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Study of Resonance-Based Wireless Electric Vehicle Charging System in Close Proximity to Metallic Objects

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Abstract—A typical magnetic resonance coupling based wireless Electric Vehicle (EV) charging system consists of a transmitting coil at the charging station and a receiving coil in the vehicle. In order to maintain good energy transfer efficiency of the wireless charging system, the effect of the proximal metallic object in the vicinity of the receiving coil has been investigated. Both from the simulation and experimental measurement, it has been observed that the resonance based wireless energy transfer system is very sensitive to the nearby metallic objects, leading to significant deterioration in energy transfer efficiency. This effect on the energy transfer efficiency is also seen to be different for different physical spacing between the transmitting and receiving coils. It is also found that the operating resonant frequency for optimum energy transfer efficiency changes with the metallic object in close proximity to the receiving coil. The simulated results well agree with the experimental results. The analysis will provide future guidelines for designing an efficient resonance coupling based wireless charging system for EVs even in the presence of metallic objects.

1. INTRODUCTION

Wireless charging systems for EVs have recently received much attention because the wireless charging can provide the convenience to power EVs wirelessly [1, 2]. Roadway electric vehicle applications using conventional inductive coupling [3, 4] and microwave energy transmission [5] have been proposed for more than two decades, but till date there has been only limited commercial development due to the difficulties of inconvenience and efficient only for very short range distance. As electric vehicles make use of large amounts of energy, any loss in energy efficiency due to the energy transfer process from the source to the vehicle, will be significant. It has been found that magnetic resonance coupling based wireless energy transfer system is an effective solution of powering or charging an EV wirelessly [6–13]. As a result of the advantage of being efficient over a relatively far distance, the magnetic resonance coupling based wireless energy transfer system has been utilized for charging EVs. In order to make the magnetic resonance coupling based wireless EV charging system more viable, it is important to investigate the effect of surrounding metallic objects along with the operating parameters on the energy transfer efficiency of the wireless charging system.

In this paper, the effect of operating parameters such as the operating frequency, physical spacing, and proximal metallic object on the wireless energy transfer efficiency have been investigated through both simulations and experiments. The electromagnetic simulations have been carried out to validate the experimentally measured results. The analysis will help to get hold of a suitable design of efficient wireless charging system even in the presence of metallic object.

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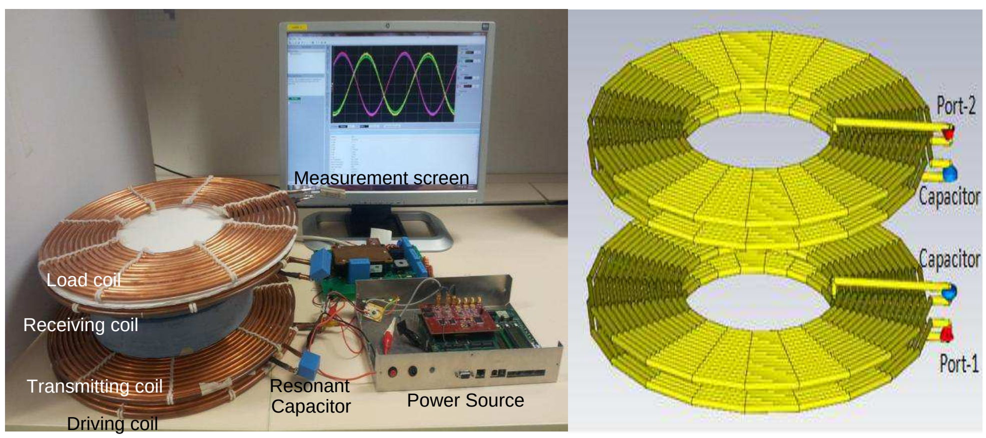
2. WIRELESS CHARGING DESIGN, OPERATING CONDITIONS AND MECHANISM

