Electrical Characteristics of Wireless Power Transfer System with Repeating Coil for AGV Considering the Misalignment of Coils

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Abstract: This paper compares the electrical characteristics of S-P (Series - Parallel) type with those of a repeating coil type wireless power transfer (WPT) system. The features of the two types of WPT systems are described for same output power using the same coil model. In general, the misalignment of power transmitting and receiving coils causes an output power to decrease using resonance capacitors with large operations current and voltage. From the viewpoint, a compensation method for the misalignment is investigated to reduce this burden of the resonance capacitor. Simulation is made on electrical characteristics such as output power and power transfer efficiency of a proposed WPT system applied to an automatic guided vehicle (AGV) based on an equipment circuit combining the results of an electromagnetic analysis. As a result, it is found that a repeating coil keeping the center position between the primary and secondary coils can suppress the burden of the resonance capacitor so as to improve the transmission power of WPT system.

Keywords: wireless power transfer, repeating coil, automatic guided vehicle, relay coil

1. Introduction

In recent years, wireless power transfer (WPT) system has been researched for various applications, such as electric vehicles (EV) and automatic guided vehicles. There are a number of circuit configurations with different electrical characteristics for the WPT system [1]~[4]. Circuit configuration of the S-P type WPT system commonly used for EV applications has two resonance capacitors: one connected in series with a primary coil, and the other connected in parallel with a secondary coil. On the other hand, the WPT system with a repeating coil (repeating coil type) is well known for its robust performance in the coil position. It is crucial to investigate the electrical characteristics against misalignment of the coil position for transmitting power to the load with high efficiency. A lot of other researchers [1][4] have been made on the electrical characteristics of other coil types such as S-P type and repeating coil type for WPT system. However, it is difficult to compare the electrical characteristics under the same conditions, because each type of WPT system has different circuit configurations and coil shapes. Thus, it is needed to determine conditions suitable for each type of WPT system to be reasonably compared. Moreover, an investigation is also needed on parameters in the electrical characteristics to reduce time to conduct a simulation.

This paper compares the electrical characteristics of the S-P type and the repeating type WPT system. Namely, the

two types of WPT system are compared under the conditions with the same output power using same coil model. In general, the misalignment of power transmitting and receiving coils causes an output power to decrease using resonance capacitors with large operations current and voltage. From the viewpoint, a compensation method for the misalignment is investigated to reduce this burden of the resonance capacitor. Simulation is made on electrical characteristics such as output power and power transfer efficiency of a proposed WPT system applied to an automatic guided vehicle (AGV) based on an equipment circuit combining the results of an electromagnetic analysis.

One of the main purposes of this paper is to provide optimum design conditions in the WPT system. Yamamoto *et al.* [5] investigated the burden of the resonance capacitor in a WPT system, while, Kitazawa *et al.* [6] and Zaher *et al.* [7] studied compensation method for a coil misalignment using control or coil shapes. In addition, the literature [8]~[10] showed two types dynamic WPT system using parallel line feeder or relay coil(repeating coil), respectively. On the other hand, we have studied the WPT system using the repeating coil with controlling the coil position [11][12]. In this paper, we investigate the electrical characteristics, compensation method, and the burden of the capacitor, when the repeating coil maintains its position at the center between the primary and secondary coils.

2. Proposed Wireless power transfer system configuration for automatic guided vehicle

2.1 Overall WPT system for AGV Fig. 1(a) and (b) show electrical circuit and coil models of WPT system for

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Figure 1: Wireless Power Transfer system with repeating coil for Automatic Guided Vehicle.

AGV investigated so far. As shown in Fig. 1(a), the circuit consists of a voltage booster to control the battery current, DC link capacitor used commonly in WPT system, and three-phase inverter for driving a motor of AGV. Fig. 1(b) shows the coil model and motions of repeating coil and secondary coils. Note that the secondary coil is located at an AGV. In contrast, the repeating coil is set at the center between the primary and secondary coils to keep the output voltage constant. In other words, movement of the repeating coil is controlled to suppress the decrease in the output power.

2.2 Simulation model of S-P and the repeating coil types Fig. 2(a) and (b) show simulation models of the S-P type and repeating coil type, respectively. Note that both types consist of same coil shape and the number of turns, while, the later type additionally includes the repeating coil set at the center of the primary and secondary coils. The gap length G of 20 mm and misalignment are defined in Fig. 1 as parameter in the simulation.

Table 1 lists physical property values and size of the coil. In addition, the input voltage V_1 and the load resistance R_L were set as sine waveforms and 100Ω , respectively, in the simulation.

First, the output voltage and current of the power transmitting coil, receiving coil and repeating coil were simulated using electromagnetic analysis software (ANSYS, Maxwell and Simplorer), which also provided inductance and mutual inductance as the parameters as shown in Fig. 2.

