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Analysis of an Inductive Coupling Wireless Power Transfer System with a Finite Element Method for Charging Applications of Electric Vehicles

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Abstract
With the development of technology, Wireless Power Transfer (WPT) systems have also started to be used in charging applications for electric vehicles. The basic methods of WPT systems are based on power transmission systems with laser, microwave, magnetic induction, and magnetic resonance. Factors such as the limited use of fossil fuels and environmental pollution have led researchers to see electric vehicles as a solution and to charge these vehicles with wireless systems. Most commercial wireless power transmission applications are currently limited to close contact transmission distances. There are challenges in increasing coverage, routing transmissions, and safely exploiting sufficiently strong electric fields. To provide power efficiently, highly directional transmitters must be used. Otherwise, with an omnidirectional transmission, only a small part of the transmitted power will reach the receiver. Especially in order to distribute power over long distances, it is often necessary to resort to radiation transfer methods that tightly combine electric and magnetic fields. In this study, important studies on WPT systems were investigated and examined. Then, a WPT transformer is modeled with the Finite Element Method based ANSYS-Maxwell-3D. The results obtained using the simulation method are presented in comparison with the research findings. Determining the efficiency of wireless power transfer used in electric vehicle charging applications is the expected result of the study.

1. Introduction

Wireless Power Transmission is the transmission of electrical energy through electric, magnetic or electromagnetic fields rather than wires or cables. Wireless power transmission can be used attractively in situations where it is dangerous or impossible to use interconnected cables. Wireless power transmission is widely used in electric vehicle charging systems, implantable medical devices such as artificial cardiac pacing, RFID tags, and many other applications. The basic concepts of wireless communication and wireless power transmission are very similar in that they use the same area and waves, but the main goal in wireless communication is to transfer data. In wireless communication, the transmitted power is not important as long as the signal-to-noise ratio of the received signal is acceptable. On the other hand, wireless power transmission aims to maximize power transmission efficiency and coverage while ensuring people's health and safety.

Most commercial wireless power transmission applications are currently limited to close contact transmission distances. There are two main challenges in increasing coverage: routing transmissions and safely benefiting from sufficiently strong electric fields. First of all, highly directional transmitters need to be applied to deliver power efficiently [1]. Otherwise, with an omnidirectional transmission, only a small part of the transmitted power will reach the receiver. Second, to distribute

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power over long distances, it is often necessary to resort to radiation transfer methods that tightly combine electric and magnetic fields [3]-[5]. Unfortunately, prolonged exposure to large electric fields causes serious injury to living tissues. Thus, safety concerns require small electric fields, while long-distance transmissions require strong emissions of electromagnetic waves [6].

To overcome the above problems, Disney-Research engineers have recently proposed a system that can safely transfer kW-level power from a room to mobile devices. The main contribution of this research is to provide a sufficient amount of power, taking into account safety concerns. For this purpose, by simulating the resonant electromagnetic mode of a metallic room by allowing current to flow through the walls, ceiling, and floor, the researchers produced uniform magnetic fields penetrating into the room.

To separate potentially harmful electric fields from magnetic ones, Disney engineers diverted the current through some discrete capacitors. In this way, the resonant frequency of the chamber is significantly lowered so that the cavity enters the deep sub-wavelength pattern. Working in the deep sub-wavelength regime, the cavity produces magnetic fields one hundred times stronger than the electric fields produced. In conclusion, the experimental results of the new method have shown that it can successfully avoid the harmful effects of large electric fields without sacrificing the transmit power.

Wireless power transfer systems are usefully used in many areas, such as charging electric vehicles (EV), depending on the developing technological developments. Wireless power transfer offers many such advantages to the user [7]. Among the earliest records of work to use a lot of power in wireless power transfer, it is known that it provided power to electric trains running in a mine in the Soviet Union in 1980 through wireless power transfer. It is possible to control large amounts of currents, which has rapidly developed wireless power transfer innovation [8].