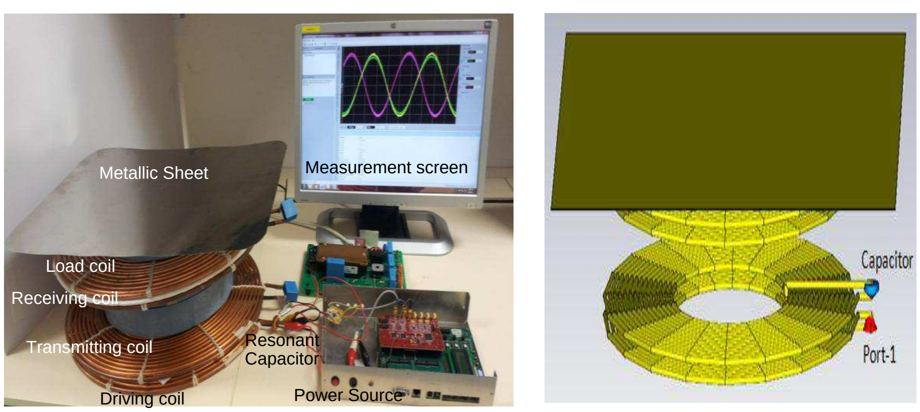
The experimental setup of wireless energy transfer system based on magnetic resonance coupling for charging of EVs is shown in Fig. 1(a). The wireless energy transfer system consists of a Radio Frequency (RF) power source, driving coil, transmitting resonant coil, receiving resonant coil, load coil and resistive load. The input RF power source is supplied to the driving coil. The transmitting coil is inductively coupled with the driving coil so that the transmitting coil is energized at its resonant frequency. The receiving coil is magnetically coupled at its resonant frequency with transmitting coil placed away from each other. The strong magnetic field coupling between the transmitting and receiving resonant coils enables the energy to be transferred from one coil to the other at the operating resonant frequency over a relatively large distance. The load coil is inductively coupled with the receiving coil. The received energy is then transferred to the load coil, and finally delivered to the load resistance connected across the load coil. For the analysis, the magnetic resonance-based wireless charging system is accurately modeled using electromagnetic simulation tool (CST Microwave Studio). The developed electromagnetic simulation model of the wireless energy transfer system is shown in Fig. 1(b). The simulated model is used to analyze the performance of the wireless charging system for EVs.

For both the simulation and experiment of resonant wireless energy transfer efficiency, the



(a) (b)

Figure 1. Magnetic resonance coupling based wireless energy transfer system for EV charging. (a) Experimental setup. (b) Electromagnetic simulation model.



(a) (b)

Figure 2. Magnetic resonance coupling based wireless energy transfer system with proximal metallic object. (a) Experimental setup. (b) Electromagnetic simulation model.

transmitting and receiving coils are wound to form spiral coils of 45 cm outer diameter, 14 turns, and 0.8 cm coil spacing. The spiral coils are made of copper wire with diameter 0.64 cm. Both the transmitting and receiving coils are connected with adjustable lumped capacitor to make the energy transfer system resonant. In order to analyze the effect of metallic object on the energy transfer efficiency, a metallic sheet (Aluminium metal) is placed above the load coil of the wireless energy transfer system. The size of the metallic sheet used in the experimental investigation and simulation model is $0.25\,\mathrm{m}^2$. Unless and otherwise specified, the metallic sheet is placed at 5 cm away from the load coil of the wireless energy transfer system. The experimental magnetic resonance coupling based wireless energy transfer system with the metallic sheet is shown in Fig. 2(a) and simulated model of the wireless energy transfer system in the presence of metallic sheet is shown in Fig. 2(b).

In the magnetic resonance coupling based wireless energy transfer system, electromagnetic resonance coupling entails an LC resonance. The LC resonance occurs at a particular frequency called resonance frequency at which the inductive reactance ($X_L = 2\pi f L$) is equal to the capacitive reactance ($X_C = 1/2\pi f C$), leads to the maximum energy transfer from the transmitting coil to receiving coil. The resonant frequency (f) of the transmitting and receiving coil is determined by the well known formula [3]

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The experimental energy transfer efficiency depends on the input supply power (P_{in}) and the output power (P_{out}) delivered to the load resistance connected across the load coil. The efficiency is given by [3]

$$\eta\,(\%) = \frac{P_{out}}{P_{in}} \times 100 \tag{2}$$

The wireless energy transfer is based on the strongly coupled magnetic resonance mechanism [3]. When the resonant transmitter and receiver coils are in the midrange proximity (distance equal to several times of resonant coil size) their near fields will strongly couple with each other. The strong magnetic field coupling between the resonant coils allows the energy to be concentrated at a specific resonant frequency to transfer from one resonating coil to the other placed away from each other even over a relatively far distance. This coupling mechanism enables the receiver resonant coil to capture energy efficiently from the magnetic fields generated by the resonant transmitting coil.

