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Research article

Analysis and experimental verification of efficiency parameters affecting inductively coupled wireless power transfer systems

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ABSTRACT

Wireless power transfer (WPT) provides a safe and independent transfer of energy without the constraints of cables. The most suitable method for wireless charging of Electric Vehicles (EVs) is magnetic resonance coupling, which transfers energy in the near field. In this study, the effect of quality factor on the wireless charging system of an EV is investigated. After determining 85 kHz frequency, 20 kW power and 150 mm inter-coil distance, the design of the WPT system was realised according to the quality factor. It was observed that the quality factor affects the efficiency, critical air gap and voltage stress on capacitors. As the quality factor increases, the critical air gap increases and longer distances can be transmitted efficiently. However, as this factor increases, the voltage stress on the capacitors also increases. In this study, the critical air gap was determined according to the quality factor. Although high quality factor increases efficiency at high air gaps, it decreases efficiency in applications where air gaps are close. In fact, increasing the quality factor by increasing the inductance means increasing the internal resistance and this has been observed to reduce the maximum efficiency. In this study, the effects of Q factor on transmission power and transmission efficiency are investigated through experimental study and simulation.

1. Introduction

The development and diversity of electric vehicle charging systems is a really important topic. Wireless Power Transfer (WPT) systems offer many advantages by utilising wireless transmission for charging electric vehicles. The fact that WPT eliminates cable clutter makes the charging process more user-friendly. Furthermore, these systems are used in areas other than electric vehicles, and have great potential for wireless charging of mobile devices such as biomedical devices, mobile phones and unmanned aerial vehicles. High energy efficiency and low carbon footprint are important goals to increase the sustainability of electric vehicles. In this context, wireless charging systems can help users to charge their electric vehicles more easily and efficiently. Studying the interaction between electric motors, electromagnetic fields and wireless power transfer can make an important contribution in this field [1–3]. The battery of an electric vehicle can be charged in two ways, wired and wireless. WPT systems save the charging system from the cable complexity caused by wired charging. It also offers a more reliable and practical solution than wired charging. WPT systems are used in many different areas such as biomedical devices, mobile phones and unmanned aerial vehicles besides electric vehicles [4,5].

Energy transfer with WPT can be achieved in many ways such as microwave, capacitive coupling and inductive coupling. The methods vary according to the application areas. The purpose of wireless charging for electric vehicles is to efficiently transfer high power in the near field. The most suitable method for these applications is magnetic resonance coupling [6]. The wireless charging

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system for EVs is presented in Fig. 1.

WPT technology using magnetic resonance coupling allows power transfer through magnetic connections between two coils without physical electrical connections. Unlike the classical induction method, capacitors are connected to the transmitting and receiving coils. These capacitors provide compensation in the transmitter and receiver system and thus energy is transferred efficiently. To ensure full compensation, the WPT system must operate at the resonant frequency. It is important to follow the resonant frequency for high efficiency under all conditions. In addition, if the resonant frequency is desired to remain constant in applications, resonance can be achieved by changing the value of the capacitors [7,8]. There are various topologies according to the way capacitors are connected to the coils. Series-Series (SS) topology is the most efficient and simple WPT topology and can operate in a wide load range [9].

The efficient transmission of energy in a magnetic resonance coupling system depends on the operating frequency, coil size, distance between coils and alignment of the coils [10]. Increasing the distance between the coils or misalignment reduces the coupling factor and may cause a decrease in efficiency. It is important to estimate the position of the transmitter and receiver relative to each other and to ensure alignment [11]. Increasing the frequency or coil size allows WPT to be efficient even at higher air gaps and misalignment [12,13]. However, increasing the frequency may also increase the losses due to skin and proximity effects. For this reason, Litz wire is often preferred in high frequency applications [14]. There are studies using coaxial cable structures in WPT. High efficiency has been achieved in WPT with high quality factor coaxial resonator structure [15]. In WPT applications, coupling coefficient, quality factor and frequency are the most important parameters to realise maximum energy transfer.

In this study, the effect of quality factor on the wireless charging system of an EV is investigated. After determining the optimal parameters for WPT, it is shown that the quality factor affects the efficiency, critical air gap and voltage stress on capacitors. Increasing the quality factor improves the critical air gap, resulting in more efficient transmission over longer distances. However, it also increases the voltage stress on the capacitors. Therefore, the choice of quality factor should be carefully evaluated depending on the specific application requirements. In this study, circuit modelling, coil design and magnetic analysis were performed using Ansys Maxwell-3D. The contributions of this study are the design of a transceiver for charging a battery-based electric vehicle with a capacity of 20 kW, the selection of the optimal compensation topology suitable for the battery charging condition of the developed WPT system, the establishment of the optimal design method of the compensation topology and its experimental verification.

2. Material and method

In magnetic induction WPT systems, energy is transferred by magnetic coupling using coils. The mutual inductance between the receiving and transmitting coil directly affects the efficiency. Efficiency tends to be high when there is a strong connection. On the other hand, lower coupling usually results in lower efficiency. In order for this structure to operate at lower coupling factor, magnetic resonance coupled WPT systems are used. Resonance is provided by capacitors connected in series or parallel to the coils. SS topology is a simple and effective configuration that is frequently used in WPT applications. The WPT circuit using SS topology is given in Fig. 2.