There are three different charching methods hat are effectively used in electric vehicles: battery replacement, wired charging, and wireless (inductive) charging [8]. The advantage of inductive power transfer is its high efficiency and high-power capacity. It has also been the most commercially successful wireless power transmission technology. Its application areas include widely integrated circuits, biomedical devices, sensor networks, portable electronic products, and electric vehicles. High efficiency can be achieved by regularly adjusting the system efficiency, circuit resonances, and energy transfer distance. The distance can be further extended using intermediate resonant coils without significantly affecting efficiency. Due to its technological features, it can be concluded that an inductive power transfer system is a good solution to realize wireless power transfer for electric vehicle charging applications. In this paper, wireless power transfer methods for electric vehicles were examined, and a wireless power transfer circuit for inductive wireless power transfer for electric vehicles was modeled in the Finite Element Method (FEM) based ANSYS-Maxwell program, and results were obtained according to the technical data of the circuit.

2. Material and Method

An inductive power transfer system uses a non-radioactive magnetic field, typically in the kHz to MHz range, to affect the power transfer. Since there are resonances in the circuit, it is also called magnetic resonance. Two planar coils form a loosely coupled transformer called a magnetic or inductive coupler to create a magnetic field. Since there is a large air gap between the coils, their magnetic coupling is relatively low [9]. The basic idea of the inductive power transfer system used in the wireless charging system is based on the well-established Ampere's law of circulation and Faraday's law of induction. The basic structure of the system is shown in Figure 1 [10].

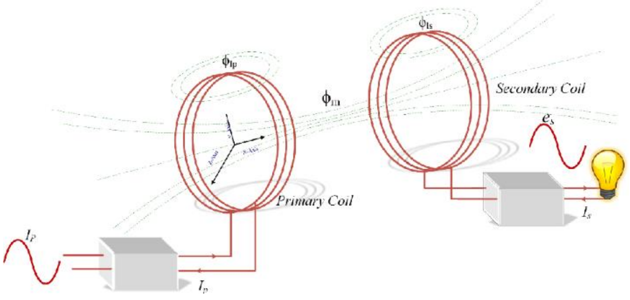

Figure 1. Structure of the inductive power transmission system

Figure 1 shows two coils connected by inductive coupling. Here, the subscript P and S denote the primary and secondary coil, respectively. The terms $\emptyset_m$, $\emptyset_{ip}$, and $\emptyset_{is}$ are mutual flux, primary leakage flux and secondary leakage flux, respectively. M, L_P and L_s are represent mutual inductance, self-inductance of primary coil and self-inductance of secondary coil, respectively. When a time varying current is applied to the primary coil, a time varying flux of the same frequency is produced in the region surrounding the primary coil. The strength of the magnetic field around a closed path is directly proportional to the current carried by the coil and can be found by Ampere's law. A generalized block diagram of the inductive power transmission system for EV battery charging can be drawn as in Figure 2 [11].

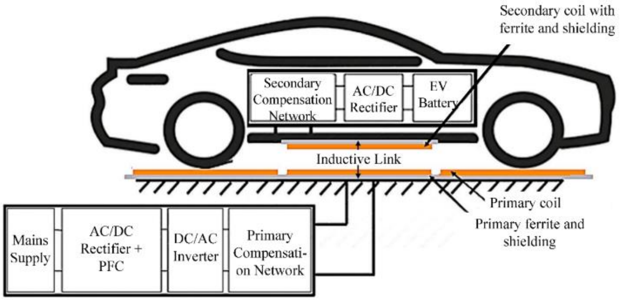

Figure 2. Block diagram of the inductive power transfer system for EV battery charging

Usually mounted under the vehicle, the receiving coil converts the oscillating magnetic flux fields into high frequency AC. The high frequency AC is then converted into a stable DC source used by the onboard batteries. Magnetic planar ferrite plates are used on both the transmitter and receiver sides to reduce any harmful leakage flux and improve the magnetic flux distribution [12]. The energy is then transferred to the vehicle side via the secondary coil, which is reciprocally connected to the primary coil via the flux produced in the air gap by the primary coil current [13]. The energy received by the secondary coil is then processed by the secondary compensation circuit, which is added to improve the power transmission capacity of the system [14]. Finally, the voltage received in this way is corrected to make it usable by the load [15].