3. RESULTS AND DISCUSSION

The electromagnetic simulation is carried out for different physical spacing between the transmitting and receiving resonant coils of the wireless energy transfer system. The distance between the transmitting and receiving coils is varied from 5 cm to 15 cm vertically along the central axis of the coils. The simulated frequency characteristics of energy transfer efficiency for different vertical spacing between the transmitting and receiving resonant coils of wireless energy transfer system is shown in Fig. 3. It can be seen that the energy transfer efficiency reaches the maximum at a particular frequency. That frequency for which maximum energy transfer occurs is known as resonant frequency of the system. This means that the magnetic field generated by the transmitting coil is strongly coupled with receiving coil at that frequency. For the sample case of where the physical spacing is 12 cm between the transmitting and receiving resonant coils, the maximum energy transfer occurs with efficiency of 90% and the resonant frequency is 31.57 kHz. It is also observed that the energy transfer efficiency and the operating resonant frequency are different for different vertical separation distance between the transmitting and receiving coils. For each vertical separation distance between the transmitting and receiving resonant coils, the wireless energy transfer system has its own strongly coupled region that is an optimum operating frequency for which maximum energy transfer occurs.

The experimental frequency characteristic of energy transfer efficiency for different vertical distance between the transmitting and receiving resonant coils of wireless charging system is depicted in Fig. 4. The measurement is carried out for different vertical distances similar to the case of simulation. The maximum energy transfer efficiency is 90% for the measured case compared to 91% in the simulation at 12 cm physical spacing between the transmitting and receiving resonant coils for resonant frequency of 31.57 kHz. The simulated results are compared with the experimentally measured results. Both the

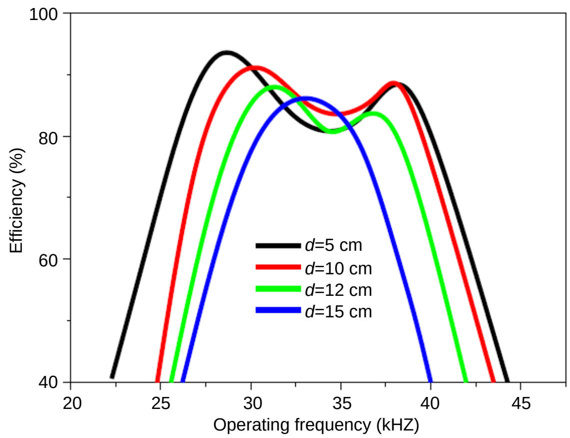


Figure 3. Simulated frequency characteristics of energy transfer efficiency for different vertical spacing between the transmitting and receiving resonant coils of wireless energy transfer system.

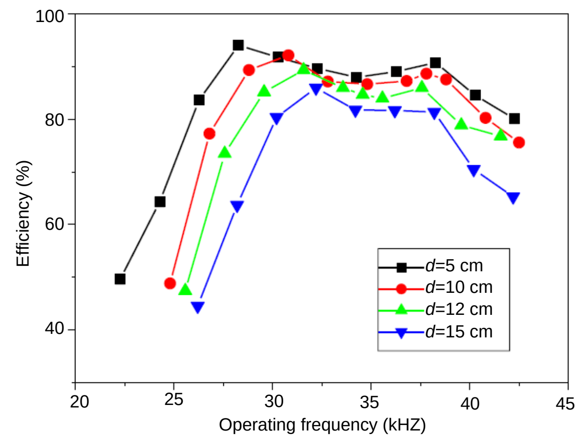


Figure 4. Measured frequency characteristics of energy transfer efficiency for different vertical spacing between the transmitting and receiving resonant coils of wireless energy transfer system.