Where R_1 and R_2 are the internal resistance of the transmitter and receiver systems, respectively. V_1 is the input voltage, I_1 is the input current and I_2 is the output current. L_1 and L_2 are the inductances of the transmitting and receiving coils respectively. Lm is the mutual inductance and R_L is the load impedance. C_1 and C_2 are the capacitances of the transmitter and receiver respectively. The

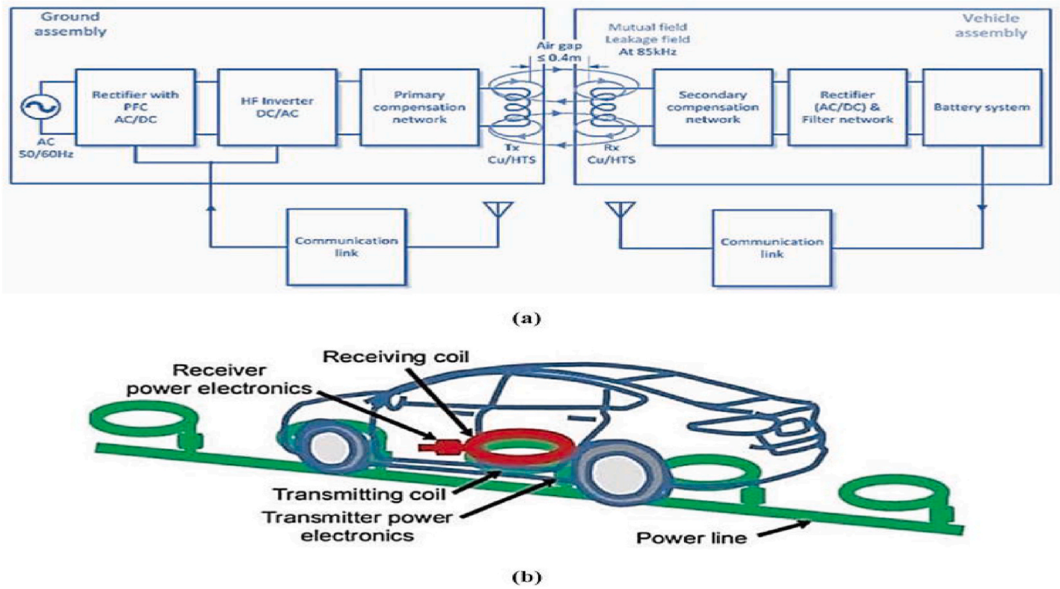

Fig. 1. a) Block Diagram, b) WPT system for Electric Vehicle.

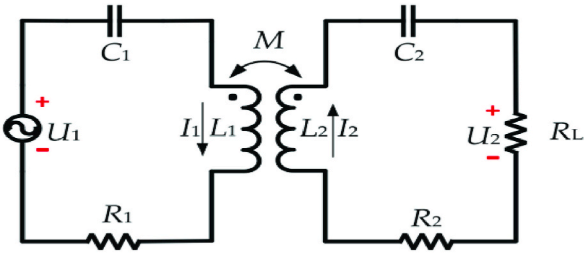

Fig. 2. Equivalent circuit of the WPT system using SS topology.

natural angular frequency of the resonator is shown in equation (1) and the quality factor is given in equation (2).

$$\omega_0 = \sqrt{\frac{1}{LC}}, \tag{1}$$

$$Q = \sqrt{\frac{L}{C}}\ \frac{1}{R} = \frac{L\omega_0}{R}, \tag{2}$$

where L, R, Q and C are the inductance, internal resistance, quality factor and capacitance of the resonator respectively. ω_0 is the natural angular frequency. The mutual inductance between the transmitter and receiver coil depends on the coupling factor and the self-inductance of the transmitter and receiver. The mutual inductance is given in equation (3).

$$L_m = k\sqrt{L_1 L_2}, \tag{3}$$

where k is the coupling coefficient. The equivalent impedance and efficiency for SS topology are given in equations (4) and (5) respectively.

$$Z_{Eq} = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + \frac{{L_m}^2\omega^2}{j\omega L_2 + \frac{1}{j\omega C_2} + Z_0 + R_2}, \tag{4}$$

$$\eta = \left(\frac{j\omega L_m}{j\omega L_2 + \frac{1}{j\omega C_2} + R_L + R_2}\right)^2 \times \frac{R_L}{Z_{Eq}}. \tag{5}$$

In a WPT system with magnetic resonance coupling, the efficiency does not change even if the mutual inductance decreases up to the critical mutual inductance. After falling below the critical mutual inductance, the efficiency starts to decrease rapidly. The critical mutual inductance depends on the natural angular frequency, load impedance and internal resistance. The critical mutual inductance is calculated by equation (6). As in Equation (7), if Lm is below the critical mutual inductance, the efficiency of the WPT system decreases. If Lm is above the critical mutual inductance, as in Equation (8), high efficiency is achieved in the WPT, but the resonant frequency is bifurcated.

$$L_{m_{Critical}}^2 = \frac{R_L^2 - R^2}{\omega_0^2}, \tag{6}$$

$$L_m^2 < \frac{R_L^2 - R^2}{\omega_0^2}, \tag{7}$$

$$L_m^2 > \frac{R_L^2 - R^2}{\omega_0^2}. \tag{8}$$

The internal resistance of the coil depends on the length and thickness of the wire and the conductivity of the conducting material and is calculated by equation (9).