In the case of using a magnetic induction system to wirelessly charge electric vehicles, a suitable air gap should be selected between the transmitter coil mounted on the road and the vehicle. Because of this large air gap, the leakage flux is very high, and the coupling coefficient remains constant at certain ranges. Such applications are classified as loosely coupled systems [16-19]. Weak connections in loosely coupled systems lead to poor power transmission. To improve coupling and compensate for leakage inductance, capacitive compensation is required in the primary and secondary windings.

2.1. Compensation Topologies

Compensator networks, which are capacitors, are made to resonate with the coil inductance, thereby creating a resonant inductive connection. Depending on the connection of the compensation capacitor in the primary and secondary windings, four types of resonant inductive connections can be identified. These are Serial-Serial (SS), Serial-Parallel (SP), Parallel-Serial (PS), and Parallel-Parallel (PP) connections as shown in Figure 3 [15].

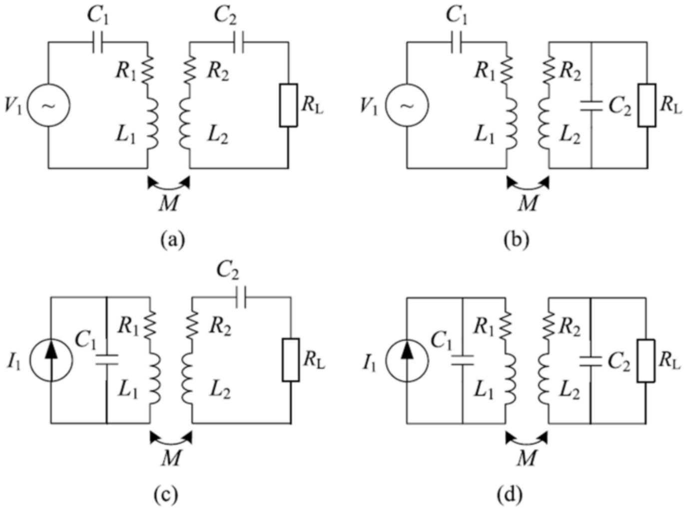

Figure 3. Compensation topologies

In this study, the Serial-Serial topology example is preferred. The Series-to-Series topology option allows selection of compensation capacitances based only on self-inductance, regardless of load and magnetic coupling. Therefore, in case of misalignments between coils, the system continues to operate under resonance despite the mutual inductance changes. Accordingly, the Serial-to-Serial topology becomes suitable for EV battery charging. A Series-Series resonant inductive connection is theoretically the best in terms of efficiency, number of components, less complexity of control, and cost, and therefore, in this study, a simulation study was carried out on a Series-Series inductively connected circuit.

The Figure 4 shows the equivalent circuit of a series-to-series compensated resonant inductive power transfer system. The primary side of the series-to-series compensated resonant inductive power transfer junction is powered by a voltage source full bridge inverter that converts direct voltage V_{DC} to high frequency alternating voltage V_{AB}. On the secondary side, a rectifier with capacitive filter C_{Cf} converts the high-frequency voltage into direct voltage V_0 and direct current I_0 required by the load R_0. The Series-Series topology acts as a current source when powered from the primary voltage source in ideal resonance condition. Therefore, a simple capacitive filter is sufficient. The full bridge inverter generates a square wave voltage V_A with an infinite number of harmonics. However, the Series-to-Serial inductive power transmission junction acts as a bandpass filter that blocks unwanted frequency components generated from the primary-fed power electronics converter. Therefore, the current through the inductive power transmission coupling is almost sinusoidal. This allows the first harmonic approximation method to be used to calculate the parameters of the Series-to-series-inductive power transmission connection.

