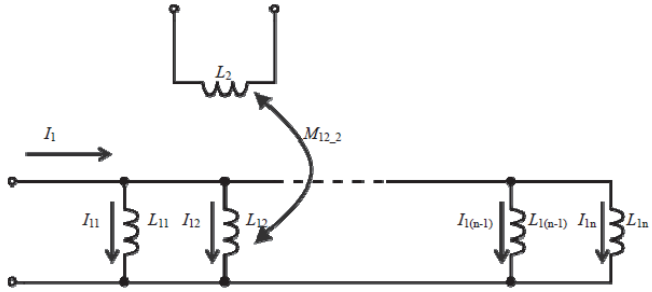
II. Circuit Of Wireless Power Transfer System For Moving Ev

A. *Series connection of primary coils*

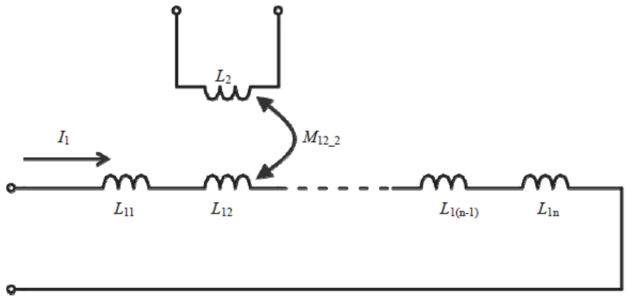
The outline of an H-shaped solenoid coil is shown in Fig.2. In proposed system a number of H-shaped core coils need to be set as the primary coil. However, equipping each primary coil with a power source and operating many switches separately in order to activate each coil is undesirable in terms of cost and complexity. Therefore several coils should be connected to one power source in series or in parallel. Fig.3 shows a series connection and parallel connection of the primary coils. When several coils are connected to a power source, the coil which does not form coupling with the secondary coil shows lower impedance than the one with coupling. Taking this into account, primary coils are connected to power source in series. This connection allows the total impedance of the load of the power source to be the sum of each coil's impedance. Owing to this, the system can protect the inverter and coils from high current caused by small input impedance of load, as long as there is a primary coil forming coupling with the secondary coil. The proposal system is shown in Fig.4. Intervals between primary transformers is determined in considering the power feeding range when magnetic gap is 160mm.

B. *Circuit constants of the series connection coil*

State of mutual coupling when connected in series to the n primary coils is shown in Fig.5. In this case the self-inductance L_1 of the entire primary side as viewed from the primary side of the terminal is expressed as equation (1).

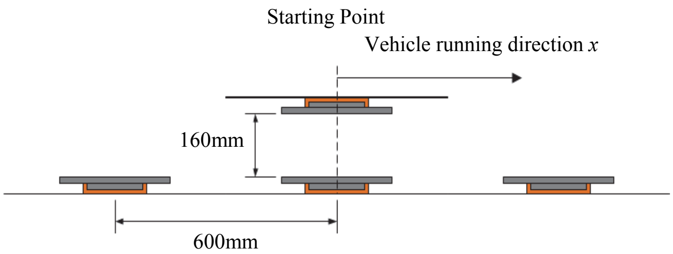


(a) Parallel connection

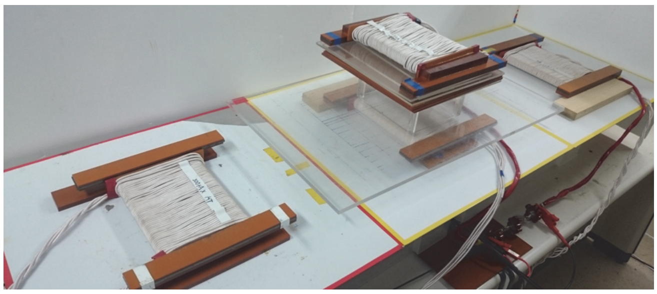


(b) Series connection

Fig. 3 Connection method of the primary coil



(a) Outline of the proposal system



(b) Photograph of the proposal system

Fig. 4. Proposal system.

$$L_1 = \sum_{i=1}^{n} L_i + \sum_{i=1}^{n}\sum_{j=1}^{n} M_{1i\_1j} (i \neq j) \tag{1}$$

Moreover, the primary coils regarded as interconnected only between adjacent coils, the equation (1) is simplified as shown in equation (2).

$$L_1 = \sum_{i=1}^{n} L_i + 2\sum_{i=1}^{n-1} M_{1i\_1(i+1)} \tag{2}$$

Meanwhile, the mutual inductance M of the primary coils across the secondary coil is represented by the equation (3).

$$M = \sum_{i=1}^{n} M_{2\_i} \tag{3}$$

Therefore, it can be regarded as a plurality of primary coils connected in series with one coil of the self-inductance L_1. Equivalent self-inductance L_1 and mutual inductance M is capable of directly measured by using a LCR meter in a state where the primary coils are connected in series.