$$R = \rho\frac{l}{s}, \tag{9}$$

where s is the surface area of the conductor, ρ is the conductivity coefficient and l is the length of the conductor. One of the important concepts in wireless power transmission systems is the figure of merit, which is calculated by equation (10).

$$U = \frac{\omega L_m}{\sqrt{R_1 R_2}} = k\sqrt{Q_1 Q_2}, \tag{10}$$

where U is the merit figure. Q1 and Q2 are the quality factors of the giver and receiver respectively. Efficiency can be increased by increasing the merit figure. In order to increase the merit figure, the quality factor or the connection factor must be increased. The optimum efficiency depending on the figure of merit is calculated by equation (11).

$$\eta_{opt} = \frac{U^2}{1 + \sqrt{1 + U^2}}, \tag{11}$$

where ŋ is the optimum efficiency. Equations (2), (10) and (11) show that the self- and mutual inductance of the coils have a significant effect on the efficiency. The circular planar spiral coil is shown in Fig. 3.

Where W is the wire diameter, S is the gap between the wires, D_0 is the outer diameter of the coil and D_i is the inner diameter of the coil. The self-inductance of a circular planar spiral coil can be calculated by Wheeler's formula and is given in equation (12) [16].

$$L = \frac{N^2(D_o - N(W + S))^2}{16D_o - 28N(W + S)} \frac{39.37}{10^6}. \tag{12}$$

2.1. Components of a wireless charging system

In this study, the main components of a wireless charging system are analyzed. One of these components is mounted on the road and the other is mounted on the bottom of the car. The transmitter component is fixed to the road. The moving part of the WPT system is fixed to the car. The transmitting component generates a magnetic flux at high frequency. This magnetic flux is converted by magnetic induction with the receiving coil into electrical energy which is used to charge the electric vehicle battery. A simulation of two representative vehicles charged by wireless charging is presented in Fig. 4. One of these vehicles has one receiver and the other has two receivers [13].

2.2. Compensation topologies

Wireless Power Transfer (WPT) is a technology that enables the transmission of electrical energy from a power source to an electrical load without any physical connection. Compensation topologies in WPT play a crucial role in achieving efficient power transfer. Here are some common compensation topologies used in WPT.

1. Capacitive Compensation
   - In capacitive compensation, a capacitor is connected in series or parallel with the coil of the transmitter or receiver.
   - This helps in compensating for the reactive components in the system, improving the power factor and overall efficiency of power transfer.
2. Inductive Compensation
   - Inductive compensation involves the use of an additional coil, either in series or parallel with the primary coil.
   - This helps in tuning the system to the resonant frequency, maximizing the power transfer efficiency.
3. Resonant Compensation

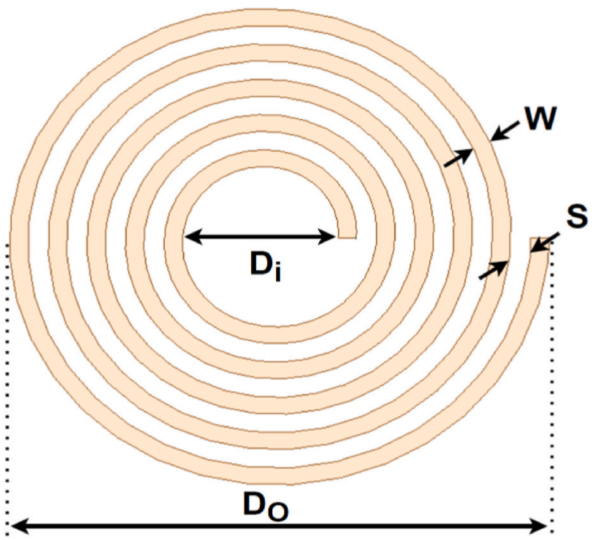

Fig. 3. Circular planar spiral coil.

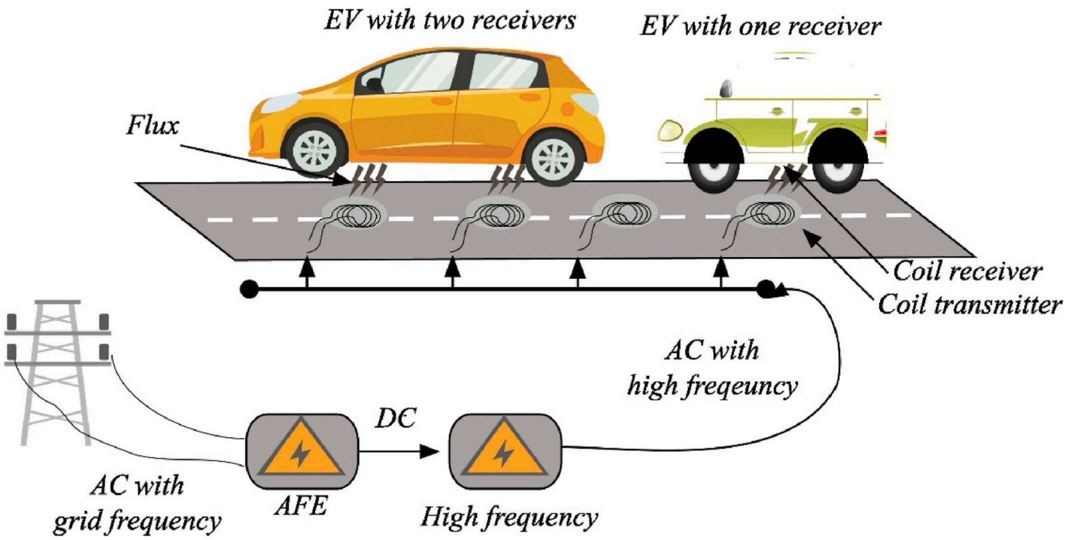

Fig. 4. Two representative vehicles charged by wireless charging.