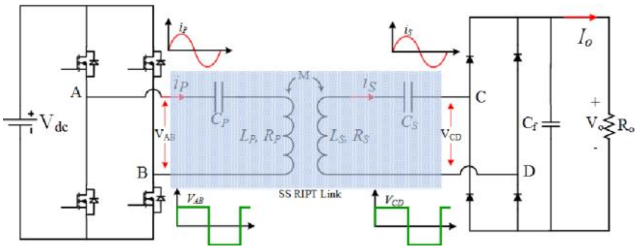

Figure 4. Equivalent circuit of Series-Series compensated resonant inductive power transfer system

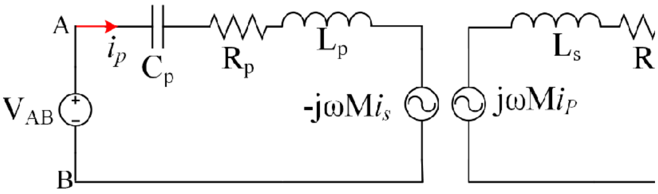

Figure 5. Simplified equivalent model of Series-Series inductive power transmission circuit

2.2. Calculation of Electrical Parameters

Figure 6 shows the block diagram and components of an SS-inductive power transfer based wireless charger. The aim is to calculate the parameters of the SS-inductive power transmission coupling (shown in the red dotted box) for a given load (battery).

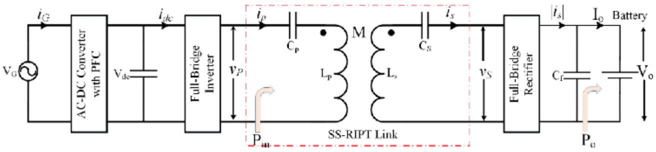

Figure 6. Block diagram of a SS-inductive power transfer based wireless charger

To simplify the calculation of the parameters of the SS-inductive power transmission coupling, the following assumptions are made:

- The efficiency of the SS-inductive power transmission link is assumed to be full. This assumption is valid since the value of the coil resistance is not known prior to the connection design and is therefore assumed to be negligible.
- Only the fundamental component of the input voltage V_P (first harmonic) and the output voltage of the SS-inductive power transmission link are taken into account, and higher order harmonics are neglected. In other words, the quality factor of the primary and secondary circuit is considered high to obtain sinusoidally varying primary and secondary currents.
- All switching elements are considered ideal with zero commutation time (instant on and off). In other words, all converters are assumed to be fully efficient.
- The magnitude of the input voltage to the SS-inductive power transmission connection, ie V_P, is considered equal to the grid (supply) voltage magnitude V_S. This assumption is valid as there is usually a power factor correction stage between the grid supply and the full bridge inverter. At this stage, the DC junction voltage of the full-bridge inverter can adjust V_{DC} so that V_P is equal to the grid voltage.
- Ideal resonance is assumed on the primary and secondary sides. Let the desired output power be P_0. Because the load is a battery pack, the charging voltage is known as defined by the manufacturer of the battery pack. If V_0 denotes rated charging voltage or output voltage, DC resistance (battery resistance) R_0 can be calculated by equation (1).

$$R_0 = \frac{V_0^2}{P_0} \tag{1}$$

The AC equivalent of a DC resistive load with a diode rectifier and a capacitive output filter can be given by equation (2). This is the value of the resistance seen from the secondary side of the SS-inductive power transmission link.

$$R_0 = \frac{\pi}{8}\frac{V_0^2}{P_0} \tag{2}$$

The secondary voltage V_S is a square wave due to the capacitive output filter. The RMS value of the principal component V_S can be given by equation (3). The RMS value of secondary current i_S, can be calculated by equation (4).

$$V_{S_{rms}} = \frac{2\sqrt{2}V_0}{\pi} \tag{3}$$

$$I_{S_{rms}} = \frac{V_{S_{rms}}}{R_L} \tag{4}$$

Assuming that V_P is equal to the mains voltage V_S, the RMS value of the primary current can be given by equation (5).