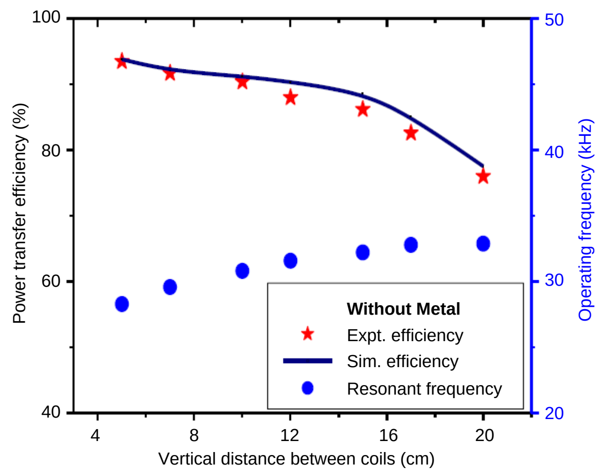


Figure 5. Both the simulated and experimental resonant frequency characteristics of optimum energy transfer efficiency of the wireless energy transfer system without metal plate.

simulated and experimental resonant frequency characteristics of optimum energy transfer efficiency of the wireless energy transfer system are illustrated in Fig. 5. It has been found that the relative error between the experimental and simulated energy transfer efficiency is about 1%, i.e., simulated results agree well with the obtained experimental results. The close agreement between the simulation and experimental results demonstrates the effectiveness of the electromagnetic simulation model used.

The effect of proximal metallic object on the performance of the wireless charging system for EVs has been investigated. Both the simulation and experimental measurement have been carried out in order to determine the effect of the proximal metallic sheet on the wireless energy transfer efficiency. The effect is studied for a metal sheet placed at a distance of 5 cm away from the receiving load coil of the wireless charging system. The characteristics of the optimum energy transfer efficiency in the presence of metallic plate corresponding to the resonant frequency for different vertical distance between the coils is shown in Fig. 6. It can be observed that the simulated results agree with the experimentally measured results. The energy transfer efficiency decreases drastically if the metallic object is placed near to the wireless energy transfer system. For the vertical distance of 12 cm between the transmitting and receiving resonant coils, the optimum energy transfer efficiency reduces from 90% to 57% at the resonant frequency of 31.57 kHz in the presence of metallic sheet. This is due to the change in resonant frequency

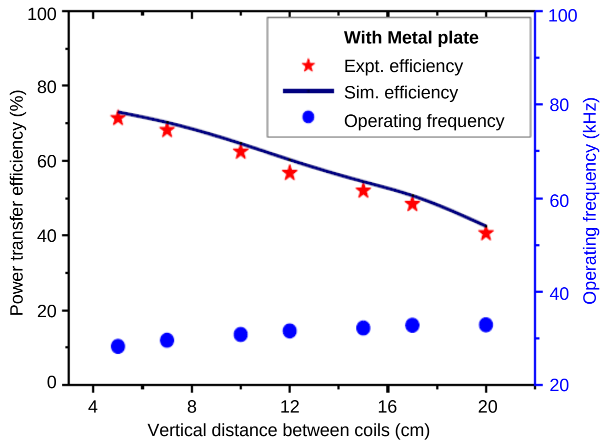


Figure 6. Both the simulated and experimental resonant frequency characteristics of optimum energy transfer efficiency of the wireless energy transfer system with metal plate.

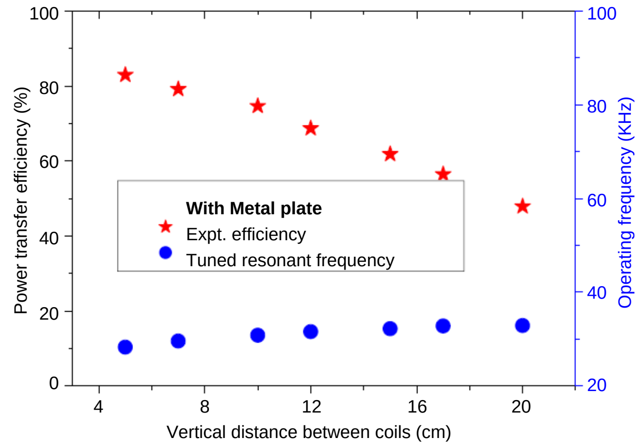


Figure 7. Measured frequency characteristics of optimum energy transfer efficiency with different vertical spacing between the coils in the presence of metallic plate.