Next, simulated results using the electromagnetic software and calculated ones using circuit equations were compared. As a result, the validity of calculation results using circuit equations was confirmed. Namely, calculated results derived using parameters such as the inductance L and mutual inductance M were simulated using the electromagnetic software. In general, circuit equations are useful to design an optimum WPT system when the influence of circuit parameters on the electrical characteristics of the WPT system is investigated.

Finally, the S-P type and repeating coil type calculation results were compared and discussed so as to investigate a

Figure 2: Circuit and coil simulation models using electromagnetic analysis.

compensation method.

2.3 S-P type and the repeating coil type models

Equations of the S-P type and the repeating coil type WPT system are expressed as equations (1) and (2), respectively. The capacitance of a resonance capacitor is set to adjust a power factor of the circuit at 1.0. Fig. 3 shows thus obtained

Table 1: Simulation conditions.

Parameters	Value
Input voltage V_1 (S-P type)	141V _{rms}
Input voltage V_1 (Repeating coil type)	141V _{rms}
Input voltage V_1 (Repeating coil type) The output power is same value in the S-P type and the repeating coil type	254V _{rms}
Frequency of input voltage V_1	25kHz
Gap length G	20mm
Misalignment X	0-80mm
Load resistance R_L	100Ω
Inductance L_1 (S-P type)@No misalignment	638μH
Inductance L_2 (S-P type)@No misalignment	637μH
Inductance L_1 (Repeating coil type) @No misalignment	573μH
Inductance L_r (Repeating coil type) @No misalignment	638μH
Inductance L_2 (Repeating coil type) @No misalignment	638μH
Resonance capacitor C_1 (S-P type)	92nF
Resonance capacitor C_2 (S-P type)	64nF
Resonance capacitor C_1 (Repeating coil type)	71nF
Resonance capacitor C_r (Repeating coil type)	71nF
Internal resistance of coil r_1, r_r, r_2	0.173Ω
Relative permeability of ferrite core	2300
Ferrite core size	125 × 125 × 5mm
Diameter of coil	Φ 175mm
Number of turns of coil	75

an equivalent circuit model of a repeating type WPT system. It can be seen that the equivalent circuit model of the repeating coil type is similar to that of the S-P type system. Furthermore, if the mutual inductances M_{1r} and M_{r2} have the same value, and the repeating resonance capacitor value is chosen as providing a resonance frequency with the repeating coil L_r , the output voltage can be constant. Fulfilling the above conditions allows us to eliminate the resonance capacitor C_2 in the circuit of the WPT system. If the repeating coil position is controlled at the center between the primary and secondary coils, the output voltage can be maintained at constant with the input voltage V_{in} . Thus, the simulation on the electrical properties of the repeating coil type was made without the resonance capacitor C_2 , as reported in the previous investigation [12] where the WPT system used not only repeating resonance capacitor but secondary resonance one. However, electrical characteristics of the S-P type and repeating coil type WPT system have not compared in detail under the condition that the repeating coil is controlled at the center of the primary and secondary coils intentionally.

$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 + j(\omega L_1 - \frac{1}{\omega C_1}) & -j\omega M_{12} \\ j\omega M_{12} & -r_2 - j(\omega L_2 - \frac{R_L}{\omega C_2}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 + j(\omega L_1 - \frac{1}{\omega C_1}) & -j\omega M_{1r} & -j\omega M_{12} \\ j\omega M_{1r} & -(r_r + j(\omega L_r - \frac{1}{\omega C_r})) & -j\omega M_{r2} \\ j\omega M_{12} & -j\omega M_{r2} & -(r_2 + j(\omega L_2 - \frac{R_L}{\omega C_2})) \end{bmatrix} \begin{bmatrix} I_1 \\ I_r \\ I_2 \end{bmatrix} \quad (2)$$

Therefore, this paper dealt with each WPT system designed with the same output power using the same coil model, as well as, the burden of each resonance capacitor and change in the impedance locus observed according to the increase in the misalignment.

Figure 3: Equivalent circuit model of the repeating coil type WPT system.

Since the number of parameters influencing the electrical characteristics is large, the calculation was carried out using derived from the electromagnetic analysis. Note that output voltage of the S-P type WPT system larger than that of repeating coil type as expressed by equations (3) and (4), respectively.

$$V_{out.SP} = \frac{L_2}{M_{12}} V_1 \quad (3)$$

$$V_{out.RC} = V_1 \quad (4)$$

The simulation was performed with the same output power, meaning that the repeating coil type needs an inverter providing high voltage than the S-P type.