- Resonant compensation involves the use of resonant circuits, such as series or parallel LC circuits, to achieve resonance between the transmitter and receiver coils.
- This resonance allows for efficient energy transfer and minimizes losses.

4. Impedance Matching Networks
   - Impedance matching networks are employed to ensure that the impedance of the source matches the impedance of the load.
   - This helps in minimizing the reflection of power back to the source, optimizing power transfer.
5. Frequency and Phase Control
   - Adjusting the frequency and phase of the transmitted signal can be used for compensation.
   - This technique helps in achieving resonance and maintaining efficient power transfer under varying conditions.
6. Adaptive Compensation
   - Adaptive compensation techniques involve dynamically adjusting parameters based on the real-time operating conditions.
   - This can include automatic tuning of resonance frequency or adapting compensation strategies to environmental changes.
7. Feedback Control Systems

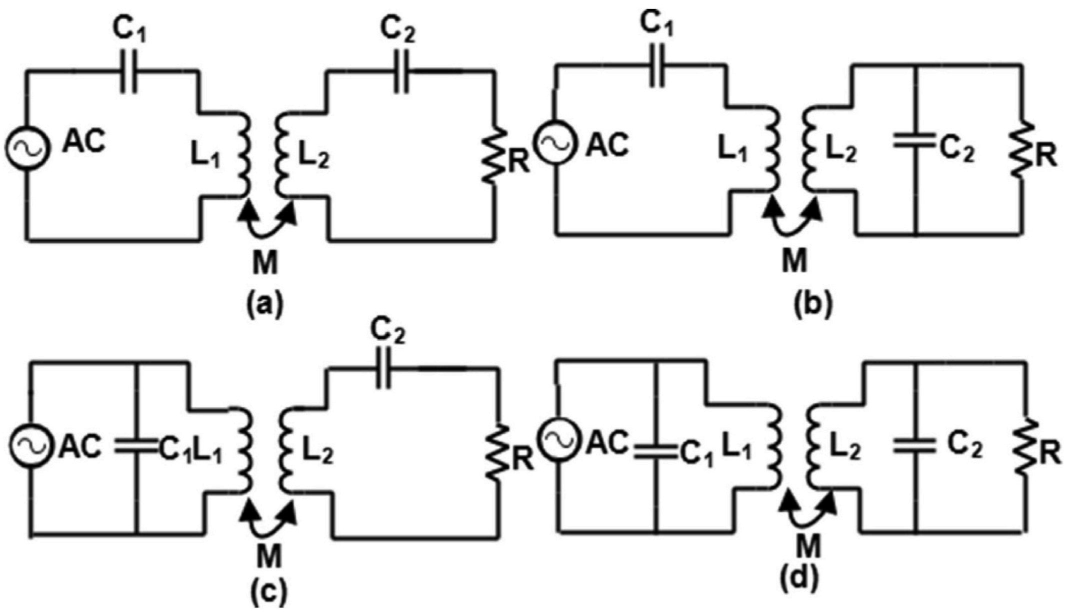

Fig. 5. WPT topologies: (a) SS, (b) SP, (c) PS, and (d) PP.

- Closed-loop control systems can be employed to monitor the performance of the WPT system and adjust compensation parameters accordingly.
- This ensures stability and optimal power transfer efficiency.

It's important to note that the choice of compensation topology depends on the specific requirements of the WPT system, such as distance between coils, power levels, and environmental factors. The wireless power transfer (WPT) technologies employed in the charging system include four resonant circuit topologies. Series-Serial (SS), Series-Parallel (SP), Parallel-Serial (PS), and Parallel-Parallel (PP) are the topologies, assuming that the connection can be either series (S) or parallel (P) with the coil. Fig. 5 displays these topologies.

2.3. Inductive power transfer

Wireless Power Transfer (WPT) systems involve inductive power transfer, which is an essential concept. As an electrical and electronics engineer, you might be familiar with this topic. Inductive power transfer allows the wireless transmission of energy using two coils. The working principle of inductive power transfer is essentially creating a magnetic connection between a primary coil (transmitter) and a secondary coil (receiver). The primary coil is powered by a source and generates a magnetic field. The secondary coil captures this magnetic field and converts it into electrical energy. This technology is crucial for applications such as electric vehicle charging stations, wireless charging for electronic devices, and medical devices. The equivalent circuit for inductive power transfer is given in Fig. 6.