C. Capacitors' Effect on Power Factor

Since the wireless power transfer system has a poor coupling coefficient, resonance capacitors are generally used to compensate for the leakage inductances. As two main ways to insert resonance capacitors, our research has proposed SP and SS topology. Although capacitors on ground side in both SP and SS topologies has the ability to compensate the power factor of power source output in the wireless power transfer system for parked EVs, the system for moving EV need to take variation of the circuit constant into account in order to evaluate appropriate methods from the perspective of the power factor of power source output. The resonance circuits of SP and SS topology are shown in Fig.6.

III. Evaluation Trough Power Transfer Experiment

Performance of the system with both SP and SS circuits is measured. The experimental conditions are shown in Table 1, and three of the coils in Fig.2 are used as primary coils. In order to cut off the flux lines which are not shaped towards the coil in the other side, aluminum shielding (600mm×600mm thickness 2mm) is placed behind each coil. Capacity of the capacitor on secondary side C_2 is fixed to the value which is resonant with the self inductance of secondary coil L_2. C_2 is shown by equation (4).

$$\frac{1}{C_2} = \omega_0^{\,2} L_2 \tag{4}$$

Capacity of the capacitor on ground side C_1 is decided so that the output of the inverter does not take an advancing state phase within any secondary coil position. Taking this into account, C_1 for SP topology C_{1SP} and C_1 for SS topology C_{1SS} are determined by equation (5). L_1 expresses the self inductance of primary coil, k expresses the coupling coefficient of the primary coil and the secondary coil.

$$\frac{1}{C_{1SP}} = \omega_0^{\,2} L_1 (1-k^2), \qquad \frac{1}{C_{1SS}} = \omega_0^{\,2} L_1 \tag{5}$$

TABLE I: Experimental Conditions.

Capacitors Topology	SP	SS
Frequency of Power Source	85kHz	
Intervals between primary transformers	600mm	
Magnetic Gap	160mm	
Number of Turns of Primary Coils	14T	
Number of Turns of Secondary Coils	4T	14T
Primary Coil Inductance L_1	204.6μH	
Secondary Coil Inductance L_2	6.21μH	67.0μH
Coupling Coefficient k	0.182	0.185
Capacitor on Ground Side C_1	0.0171μF	0.0173μF
Capacitor on Secondary Side C_2	0.583μF	0.0493μF
Resistance Load R_L	50Ω	10Ω

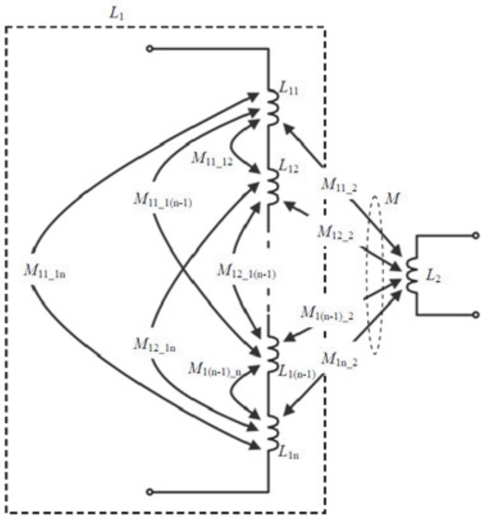
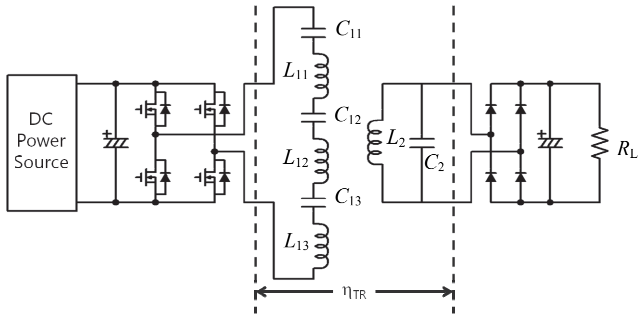
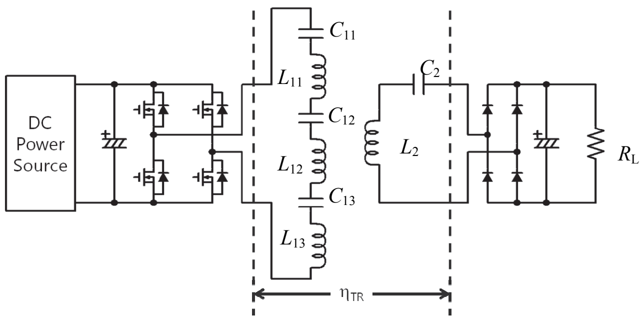