3. Simulation results and discussion

Fig. 4 and 5 show misalignment dependence of the output voltage and coil current characteristics of the S-P type and the repeating coil type WPT system obtained from the electromagnetic analysis and equations (1) and (2), respectively. As shown in the figures, results obtained from the electromagnetic analysis agree with those derived from the equations indicating a validity of the two different ways to the equations from the results of comparison between misalignment dependence of V_{out} . As well as other characteristics such as coil efficiency, output power, output voltage, and coil current and so on.

Note that the inductance L and mutual inductance M were calculated from the electromagnetic analysis.

Fig. 5(a) and (b) show the output voltage and coil current as a function of the misalignment for the S-P type and repeating coil type WPT system, respectively. Note in Fig. 6(a) that V_{in} of the repeating coil type was set two times that of the S-P type to adjust the output power to that of the S-P type without misalignment.

Fig. 6(a) and (b) show the output power characteristics for misalignment. For this, the load was set at 100 Ω. In addition, in Fig. 6(a) and (b), the input voltage V_{in} are different for the repeating coil type. In Fig. 6(a), the input voltage V_{in} of the repeating coil type was set at the same value as that of the S-P type. In (b), the input voltage V_{in} of the repeating coil type was set about two times that of the S-P type to

Figure 4: Simulation results of the S-P type.

Figure 5: Simulation results of WPT_{RC}.

adjust the same output power of the S-P type under the no misalignment.

It is evident from Fig. 6(a) the repeating coil type WPT

Figure 6: Output power as a function of coil misalignment of two types of WPT system.

Figure 7: Coil efficiency as a function of misalignment of the two

system provides the lower output voltage and lower output power than the S-P type does. As a consequence WPT_{SP} is superior to WPT_{RC} for the same input voltage V_{in} . On the other hand, as shown in Fig. 6(b), the output power of the WPT_{RC} has the same value as WPT_{SP}, indicating WPT_{RC} is superior to WPT_{SP} in a low output power area. For example, WPT_{SP} can provide 400 W of power transmission for about 40 mm of misalignment, while WPT_{RC} can transmit the same power even for 80 mm in misalignment.

Next, an attempt was made to compare the coil efficiency defined as the only copper loss of a coil for the two types of WPT system.

Fig. 7 shows the coil misalignment dependence of the coil efficiency of the two types of WPT system. It is obvious the figure that WPT_{RC} provides larger efficiency than WPT_{SP},

Figure 8: Resonance capacitor's burden for misalignment of the two types of WPT system.

especially for larger misalignment. This result can be explained by a rapid decrease in the output power of WPT_{SP} resulting in an increase in a reactive power. On the other hand, WPT_{RC} maintains high coil efficiency even for low output power.

Fig. 8(a) and (b) show coil misalignment dependence of coil current and resonance capacitor voltage for the two types of WPT system. Note that input voltage V_{in} of WPT_{RC} was set two times that of WPT_{SP} . As shown the Fig. 8(b), the primary resonance capacitor has a larger burden than the secondary resonance capacitor in WPT_{SP} . In addition, the repeating resonance capacitor in WPT_{RC} provides a larger burden than the primary resonance capacitor. The result indicates that the repeating resonance capacitor's burden should be considered in designing.

Next, we compared the impedance locus for misalignment of the two types of WPT system. Fig. 9 shows impedance viewed from the primary side. Circles and triangles in the figure indicate the impedances of WPT_{SP} and WPT_{RC} , respectively. The result explains a robustness of WPT_{RC} . Namely, even if a large misalignment occurs, then leakage inductance increases, leading to an increase in the reactive power. As shown in Fig. 9, WPT_{SP} provides the almost inductive load at 80mm of the misalignment, while WPT_{RC} does not the completely inductive load for the same misalignment. WPT_{RC} has different impedance locus from WPT_{SP} .

The equivalent circuit of WPT_{RC} as shown in Fig. 3 allows us to confirm a constant output voltage V_{out} for same M_{1r} and M_{r2} and a repeating resonance capacitance with

Figure 9: Impedance locus for misalignment of the two types.

Figure 10: Ideal resonance capacitance as a function of the misalignment of WPT_{RC} .

a repeating coil L_r to provide a resonance. Note, however, that the output power (output voltage) gently decreases with increasing misalignment, as shown in Fig. 6.

Fig. 10 shows ideal resonance capacitance C_1 and C_r as a function of the misalignment of WPT_{RC} . As can be seen in the figure, both C_1 and C_r decrease with an increase in misalignment, resulting in the decrease in output voltage with deviating from a designed value. Thus, additional control will be needed to maintain V_{out} as a constant.

4. Compensation method of misalignment and burden for resonance capacitor

In this section, an investigation is made on a compensation method of the misalignment and burden for the resonance capacitor. Note that WPT_{RC} can ignore C_2 irrespective of the misalignment.