2.4. WPT design

The WPT design is based on SEA J2954, the wireless charging standard for electric vehicles [17,18]. According to the standard, the frequency should be between 79 kHz and 90 kHz and a common frequency band of 85 kHz has been determined. In order to examine the effects of the quality factor, a WPT system with quality factor for different distances was designed. The internal resistances and resonant capacitors of the coil were calculated. Using Ansys Maxwell simulation, the 20 kW transceiver in this study is constructed by examining the worldwide standard "IECTS61980-3″ that was established by the IEC [19,20]. The WPT3 level reference, the maximum power handling capability among the current international standards, is used for Maxwell modeling in order to strengthen the dependability of the Maxwell simulation-based modeling. Consistency between the modeling findings and WPT3 level reference parameters was confirmed. A 20 kW class transceiver was predicted and designed using the WPT3 level as a guide, based on the reliability that was supplied. This WPT transceiver's horizontal and vertical separation distances between the transmitter and reception pads are determined by the (0, 0) alignment, which is a standard condition applied to all phases of the WPT1/WPT2/WPT3 international standard. The chosen criteria are X axis ±75 mm, Y axis ±100 mm, and Z spacing 110 mm. The design specifications of the 20 kW class transceiver, estimated and designed using the WPT3 stage reference, are shown in Table 1. The 20 kW class transceiver model, which was created using the WPT3 level reference model, is seen in Fig. 7.

Additionally, the transceiver's winding count matches that of the WPT3 stage reference design result. Kapton litz wire is used in its construction for insulation and heat resistance. The designed equivalent circuit and WPT system are given in Figs. 8 and 9.

3. Result and discussion

The transceiver parameters and Maxwell modeling outcomes derived from the hardware manufactured in accordance with Table 1 are listed in Table 2. Mutual inductance is M, coupling coefficient is k, and the self-inductances of the transmitter and receiver sides are

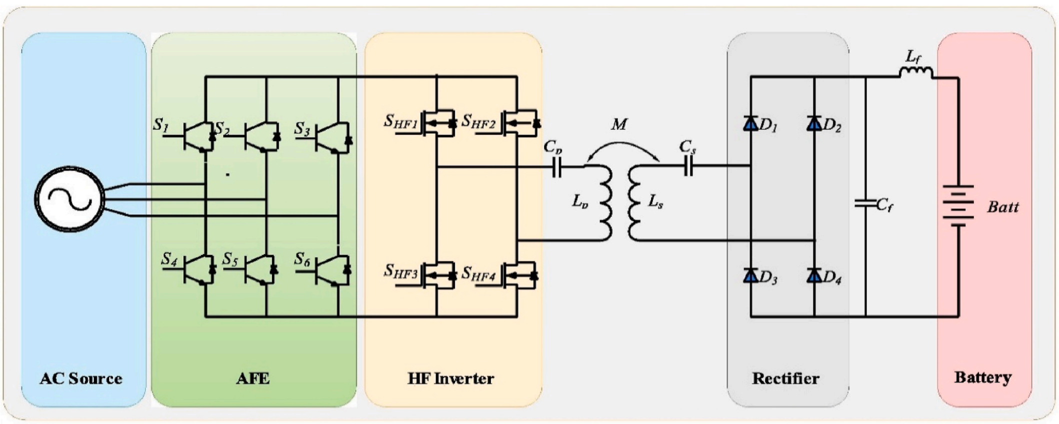

Fig. 6. Structure of inductive power transmission system.

Table 1
Designed transceiver parameter.

	Reference Model		20 kW Model	
Core	TX- Transmitter 650x510x5 (mm)	RX- Receiver 284x284x5 (mm)	TX- Transmitter 590x590x5 (mm)	RX- Receiver 395x395x5 (mm)
Winding	2 parallel 8 Turn	 10 Turn	2 Paralel 8 Turn Litz wire	 10 Turn

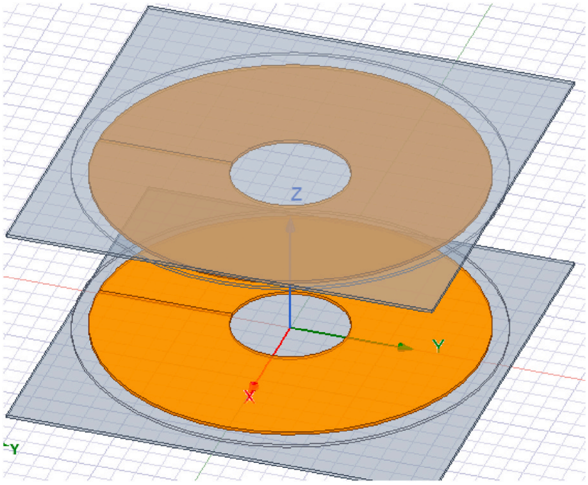

Fig. 7. WPT model.

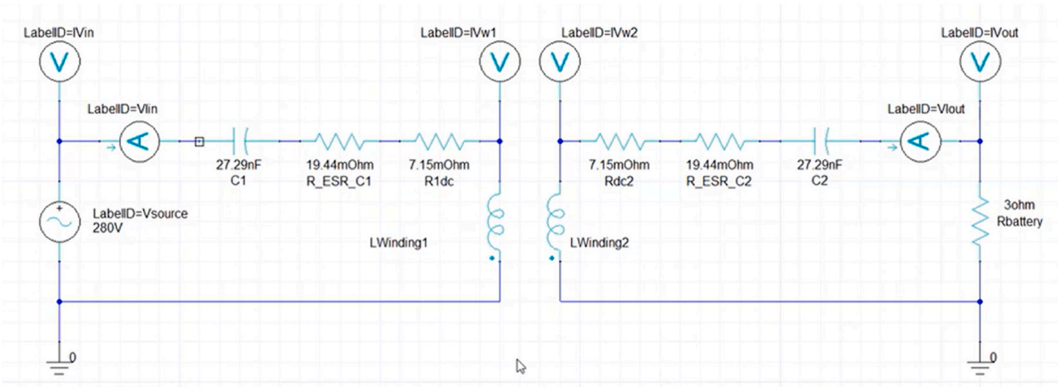

Fig. 8. Equivalent circuit system.