$$I_{P_{rms}} = \frac{P_{in}}{V_{P_{rms}}} \tag{5}$$

Once the values of the primary and secondary currents are known, the mutual inductance value for the desired amount of output power can be derived by applying Kirchhoff's voltage law equation on the secondary side of the SS-inductive power transmission junction. From Figure 8, it can be written as equation (6) at the resonant frequency.

$$\left| j\omega_0 M i_P \right| = R_L \left| i_S \right| \tag{6}$$

The secondary inductance is calculated from the secondary quality factor Q_S. As mentioned earlier, the value of Q_S should be chosen as a higher value may complicate the tuning of the system and will generate harmonics in a lower current and voltage waveform. Equation (7) gives the required secondary inductance value.

$$I_S = \frac{Q_S R_L}{\omega_0} \tag{7}$$

$$Q < \frac{1}{Q_S}\sqrt{1-\frac{1}{4Q_S^2}} \tag{8}$$

Equation (8) can calculate the minimum air gap between the primary and secondary coils. Also, the coupling factor must be well chosen for high efficiency. This is an important difference between a loosely coupled system, such as an SS-inductive power transmission system, and a closely coupled system, such as power transformers, if possible. Once the k value has been decided, the primary inductance value can be calculated using equation (9).

$$L_P = \frac{M^2}{L_s k^2} \tag{9}$$

2.3. Design of Rectangular WPT Transformer Model

In this section, the design of rectangular coil transformers using ANSYS-Maxwell software is explained. In this study, a unique rectangular coil arrangement is considered, as shown in Figure 7. The rectangular transformer model consists of a coil of circular cross section wound in a rectangular shape. The side lengths of the rectangular transformer model are taken to be equal to the diameter of the circular transformer model. The dimensions of the rectangular transformer model are given in Table 1.

Table 1. Dimensions of rectangular WPT transformer

Parameter	Receiver coil	Transmitter coil
Turn Number	42	24
Material thickness	2 mm	2 mm
Coil dimension	(395x395) mm	(395x395) mm

The primary and secondary winding numbers of this model are the same as the circular transformer model. Figure 7 shows the coreless circular transformer coils.

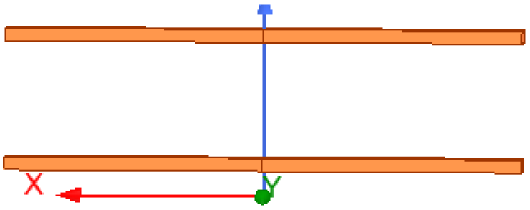

Figure 7. Coreless transformer model

3. Results and Discussion

The system's circuit was installed on the Ansys Simplorer interface, the coils were installed on the Maxwell 3D interface, and the WPT system was analyzed by simulating the two programs. The input, output power and efficiency of the system are observed. The co-simulation circuit of the WPT system is shown in Figure 8.

The ANSYS/Workbench model shown in Figure 9 was used to make the inductance calculations of the system and the analysis of the variation of the mutual inductance with respect to distance. This model calculates the input inductance of the system, the capacitance value that meets the resonance condition, and the quality factor by analyzing the mutual inductance in the desired distance range. Thus, transmission power and efficiency can be interpreted more easily.

