

Research Article

Modeling, Analysis, and Implementation of Series-Series Compensated Inductive Coupled Power Transfer (ICPT) System for an Electric Vehicle

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This paper focuses on the modeling and implementation of an Electric Vehicle (EV) wireless charging system based on inductively coupled power transfer (ICPT) technique where electrical energy can be wirelessly transferred from source to vehicle battery. In fact, the wireless power transfer (WPT) system can solve the fundamental problems of the electric vehicle, which are the short battery life of the EV due to limited battery storage and the user safety by handling high voltage cables. In addition, this paper gives an equivalent electrical circuit of the DC-DC converter for WPT and comprises some basic components, which include the H-bridge inverter, inductive coupling transformer, filter, and rectifier. The input impedance of ICPT with series-series compensation circuit, their phases, and the power factor are calculated and plotted by using Matlab scripts programming for different air gap values between the transmitter coil and receiver coil. The simulation results indicate that it is important to operate the system in the resonance state to transfer the maximum real power from the source to the load. A mathematical expression of optimal equivalent load resistance, corresponding to a maximal transmission efficiency of a wireless charging system, was demonstrated in detail. Finally, a prototype of a wireless charging system has been constructed for using two rectangular coils. The resonant frequency of the designed system with a 500×200 mm transmitter coil and a 200×100 mm receiver coil is 10 kHz. By carefully adjusting the circuit parameters, the implementation prototype have been successfully transferred a 100 W load power through 10 cm air gap between the coils.

1. Introduction

Nowadays, the automotive sector is extremely motivated by the development of electric vehicles (EVs) with a projected growth of 6 million by 2020, to reduce air pollution and global warming [1]. In addition, the need to move towards clean energy resources has led to the progressive electrification of vehicles. However, some questions are still pending, in particular, on the EV battery recharge time and user safety by handling high-voltage cables, especially when rain and snow are present [2]. In this context, the wireless power transfer (WPT) system is a promising solution due to

its high safety and convenience, which are particularly important for electrical vehicles [3]. The purpose is to transfer energy without cable from the power source (the ground) to the load (onboard battery) [4]. Therefore, the WPT technology can fundamentally solve their problems of short battery life of the electrical vehicle due to limited battery storage or high initial cost due to installation of a large number of batteries [5]. In fact, the wireless charging system can be deployed as a stationary system to charge EV in garages or public parking spaces. Additionally, there is another possibility of charging EVs while they are in transit which is called EV dynamic wireless charging. In this paper,

the focus is on type of stationary wireless charging to make the charging process safer and less complicated in terms of infrastructure [6]. As users of EV manipulate a lower number of components (two coils), the robustness is another advantage of wireless charge.

Several works have focused on the wireless methods of the EV battery charging system, which treats the different ways that this technology can be used. In fact, the EV wireless charging technologies essentially depend on the frequency of the electromagnetic field and the air gap between the power emitter/receiver (installed in the vehicle). Accordingly, these two parameters determine whether the wireless power transfer will be in a far-field over long distance or a near-field over low and medium distance [7, 8]. In a far-field approach, generally labeled the microwave power transfer (MPT) technology, the energy can be wirelessly transferred between transmitting antennas and receiving antennas (also named as rectenna), as same technology of wireless communication [9]. The MPT has the advantage that the capability to transfer power over long distances via radio waves with frequencies ranging from 1 to 30 GHz [7, 10]. However, this technology has the disadvantage of increasing the cost and the size of the antenna. Taking into account the typical distance ranges between the transmitter coil and the receiver coil (10–30 cm) for EV application, the near-field category can be divided into two groups: inductive power transfer (IPT) [11] and inductively coupled power transfer (ICPT) [12, 13]. In the IPT method, a transmitter coil (in the ground) is excited with an alternating (AC) current, which generates a magnetic field. Therefore, when the magnetic field traverses the receiver coil, an induced voltage is created to charge the EV battery, as explained by Faraday's laws. However, this method is limited by the capability of transmission distance, necessity of very low air gap between coils to keep the power transmission more efficient. In most WPT for EV application, the IPT technology is not largely used due to its poor magnetic coupling between the transmitter and the receiver coils (usually 0.05~0.2), which result in large equivalent leakage inductance [14]. Indeed, as the WPT system would be fixed in a vehicle, it is important to verify that the values of the electromagnetic field around the vehicle are in the safety limits of human exposure, as recommended by the World Health Organization [15, 16].