Fig. 11 shows output voltage as a function of misalignment of WPT_{RC} with the secondary resonance capacitor C_2 added. Note that C_2 was set at the value of 10% and 100% C_r . As can be seen in the figure, V_{out} increases with increase of C_2 , and then the output power increases with increasing in the misalignment. Obtained output voltage charac-

Figure 11: Output voltage as a function of the misalignment of the two types of WPT system with the resonance capacitor C_2 added.

Figure 12: Primary coil current as a function of frequency of WPT_{RC} for different misalignments.

teristics of WPT_{RC} resembles those of WPT_{SP} with the increase in C_2 . On the other side, the advantage of such flat characteristics of the output voltage for the misalignment in WPT_{RC} is lost with adding C_2 . In addition, the burden of the C_1 , C_r , and C_2 , such as current and voltage characteristics must be considered for the misalignment.

Next, an attempt is made to investigate a compensation method for the misalignment by controlling the magnitude of the input voltage V_{in} and the frequency f of V_{in} . As shown in Fig. 9, the impedance from the primary side is dominated by a resistance and inductive load for a coil misalignment.

If the frequency of V_{in} decreases, then the impedance will change only by the resistance component so that the power factor of the circuit will be controlled at 1.0. On the other hand, the control increases a burden of resonance capacitors C_1 and C_r . In particular, the current and voltage of C_1 increase more drastically than those of C_r . It is because the impedance viewed from the primary side is reduced to a small value by controlling the frequency.

Fig. 12 and 13 show frequency dependence of primary coil current and impedance locus for misalignment with the frequency changed of WPT_{RC}, respectively. As a result, it can be mentioned that the impedance viewed from the primary coil side changes only with the resistance by controlling the frequency of V_{in} . In addition, it is confirmed that the primary current increases with decreasing the frequency.

Fig. 14 shows input and output voltages for misalignment of WPT_{RC} with and without the controlling f and V_{in} . Note

Figure 13: Impedance locus for misalignment of WPT_{RC} with the input voltage and frequency adjusted.

Figure 14: Input and output voltage as a function of misalignment of WPT_{RC} with V_{in} and frequency controlled.

Figure 15: Resonance capacitor voltage as a function of misalignment of WPT_{RC} with V_{in} and frequency controlled.

that V_{in} was controlled to keep the output power as a constant. Two parameters *i.e.* magnitude of V_{in} and f can control the output power P_{out} as a constant.

Fig. 15 shows the misalignment dependence of the resonance capacitor voltage of WPT_{RC} with the frequency and magnitude of V_{in} changed. As can be seen, results, the voltage, and current of C_1 exceeded those of C_r , for instance, the voltage of C_1 at 80 mm of misalignment is four times of 0 mm of misalignment.

Fig. 16 shows misalignment dependence of the magnetic

Figure 16: Magnetic flux density as a function of misalignment of WPT_{RC} without V_{in} and frequency controlled (without ferrite core).

flux density distribution of WPT_{RC} when two primary coils are connected in series and set with gap lengthen G of 20 mm. Primary coils were set 250 mm interval. As can be seen results, Maximum flux density point was the shift to right side direction which is movement direction of the secondary coil with increasing the misalignment.

Finally, the advantages of WPT_{RC} will be described by reflecting simulation results. Controlling the position of the repeating coil can keep the output voltage as almost constant. Even if a relatively large misalignment occurs, the output voltages decrease in a safe direction for the load. In addition, the burden of the resonance capacitor for repeating coil is always maximized, so the system design of WPT_{RC} considering the misalignment should take it account to resonance capacitor of repeating coil.

In particular, WPT_{RC} has with the power transmitting efficiency kept high even for the large misalignment and decreased output power. In other words, even if the power factor 1 control is not performed, WPT_{RC} has no problem if allowable position range that has high power transmitting efficiency is considered.

5. Conclusion

This paper compares the electrical characteristics of S-P (Series - Parallel) type with those of a repeating coil type wireless power transfer (WPT) system. The features of the two types of WPT systems are described for the same output power using a same coil model. In general, the misalignment of power transmitting and receiving coils causes an output power to decrease using resonance capacitors with large operations current and voltage. From the viewpoint, a compensation method for the misalignment is investigated to reduce this burden of the resonance capacitor.

Simulation is made on electrical characteristics such as output power and power transfer efficiency of a proposed WPT system applied to the automatic guided vehicle (AGV) based on an equipment circuit combining results of the electromagnetic analysis. As a result, it is found that a repeating coil keeping the center position between the primary and secondary coils can suppress the burden of the resonance

capacitor so as to improve the transmission power of WPT system.

In particular, WPT_{RC} has with the power transmitting efficiency kept high even for the large misalignment and decreased output power. In other words, even if the power factor 1 control is not performed, WPT_{RC} has no problem if allowable position range that has high power transmitting efficiency is considered.

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