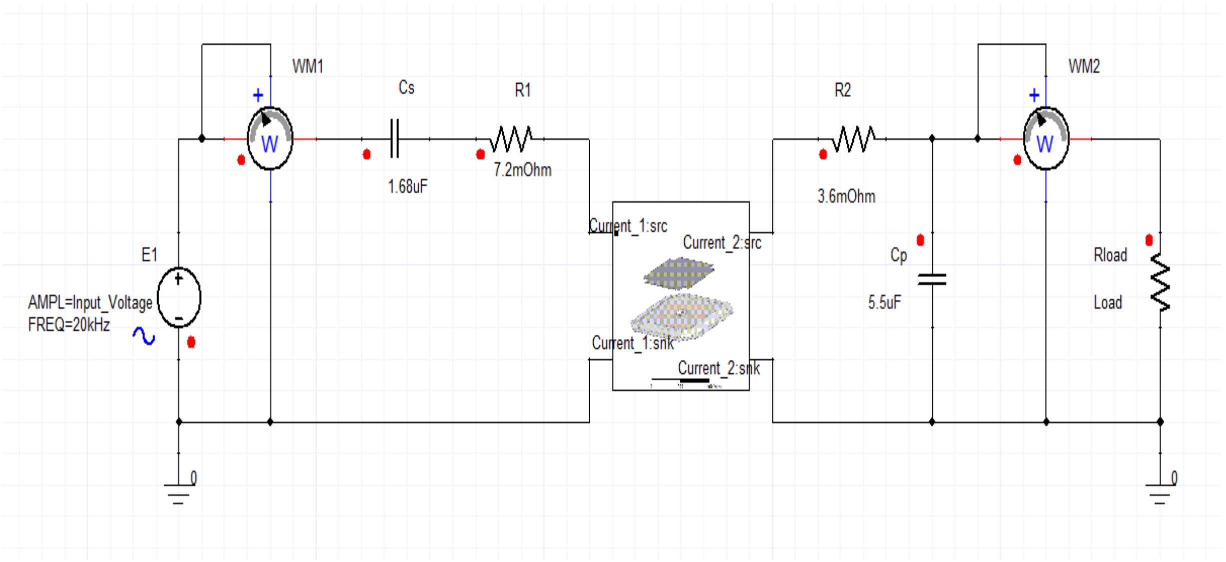

Figure 8. WPT co-simulation circuit

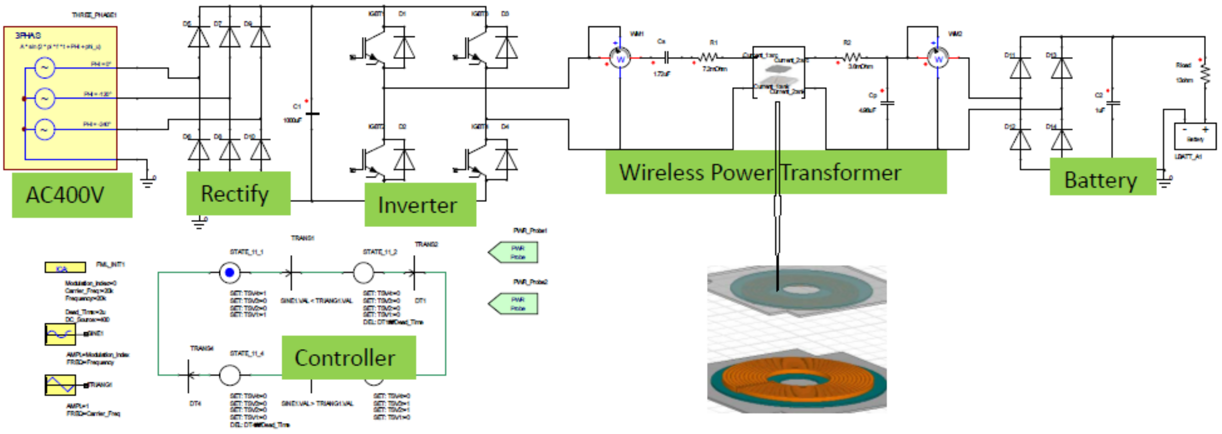

Figure 9. Inductance analysis and mutual inductance ANSYS model

The results obtained from the simulation were compared with the mathematical results. The results obtained for simulation and calculated values are presented graphically. The variation of the coupling coefficient with respect to the air gap distance is given in Figure 10.

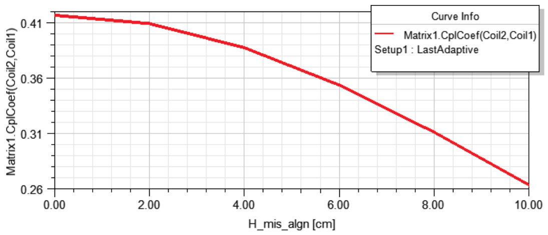

Figure 10. Coupling coefficient graph of the WPT system

The graph of the mutual inductance change is also given in Figure 11. The magnetic flux distribution between the windings is given in Figure 12. The values of the results obtained depending on the distance variation are presented in Tables 2 and 3.