In addition, the ICPT method is based on the same principle of IPT technology, with the only difference that the compensation capacitors are connected in series (S) or in parallel (P) with coils to create a "strong coupled between transmitter and receiver coils." The ICPT technology has advantages to transfer the maximum real power from the source to the load by compensating the leakage energy stored in the coils [17]. Based on the connection to the coils, four compensation topologies, labeled as series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP), are possible for ICPT technology [13, 18–20]. To compensate the total leakage inductance seen by the input circuit, the primary capacitor C_p in series is used to get input voltage and current in phase, known as zero-phase-angle (ZPA) approach. At this point, the reactive power will be

equal to zero and so the real power transferred to the load is maximum. Most researchers of resonant topologies have selected the SS compensation type as a preferable topology due to several reasons: it assures that the series primary compensation (C_p) is independent on the mutual inductance and the equivalent load resistance, so it is not necessary to retune or change the conception of the system every time that the load changes [13, 18]. In particular for high power applications, it is found that the SS topology is more economical than other topologies in terms of required copper mass for fabricating an inductively coupled coil set [12]. In an important work [4], Ibrahim et al. have developed a wireless charging of EV based on ICPT technology with series-series compensation. However, the detailed theoretical analysis of input impedance and efficiency of the system have been not studied.

Accordingly, a high efficiency wireless charging system for an EV based on ICPT technology is presented and analyzed in this paper. The input impedance of ICPT with a series-series compensation circuit, their phases, and the power factor is calculated and plotted by using Matlab scripts programming for different air gap values between the transmitter coil and receiver coil. The importance of the power factor (PF) that it is useful to determine the size and cost of the inverter used in the WPT system, so as PF is much less than one, then the inverter cost will be high. Additionally, an expression of optimal load resistance, corresponding to the maximal transmission efficiency, was demonstrated in this paper. Furthermore, the transmission efficiency characteristic of the proposed system was determined and plotted as a function of air gap. Finally, a wireless charging system prototype based on two rectangular coils has been built and tested under different transmission distance. The experimental results show a good performance of the proposed wireless charging system.

2. Proposed Wireless Charging System

A generalized configuration of EV wireless charging is proposed in this paper, as shown in Figure 1. The primary side is the one shown outside the vehicle, which includes a power source, a rectifier, and a high-frequency inverter (Power Electronics) all connected to the transmitter coil. The secondary side (power pickup system) is placed inside the vehicle. It also includes the power electronic converter and the onboard EV battery to be wirelessly charged. In fact, the EV wireless charging system can be operated in a resonance state by carefully integrated compensation topologies (the primary capacitor C_p and the secondary capacitor C_s) in both the primary and the secondary sides of the system.

2.1. Calculation of Self and Mutual Inductances. Recently, the wireless charging EV systems have been in development because they are easy to use and robust. This technology of transferring power, without cable over an air gap, is based in the magnetic coupling between inductive coils. The inductive coupling transformer consists of two coils, the transmitter (stationary), and the receiver (pick-up). In fact, the

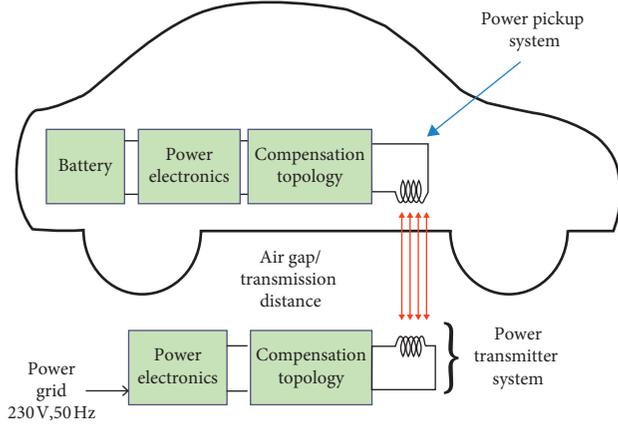


FIGURE 1: Configuration of the EV wireless charging system.

performance of the WPT system for EV charging depends significantly on the design (dimensions and shapes such as circular and rectangular) of the coils [4, 12, 21–23]. In order to transfer the power efficiency, two rectangular coils were constructed in this work (Figure 2).