Fig. 5. Mutual coupling of series connection coil



(a) SP topology



(b) SS topology

Fig. 6. Experimental circuits.

Furthermore, in order to avoid over-voltage, C_1 is split into three capacitors, $C_{11} \sim C_{13}$, which have three times more capacity, and connected alternately with each primary coil. The center point of the primary coil in the middle is defined as the starting point. In this experiment, load power, power factor of the power source output and transformer efficiency are observed when a secondary coil is moved in the running direction of the vehicle from 0mm to 1200mm at intervals of 50mm.

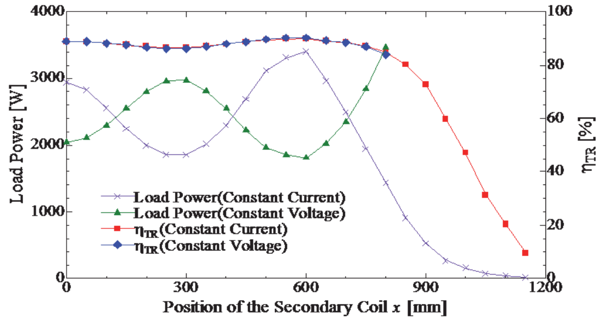
A. Comparison of Power Source Operation

Fig.7 shows the load power P_L and transformer efficiency η_{TR} at each secondary coil position with two types of resonance circuits along with two types of power source operation. Under the constant voltage operation, data was unable to be sampled over 800mm for the SP circuit, and over 700mm for the SS circuit due to a critical high current from the power source. The transformer efficiency is relatively high at the point where the secondary coil face one of the primary coils (0mm or 600mm) in both topologies, and the variation range of the value is small when the secondary coil is over the area between two primary coils (0mm~600mm). In addition, there are few differences between the values from the two types of operations. Incidentally, load power plots show different characteristics between the two power source operations. While data from a constant current operation plots the highest value at the point where the secondary coil faces one of the primary coils (0mm or 600mm), data from a constant voltage operation plots the highest value at the point where secondary coil is located at the middle of the two primary coils (300mm). Moreover, transformer efficiency at the highest load power point takes the highest value in a constant current operation and the lowest value in a constant voltage operation. Therefore a constant current operation contributes to reducing the power source capacity.

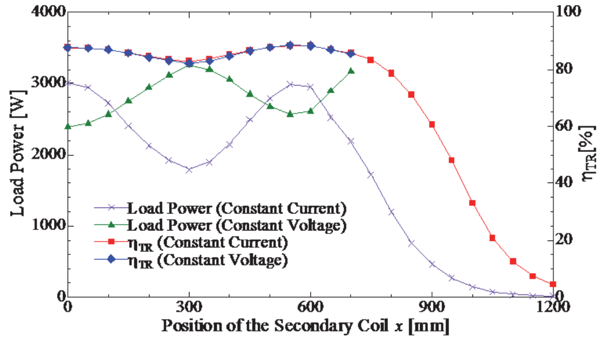
B. Comparison of SS, SP Topology

Fig.8 shows the power factor of the power source output at each secondary coil position. The power source is driven with a constant current operation. Under both topologies the power factor is relatively high at the point where the secondary coil faces one of the primary coils (0mm or 600mm), and it is low at the point where the secondary coil located in the middle of two primary coils (300mm). The variation range of the value is small when the secondary coil is over the area between two primary coils (0mm~600mm). In addition, the system under SP topology keeps a higher value whilst the secondary coil is increasingly displaced from primary coils.