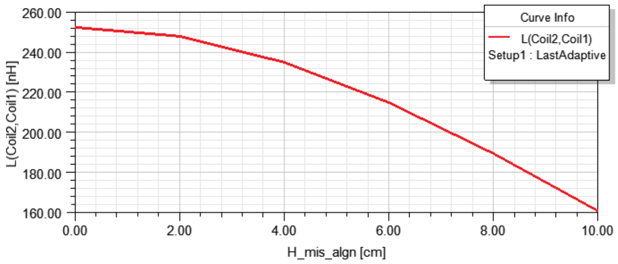

Figure 11. Variation of mutual inductance according to air gap distance

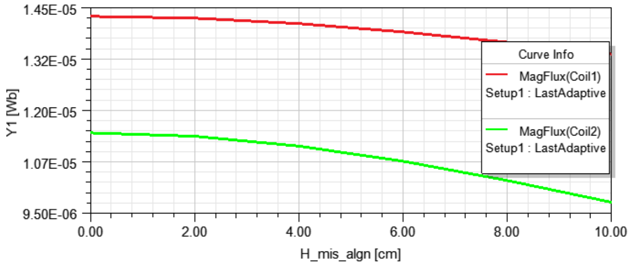

Figure 12. Magnetic flux distribution

Table 2. Coupling coefficient results

Distance (cm)	k
0	0.416
2	0.409
4	0.387
6	0.353
8	0.311
10	0.263

Table 3. Mutual inductance results

Distance (cm)	Mutual Inductance (nH)
0	252.288
2	247.851
4	234.912
6	214.867
8	189.533
10	160.946

The wireless power transfer method can be used in many different systems, including electric cars.. The simulated circuit topology is the most commonly used series-to-series topology for electric vehicles. A full-bridge inverter circuit is used to convert the rectified voltage to high-frequency AC current after the grid voltage. In this study, the efficiency obtained with a 10 cm air gap between two opposing coils at a 20 kHz operating frequency was calculated to be approximately 92.6%. In addition, the improvement of the system design is possible with the four-coil system or the compensation structures derived from the classical topologies and will increase the efficiency in common. In general, the overall performance of the circuit in terms of power and efficiency is determined by the compensation circuit on the secondary side of the topologies. Therefore, it is both experimentally and theoretically known that the efficiency decreases according to the order of Series-Series, Series-Parallel, Parallel-Serial and Parallel-Parallel. Because of its high-power output, a car to be charged is preferably charged using SS compensation or SP. In small powerful devices, generally Parallel-Parallel or Parallel-Serial topologies are preferred. In this study, the SS inductive power transmission topology was used because it is aimed to provide constant power in electric vehicles and to maximize power transfer efficiency.

4. Conclusion and Suggestions

With inductive power transfer technology, electrical power can be sent wirelessly in a safe and efficient way. Current research on Inductive Power Transfer focuses primarily on voltage source inverter technology, whereas current source technology has received very limited attention. This study also provides a comprehensive overview of compensation networks and converter topologies used in current inductive power transfer systems. Since wireless power transfer is carried out over loosely coupled windings, power transfer efficiency is expected to be low. Efficiency should be increased by using compensation topologies. In Inductive Power Transfer systems, power is transferred between the coils in the system. In inductive power transfer, the coils are not around the same core like in transformers, but there is a distance between the coils that makes the system loosely coupled. The concept of resonance is used to transfer power efficiently. There are four classical topologies, and there are also new proposed topologies derived from these topologies. It uses the series-series compensation topology, which is adequate for battery charging applications. The results obtained in the Series-Series topology show that the capacitor voltages increase very much and require special capacitors for this. In this study, WPT based on Inductive Power Transfer system was designed and analyzed. It was observed that the efficiency was high.

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Contributions of the authors

The contribution rate of the authors is equal.

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