The resistance R_i and self-inductance L_i of a rectangular coil can be calculated as follows [12, 22]:

$$R_i = N_i \cdot \rho \frac{2(a_i + b_i)}{S_i}, \quad (1)$$

$$L_i = \frac{\mu_0 N_i^2}{\pi} \left[a_i \cdot \ln \frac{2a_i b_i}{r_i(a_i + \beta)} + b_i \cdot \ln \frac{2a_i b_i}{r_i(b_i + \beta)} - 2(\alpha - \beta) + 0.25\alpha \right], \quad (2)$$

where N_i is the number of turns $= a_i + b_i$, $\beta = (a_i^2 + b_i^2)^{0.5}$, $i = p$ is used for the transmitter (primary) coil, and $i = s$ for the receiver (secondary) coil. In fact, the equivalent radius of the coil r_i (Figure 2) can be determined by the following expression [12]:

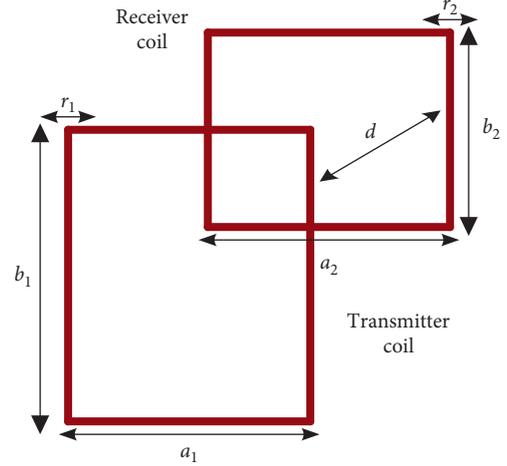
$$r_i = \sqrt{\frac{N_i S_i}{\pi}}, \quad (3)$$

where S_i is the section of the wire.

Assuming that the transmitter coil is longer than the receiver coil ($b_1 \gg b_2$), the mutual inductance M between two parallel rectangular coils can be calculated analytically by [23]

$$M = \frac{\mu_0}{\pi} N_1 N_2 b_2 \ln \left[\frac{\sqrt{d^2 + a_1^2}}{d} \right], \quad (4)$$

where N_1 and N_2 are number turns of the transmitter and receiver coils, respectively; d is the air gap (distance between the transmitter and receiver coils); μ_0 is the permeability of vacuum ($\mu_0 = 4 \times 10^{-7}$); b_2 is the length of the receiver coil; and a_1 width of the transmitter coil. In addition, the coupling coefficient, which can be used to qualify the magnetic coupling, is defined as


 FIGURE 2: Schematic of the two rectangular coils for M calculation.

$$k = \frac{M}{\sqrt{L_p * L_s}}. \quad (5)$$

In order to see the influence of the transmission distance h , Figure 3 shows the simulation result of mutual inductance and coupling coefficient as a function of air gap d using the practical dimensions coils. From these curves, it can be observed that the mutual inductance M and coupling coefficient decrease rapidly when the distance between the transmitter and receiver coils increases. Therefore, it is important to integrate compensation capacitors in series (S) or parallel (P) with coils to create a strong coupling between the transmitter and receiver coils.

2.2. Equivalent Circuit of the ICPT System. The literature review shows several equivalent circuit model of inductive power transfer systems [4, 5]. A typical equivalent electrical circuit (EEC) of the resonant series-series ICPT system is shown in Figure 4, where the left side of the circuits is the transmitters and the right side is the receiver. This circuit consisted of two resonant circuits, which coupled magnetically by mutual impedance (M) and the indices “p” and “s” indicate, respectively, the primary and secondary circuits. In this equivalent circuit, R_p and L_p are the resistance and self-inductance of the transmitter coil, R_s and L_s are the resistance and self-inductance of the receiver coil, R_L is the load resistance, and C_p and C_s are series capacitors in transmitting and receiving compensation circuit, respectively. M is the mutual inductance between the two coils. For analysis simplicity, the rectifier, filter, and resistive load circuit (RFRC) in Figure 4(a) can be replaced with an effective AC resistance R_e , as in [4].