L_P and L_S.

Depending on the alignment conditions, there is little difference in the transmitting and receiving sides' self-inductance. However, the mutual inductance and coupling coefficient differ significantly. The range of the coupling coefficient is 0.1987–0.3096. There is virtually little difference between the hardware specifications and the results of the Maxwell modeling. Under the alignment (0, 0) condition, the self-inductance is kept to the measured value, and the IPT system analysis is carried out just taking the coupling coefficient and mutual inductance variation into account for each alignment. A paramagnetic material with high conductivity and low magnetic permeability, like aluminum, should be put in the transceiver to address the issues of significant leakage flux and electromagnetic interference [17]. The cause of this interference is that an aluminum plate will produce an eddy current when it comes into contact with a magnetic flux. The direction of the magnetic flux produced by this eddy current drives the removal of the errant magnetic flux. Nevertheless, the values of Lp, Ls, k, and M drop as the overall magnetic flux diminishes. The transceiver parameters for each alignment are shown in Table 3, which was obtained from the system that had the aluminum plate installed. The WPT1/WPT2/WPT3 reference design's common size is used to determine the aluminum plate size. Table 3 demonstrates that, in comparison to the comparable values in Table 2, the values of Lp, Ls, k, and M are lower.

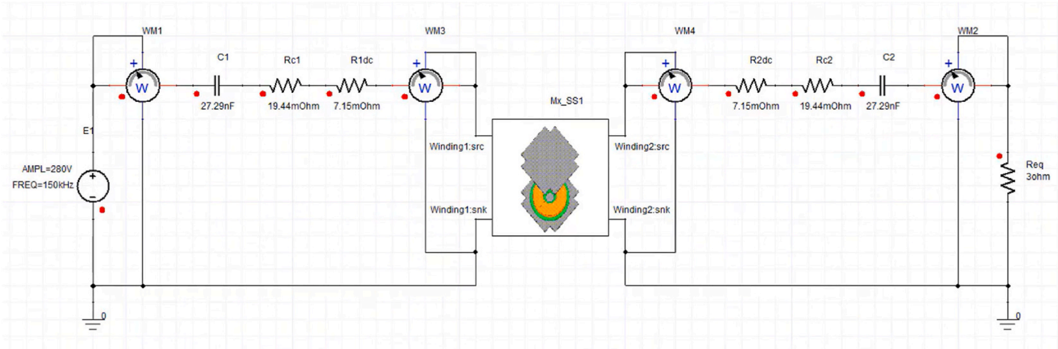

Fig. 9. Co-simulation circuit.

Table 2
Transceiver parameter comparison.

With Aluminum Plate	Center alignment (0,0)		Wrong alignment (75,100)	
	Measurement	Simulation	Measurement	Simulation
TX-Self inductance-Lp	79.82 uH	79.74 uH	82.85 uH	83.26 uH
RX-Self inductance-LS	78.17 uH	78.94 uH	77.31 uH	77.83 uH
Mutual inductance M	23.01 uH	23.94 uH	17.62 uH	19.83 uH

Table 3
Transceiver parameter.

Without Aluminum Plate	Center alignment (0,0)	Wrong alignment (75,100)
	Measurement	Measurement
TX-Self inductance-Lp	60.93 uH	62.74 uH
RX-Self inductance-LS	65.04 uH	64.43 uH
Mutual inductance M	11.71 uH	8.95 uH

3.1. Q factor analysis

Q factor analysis is very important in Wireless Power Transfer (WPT) systems. The Q factor is an important parameter that measures the ability of a resonant circuit to store and dissipate energy. In WPT systems, this factor is used to evaluate the efficiency and effectiveness of energy transfer. A high Q factor indicates a high energy storage capacity and allows energy to be transmitted over

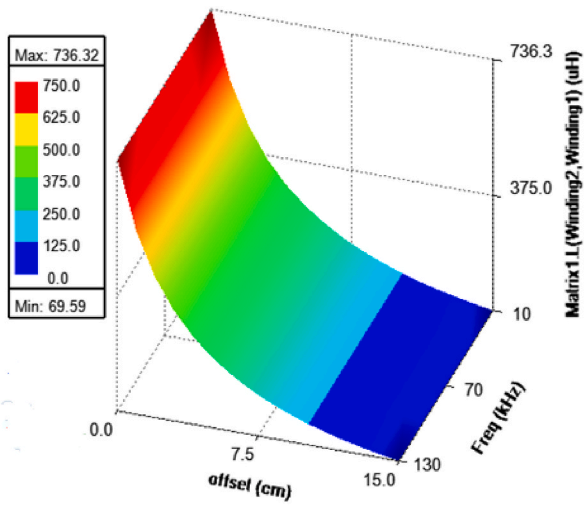

Fig. 10. Variation of mutual inductance with respect to air gap.

longer distances. When calculating the Q factor, the relationship between resonant frequency and bandwidth should be taken into account. Ideally, the bandwidth should be narrow and the resonant frequency high to achieve a high Q factor. A high Q factor means that energy transfer is more efficient. However, this should be considered in combination with other factors, because a system with a high Q factor can be more sensitive with changes in frequency. Therefore, Q factor analysis in Wireless Power Transfer systems is an important step to optimize system performance and design. This is important for the design and performance optimization of wireless power transfer systems. This factor indicates how little energy is lost in a system. The efficiency of the WPT is achieved at low coupling factors by increasing the quality factor. The quality factor of the resonator can be improved by increasing the inductance while keeping the frequency constant. However, it should be noted that this increase also leads to higher internal resistance and therefore lower maximum efficiency. Also, increasing the quality factor increases the voltage stress on the capacitor. The variation of mutual inductance between the transmitter and receiver coils with respect to air gap and frequency is given in Fig. 10. The plot of coupling factor, frequency and air gap is given in Fig. 11.