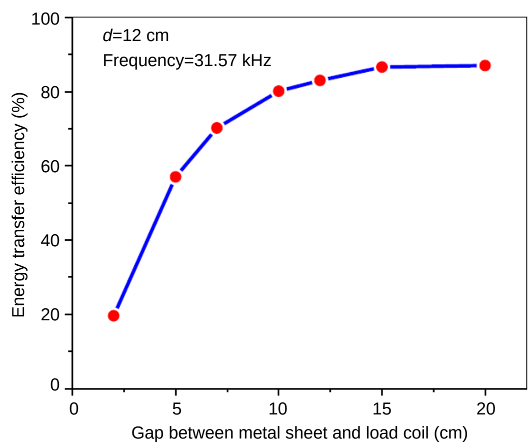


Figure 8. The experimental dependence of energy transfer efficiency on the physical spacing between the load coil and the metallic plate.

of the energy transfer system and decrease in mutual inductance between the coils. Experimentally, it is found that the resonant frequency of optimum energy transfer efficiency changes with the proximal metallic sheet at different vertical distance. The measured frequency characteristics of optimum energy transfer efficiency with different vertical spacing between the coils in the presence of metallic plate are shown in Fig. 7. It is found that the optimum energy transfer efficiency with the presence of metallic plate is improved from 57% to 63% by tuning the frequency from 31.57 kHz to the operating resonant frequency 32.27 kHz for the distance of 12 cm between the coils.

In order to maintain the optimum energy transfer efficiency of wireless charging system with the presence of metallic object, it is important to investigate the optimal physical spacing required between the proximal metallic plate and the receiving load coil of the wireless charging system. The effect is studied by varying the physical spacing between the metallic plate and the receiving load coil of the wireless energy transfer system for fixed vertical separation distance between the transmitting and receiving coils. The experimental dependence of energy transfer efficiency on the physical spacing between the receiving load coil and the metallic plate is depicted in Fig. 8. The energy transfer efficiency deteriorates drastically if the metal plate is placed very near to the load coil of the wireless system. The energy transfer efficiency increases with increase in physical spacing between the metal plate and load coil of the wireless energy transfer system. This is because the mutual inductance between the transmitting and receiving resonant coils reduces if the spacing between the metal plate and coil reduces. This leads to the reduction in coupling coefficient between the transmitting and receiving resonant coils. Hence the energy transfer efficiency reduces for the decrease in physical spacing between the metal plate and load coil of wireless energy transfer system. Experimentally, it is found that at the operating resonant frequency of 31.57 kHz and vertical distance of 12 cm between the charging coils, the wireless energy transfer system regain its original optimum efficiency for 15 cm physical spacing between the metal sheet and load coil.

4. CONCLUSIONS

The effect of surrounding metallic objects on the energy transfer efficiency of resonance-based wireless charging system has been investigated through simulation and experiment in this research work. The simulations are carried out to verify the experimental results, and the close agreement between them demonstrates the effectiveness of the electromagnetic simulation model used. It is observed that the energy transfer efficiency depends on the operating frequency, physical spacing between the transmitting and receiving coils and the metallic object in close proximity to the receiving coil. It is seen that the energy transfer efficiency of resonance based wireless energy transfer system reaches the maximum at the resonant frequency. If the system is detuned from the resonance, the energy transfer efficiency drops suddenly. The energy transfer efficiency with the corresponding resonant frequency is seen to be different for different vertical spacing between the coils. It is found that the energy transfer efficiency reduces dramatically if the metallic plate is placed in close proximity to the receiving coil of the wireless energy transfer system. In the presence of metallic sheet, the optimum energy transfer efficiency reduces from 90% to 57% at the resonant frequency of 31.57 kHz for 12 cm vertical spacing between the transmitting and receiving coils. The energy transfer efficiency can be improved by tuning the resonant frequency as it can be seen from the experiment that the operating resonant frequency changes with the gap thickness between the metal plate and receiving load coil of the system. These results show that the presence of the metallic object in the vicinity of the receiving coil has to be carefully considered for each possible usage scenario in order to maintain relatively large energy transfer efficiency of the wireless charging system for EVs.

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