The expression of the equivalent load resistive denoted R_e is given by

$$R_e = \frac{8}{\pi^2} R_L. \quad (6)$$

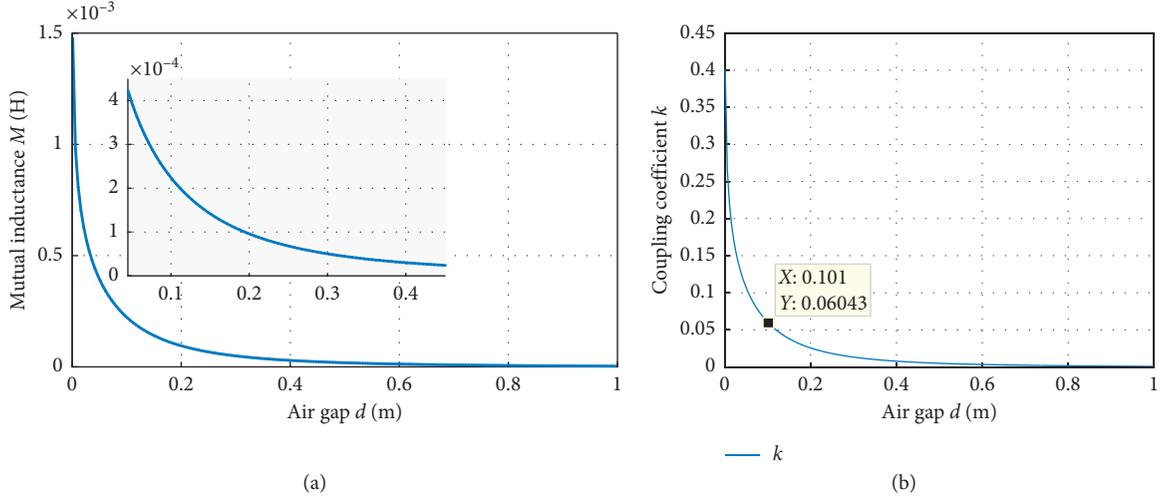


FIGURE 3: Effect of air gap distance on the (a) mutual inductance and (b) coupling coefficient.

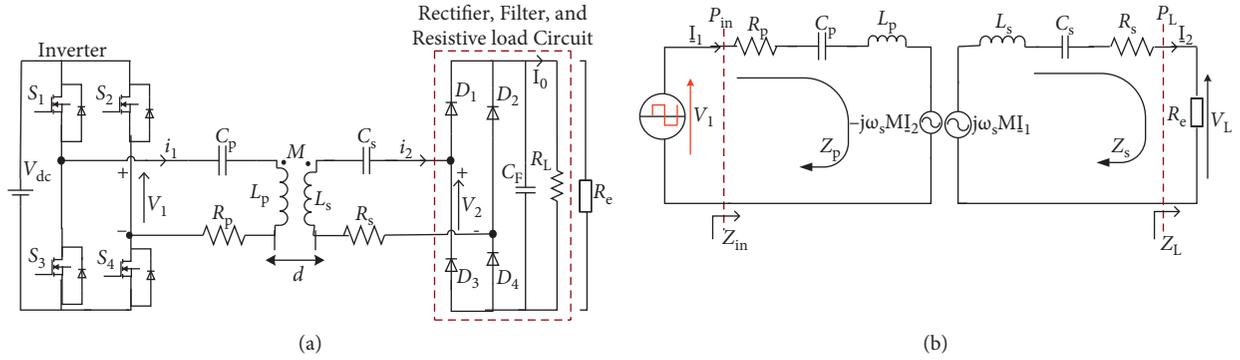


FIGURE 4: Electrical circuit of an ICPT system with series-series capacitors: (a) full circuit; (b) equivalent circuit.