As seen in Fig. 10, the critical air gap value can reach higher values as the quality factor increases. However, as the quality factor increases, the coil inductance, coil size and internal resistance also increase. Calculations revealed that at low mutual inductance below the critical mutual inductance, efficiency increases with increasing quality factor. If WPT is performed at low air gap, low quality factor should be preferred. The quality factor, efficiency and coupling coefficient plot is given in Fig. 12.

The graph of the air-gap coupling factor and slip for the WPT3 analysis is given in Fig. 13. The places shown in red color indicate that the density is high. As can be seen in the graph, the coupling factor was high when the air-spacing was low. As the air-gap distance increased, the coupling factor decreased.

Quality factor, efficiency, critical air gap, and voltage stress on capacitors are significant parameters that influence each other. Understanding the relationships between these factors is crucial for optimizing a system. Here are some explanations of the interrelationships between these factors and the trade-offs associated with increasing the quality factor.

1. Quality Factor and Efficiency
   - The quality factor (Q factor) is associated with the bandwidth of a circuit in resonance.
   - A higher Q factor implies a narrower bandwidth at the resonance frequency.
   - This situation allows energy to be transmitted more effectively, resulting in higher system efficiency.
2. Quality Factor and Critical Air Gap
   - The critical air gap is important for the transmission of the magnetic field.
   - The quality factor determines the clarity of magnetic resonance. A higher Q factor allows the magnetic field to pass through the critical air gap more effectively.
   - This contributes to the effectiveness of energy transfer over longer distances.
3. Quality Factor and Capacitor Voltage Stress
   - The quality factor influences voltage fluctuations in resonant circuits.
   - A higher Q factor can reduce voltage stress on capacitors because a narrower bandwidth means less energy fluctuation.
   - This contributes to capacitors operating for longer durations and in a safer manner.
4. Trade-offs
   - Increasing the quality factor often leads to trade-offs with other parameters.
   - For instance, a higher Q factor is generally associated with a narrower bandwidth, making the system more sensitive to environmental changes.
   - Additionally, achieving a higher Q factor may require more complex and expensive circuit designs.

To balance these trade-offs, designers typically aim to find an optimal balance based on system requirements and constraints.

3.2. Experimental results

In this study, an experimental data from the literature was used for experimental verification. A simulation study of the experimentally obtained data was performed and the results were compared. The experimental setup is shown in Fig. 14 [14].

The final selected WPT system performance verification experiment was performed over the full range of each alignment and battery charge profile. The load was simulated by means of an electronic load. The experimental conditions are as follows.

In the literature, LC matching circuits are frequently used to ensure the compatibility of the transmitter and receiver with the measuring device. In characteristic impedance measurement devices, matching circuits are designed to match the resistance values to measure the circuit. In this work, a matching circuit is constructed to ensure that the matching is broadband (low Q).

The efficiency of the WPT system was evaluated at frequencies ranging from 10 to 130 kHz in various air gaps ranging from 0 cm to 15 cm. When the results are analyzed, resonant frequencies bifurcate at air gaps below the critical air gap and maximum efficiency can be obtained at resonant frequencies. When the coupling factor increases, that is, when the air gap decreases, the bifurcations in the resonant frequency approach the natural angular frequency. It has been observed that the limit for the elimination of frequency bifurcations is the critical air gap. When the critical air gap is exceeded, a single resonant frequency is formed and the efficiency starts to decrease. In Table 4, experimental and simulation results are compared for all cases.

The magnetic field of high quality factor designs is higher than that of low quality factor designs. The graphs show that the magnetic field intensity decreases faster after the coil radius on the y-axis in all designs. The scattering around the coil was observed to be more intense. These magnetic scattering can be directed or blocked by using core and shielding. This study was carried out by analyzing the

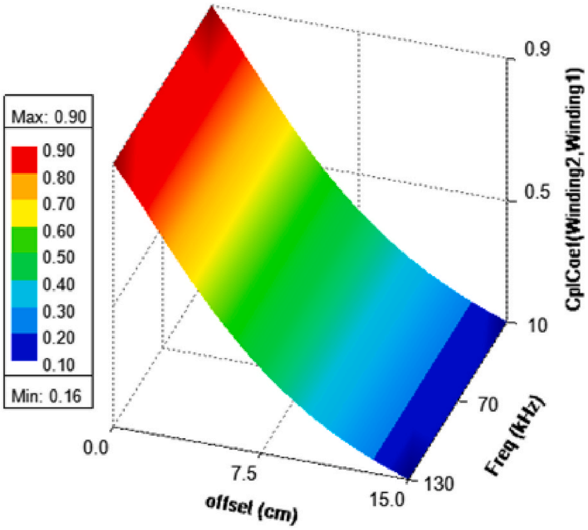

Fig. 11. Graph of coupling factor, frequency and air gap.