In the SP topology, coupling coefficient k is included in the equation of primary side capacitor C_1. In constant, it is not include in the equation of C_1 in the SS topology. k varies depending on the position of the secondary coil. However, the result of the previous section, SS system has a larger power factor variation than the SP system. Fig.9 shows the absolute value $|Z_{in}|$, the real part $Re\,(Z_{in})$ and the imaginary part $Im(Z_{in})$. Z_{in} represents the impedance of the behind the power source. $Im(Z_{in})$ in the SP topology is negative value when the secondary coil position is 500mm and 600mm. Therefore,



(a) SP topology



(b) SS topology

Fig. 7. Measured load power and η_{TR}.

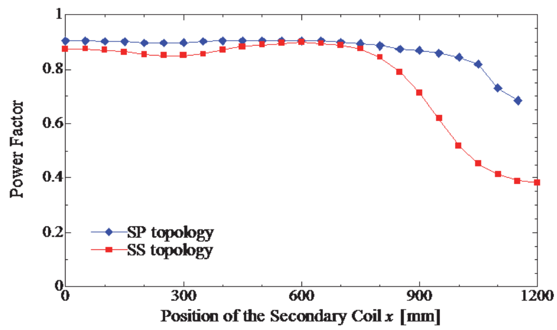
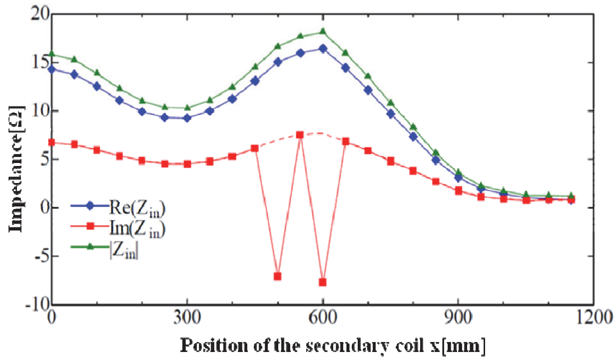


Fig. 8 Measured power factor of power source output.

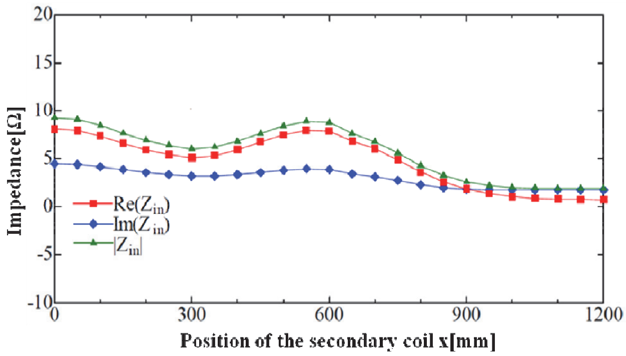
absolute values of those points are shown by a broken line. $Im(Z_{in})$ is determined by the accuracy of the capacitor on primary side C_1. In the SP topology, it is varied in response to the primary coil position. However, the variation in the SS topology is small. In the equation (5), it has appeared difference of including a coupling coefficient. It is also possible to reduce $Im(Z_{in})$ by more accurately designing C_1. Meanwhile, $Re(Z_{in})$ changes according to the secondary coil position in both topologies. This is because influence of load resistance R_L changes according to factor of k. In the SP topology, a fluctuations in the power factor is small because $Re(Z_{in})$ and $Im(Z_{in})$ change equally. In the SS topology, $Im(Z_{in})$ is fixation approximately, but $Re(Z_{in})$ is to fluctuate, so fluctuation of power factor occurs.

IV. Conclusion

In this paper, we evaluate the performance of proposed power transfer system for moving EV with two resonance circuits along with two different power source operations. Under all of the cases we tested, this system with spaced lined primary coils achieved power transfer with transformer efficiency above 85% on average when the secondary coil is over the area between two primary coils (0~600mm). The system has potential to lower the implementation and maintenance cost, and alleviates the difficulties of maintenance and extension of the system. The efficiency and the supplied load power need to be improved, and the intervals between the primary coils need to be wider for practical use. Structure of the primary coil and winding number ratio of the transformer need to be considered for further sophistication.



(a) SP topology



(b) SS topology

Fig. 9 Measured impedance Z_{in}

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