Due to the full bridge inverter configuration and the fundamental harmonic analysis (FHA), the amplitude of V_1 can be determined as

$$V_1 = \frac{2\sqrt{2}}{\pi} V_{dc}. \quad (7)$$

The induced voltage in the secondary side due to the primary current I_1 is equal to $-j\omega M I_1$, while the reflected voltage in the primary due to the secondary current I_2 is equal to $j\omega M I_2$. Indeed, the voltage induced in the secondary coil is proportional to the operating frequency ($\omega_s = 2\pi f_s$), the mutual inductance M , and the current of the primary coil I_1 . According to equivalent electrical circuit depicted in Figure 4(b) and using Kirchhoff voltage law, the corresponding equation system at both primary and secondary circuit sides can be expressed as

$$\begin{cases} \underline{V}_1 = (R_p + jX_p) \underline{I}_1 - j\omega_s M \underline{I}_2, \\ j\omega_s M \underline{I}_1 = (R_s + jX_s + R_e) \underline{I}_2, \end{cases} \quad (8)$$

where X_p and X_s are equivalent reactance of the primary and secondary circuits, respectively.

$$X_p = \omega_s L_p - \frac{1}{\omega_s C_p}, \quad (9)$$

$$X_s = \omega_s L_s - \frac{1}{\omega_s C_s}.$$

Therefore, the primary and secondary circuits can be reduced to two impedances Z_p and Z_s respectively, as shown in Figure 4(b). As a result, the secondary reflected and the input impedance Z_{in} of whole circuit equations are respectively given by

$$\begin{cases} \underline{Z}_s = R_e + R_s + jX_s, \\ \underline{Z}_{ref} = \frac{(\omega_s M)^2}{\underline{Z}_s}, \\ \underline{Z}_{in} = R_p + jX_p + \underline{Z}_{ref}. \end{cases} \quad (10)$$

In order to ensure maximum power transfer to the load, it is desirable to operate the inverter at the resonance frequency f_0 . At this frequency, the reactance of the circuits perceived by the power source is zero where the input

impedance seen by the source is purely resistive ($Z_{in} = R_p + (\omega^2 M^2 / R_s + R_e)$). In this paper, the self-inductances values (L_p and L_s) of coils are determined analytically by using equations (2), and its experimental values are given in Table 1. The resonance frequency f_0 is assumed to be equal 10 kHz due to the limited switching frequency of our inverter. Thus, the primary and a secondary compensation capacitors can be calculated, respectively, by

$$C_p = \frac{1}{4\pi^2 f_0^2 L_p}, \quad (11)$$

$$C_s = \frac{1}{4\pi^2 f_0^2 L_s}. \quad (12)$$

In fact, the amplitude of the primary current and operating point of the system can be determined by the input impedance modulus [24]. Therefore, the equivalent input impedance Z_{in} in equation (10) is plotted in Figure 5 for different air gap distances d (m). These values of mutual inductance M given in Table 1 are found from the simulation results mentioned in Figure 3, and the values of coupling coefficient are determined by equation (5).

From Figure 5, it can be noted that the impedance Z_{in} is purely resistive and minimum ($Z_{in} = R_p + (\omega^2 M^2 / R_s + R_e)$) if the operating frequency f_s is equal to resonance frequency f_0 , which means that the normalized frequency $f_N = (f_s / f_0) = 1$.

In addition, the power factor (PF) can be obtained from the phase of the impedance Z_{in} as expressed by following equation:

$$PF = \cos(\theta_{in}) = \frac{R(Z_{in})}{|Z_{in}|}. \quad (13)$$

The power factor is useful to determine the size of Volt-Ampere (VA) ratings, so Figure 6 shows the PF as function of normalized frequency for different air gap d (m) values. Then, it can be concluded that the power factor have a maximum value as the normalized frequency $f_N = 1$. This means that the module of the input impedance seen by the source is resistive at this frequency. At this point, the reactive power will be zero, so the VA value of the source is minimal. From these results, we can notice that it is essential to operate the wireless power transfer system in the resonance state.