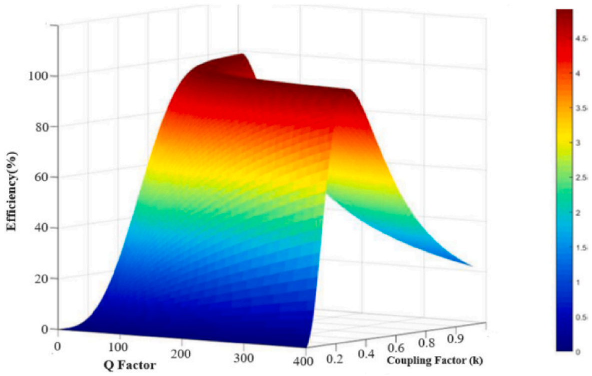

Fig. 12. Graph of quality factor, productivity and coupling coefficient.

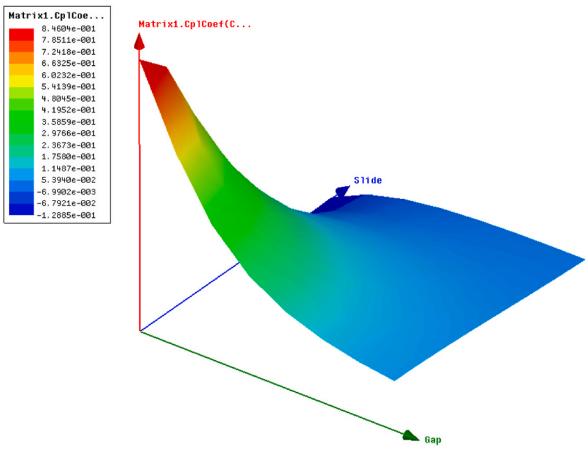

Fig. 13. Graph of air-gap coupling factor and slip.

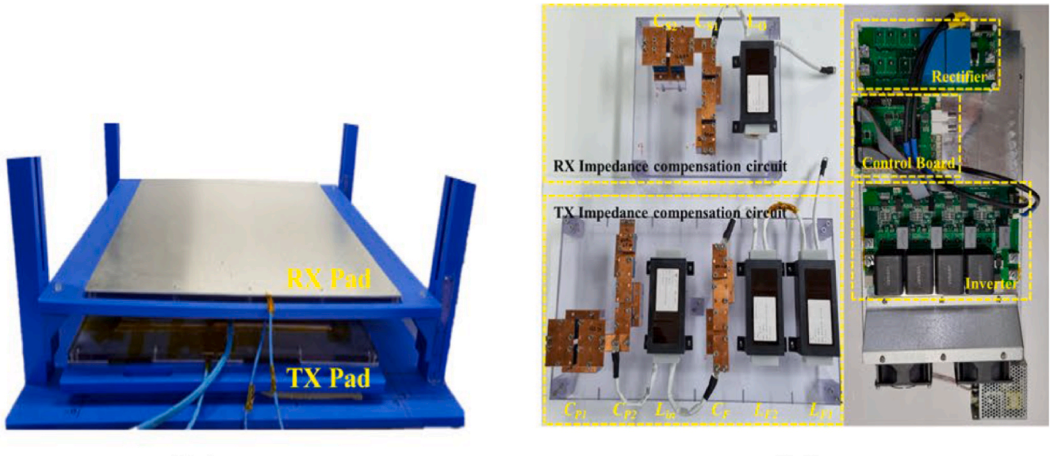

Fig. 14. WPT setup [14].

Table 4
Comparison of the results.

	Experimental results	Simulation results
Efficiency (%)	95.75	94.13
Mutual inductance (uH)	25.79	23.94
Q factor value		336

international standard "IEC TS 61980-3″ set by the International Electrotechnical Commission (IEC). Maxwell modeling was performed on the WPT3 level reference, which has the highest power handling capability among the international standards currently in force. This was done in order to increase the reliability of the Maxwell simulation-based modeling. The modeling results were verified to be in agreement with the WPT3 level reference parameters.

4. Conclusıon

In this study, the effects of quality factor in wireless energy transfer system are investigated. The design of WPT with quality factor for SAE standard WPT1 power class and 85 kHz frequency is realised. For this purpose, a WPT system capable of charging a 20 kW battery is proposed. First, Ansys Maxwell simulation is used to design and construct a 20 kW transceiver while taking international standards into consideration. Taking into account the created transceiver and battery charging profile, the best compensation architecture is chosen and designed. The suggested system's optimal compensation topology has more resonant parts than alternative architectures. Furthermore, the low and uniform voltage and current stress given to the compensation circuit makes this topology superior to other topologies in terms of cost savings and high efficiency. The effectiveness of the WPT system is empirically confirmed in order to confirm the viability of the suggested method. Furthermore, the suggested system's high efficiency performance is confirmed by reaching a maximum efficiency of 94.13%. It is important to select the most optimum quality factor according to the needs of the study. Low quality factor should be preferred for a system that will operate in low air range and high quality factor should be preferred for a system that will operate in high air range. Otherwise, efficiency decreases.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Ethical approval

There is no violation of ethical rules in this study. Ethics committee approval is not required.

Funding

Not applicable.

Availability of data and material

All data are fully available without restriction.

CRediT authorship contribution statement

Yıldırım Özüpak: Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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