2.3. Maximum Efficiency Condition for ICPT. In this section, a novel approach to determine the efficiency of the ICPT system is presented. An optimum load resistance for the maximum efficiency is demonstrated from the efficiency equation. In Figure 4(b), P_{in} and P_L represent real powers at the source and load ports, respectively, and they can be expressed as follows:

$$\begin{aligned} P_{in} &= |V_1 I_1| \cos(\angle V_1 - \angle I_1) = |V_1 I_1| \cos(\theta_{in}), \\ P_L &= |R_e I_2^2|. \end{aligned} \quad (14)$$

TABLE 1: Values of mutual inductance for different air gap distances.

| d (cm) | M (μ H) | L_p (mH) | L_s (mH) | k |
|----------|----------------|------------|------------|-------|
| 10 | 223.1 | 4.7 | 2.9 | 0.06 |
| 15 | 142 | 4.7 | 2.9 | 0.038 |
| 20 | 96.34 | 4.7 | 2.9 | 0.026 |

Then, the efficiency of the ICPT system can be determined as

$$\eta = \frac{P_L}{P_{in}} = \frac{|R_e I_2^2|}{|V_1 I_1| \cos(\angle V_1 - \angle I_1)}. \quad (15)$$

In fact, by considering only the powers losses in coils, the efficiency of the system can be rewritten as follows:

$$\eta = \frac{P_L}{P_{in}} = \frac{R_e I_2^2}{R_p I_1^2 + (R_s + R_e) I_2^2}. \quad (16)$$

To simplify the study, it is assumed supposed that both Z_p and Z_s are defined as the impedances of primary and secondary circuit as follows: $Z_p = R_p + j(\omega_s L_p - (1/\omega_s C_p)) = R_p + jX_p$ and $Z_s = R_s + R_e + j(\omega_s L_s - (1/\omega_s C_s)) = R_e + R_s + jX_s$. From equation (8), it is possible to determine the current of transmitter coil I_1 and receiving coil I_2 , as

$$I_1 = \frac{V_1}{(Z_p + (\omega_s M)^2 / Z_s)}, \quad (17)$$

$$I_2 = \frac{j\omega_s M}{Z_s} I_1. \quad (18)$$

Substituting the secondary current I_2 in equation (18) into equation (16) yields

$$\begin{aligned} \eta &= \frac{R_e}{R_p [Z_s / \omega_s M]^2 + (R_s + R_e)} \\ &= \frac{(\omega_s M)^2 R_e}{R_p [(R_s + R_e)^2 + (X_s)^2] + (\omega_s M)^2 (R_s + R_e)}. \end{aligned} \quad (19)$$

Therefore, the efficiency of the ICPT system mainly depends on the operating frequency ($\omega_s = 2\pi f_s$), the mutual inductance M between two coils, and the equivalent load resistive. Accordingly, if it is desired to increase the efficiency power transferred from the source to the load for a given application, at least one of these three parameters must be increased. Generally, the ICPT system is worked at resonance frequency where the coils are both constructed to operate at the resonance frequency ($f_0 = (1/2\pi) \sqrt{L_p C_p} = (1/2\pi) \sqrt{L_s C_s}$). Then, the expression of the power transfer efficiency in equation (19) at resonance frequency can be simplified by equation (20) when the equivalent reactance of receiver coil X_s is equal to zero:

$$\eta_{-r} = \frac{(\omega_r M)^2 R_e}{R_p (R_s + R_e)^2 + (\omega_r M)^2 (R_s + R_e)}, \quad (20)$$

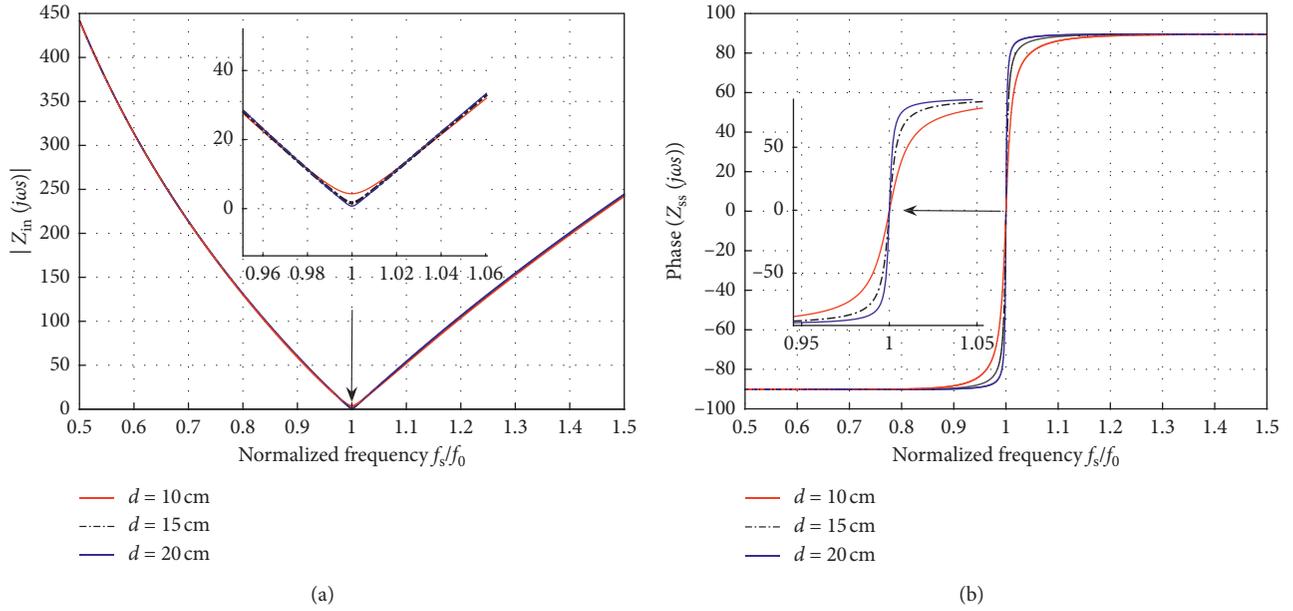


FIGURE 5: Input impedance as function of the normalized frequency ($F_N = f_s/f_0$) with different air gap (d) values: (a) magnitude of Z_{in} ; (b) phase of Z_{in} ($f_0 = 10$ kHz, $R_p = 1.15 \Omega$, $R_s = 0.78 \Omega$, $L_p = 4.7$ mH, $L_s = 2.9$ mH, $C_p = 55$ nF, $C_s = 88$ nF, $R_e = 20 \Omega$).

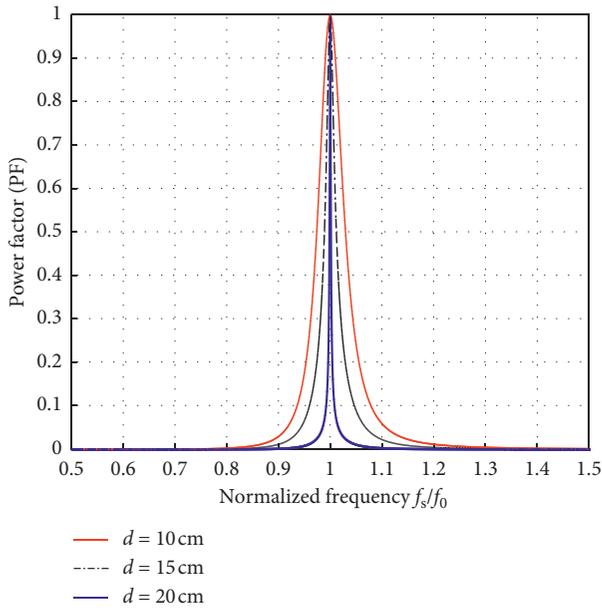


FIGURE 6: Power factor (PF) as a function of the normalized frequency ($F_N = f_s/f_0$) with different air gap values ($f_0 = 10$ kHz, $R_p = 1.15 \Omega$, $R_s = 0.78 \Omega$, $L_p = 4.7$ mH, $L_s = 2.9$ mH, $C_p = 55$ nF, $C_s = 88$ nF, $R_e = 20 \Omega$).

where $\omega_r = 2\pi f_0$.

By differentiating equation (21), we can get the optimal load resistance R_e for the maximum efficiency of ICPT system as follows:

$$\frac{\partial \eta_r}{\partial R_e} = \frac{\partial}{\partial R_e} \left[\frac{(\omega_r M)^2 R_e}{R_p (R_e + R_s)^2 + (\omega_r M)^2 (R_s + R_e)} \right] = 0. \quad (21)$$

Now and after simplification by using several hypotheses ($R_e \neq 0$, and $M \neq 0$), the optimal load resistance at maximum efficiency is given by

$$R_{e_opt} = 1 + \sqrt{\frac{(\omega_r M)^2}{R_p R_s}}. \quad (22)$$

Once the air gap distance and the coils dimensions are selected, the design process of the WPT system begins with the calculation of the resistances, self-inductances of coils, and mutual inductance. Figure 7 shows a flow diagram describing the principal steps to design a WPT system. If the optimal load resistance is determined; applying equation (22), a maximum efficiency of WPT system can be found. In fact, an interactive calculation has been done using Matlab program and the obtained values of parameters of the system are illustrated in Table 2. From these optimal values, the test bench prototype will be constructed.

For fixed values of coil resistances, resonance frequency $f_0 = 10$ kHz, and mutual inductance $M = 223 \mu\text{H}$ at 10 cm gap, it has been found that a load resistance R_L of 20Ω is optimal for the proposed ICPT system. Figure 8 shows the efficiency of ICPT system as a function of the transmission distance at different load resistances. It can be noted that the air gap between the transmitter and receiver coils has a strong influence on the transmission efficiency of the ICPT system.

3. Experimental Test

The scheme used to provide experimental tests of the proposed wireless charging system is given in Figure 9. It consisted of four major components: a power source, an inverter (DC/AC converter consists of four switches IGBTs),

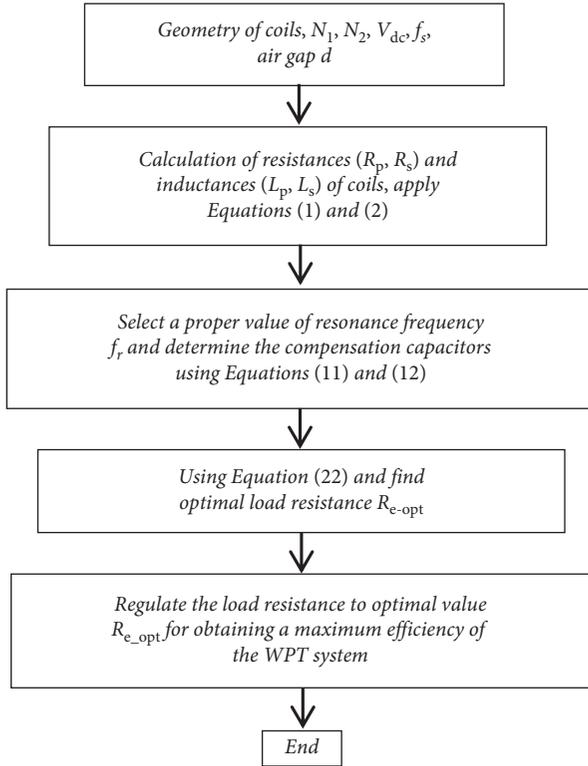


FIGURE 7: Flow diagram describing the principal steps to design a WPT system.

TABLE 2: Main parameters of the experimental test system.

| | |
|---|--|
| Dimension of the transmitter coil | 500 mm × 200 mm |
| Dimension of the receiver coil | 200 mm × 100 mm |
| Number of turns | $N_1 = 70, N_2 = 100$ |
| Resistances of the transmitter and receiver coils | $R_p = 1.15 \Omega, R_s = 0.78 \Omega$ |
| Inductances of the transmitter and receiver coils | $L_p = 4.7 \text{ mH}, L_s = 2.9 \text{ mH}$ |
| Compensation capacitances | $C_p = 55 \text{ nF}, C_s = 88 \text{ nF}$ |
| Switching frequency | $f_s = 10 \text{ kHz}$ |
| Source voltage (DC) | 60 V |
| Load resistance | $R_L = 20 \Omega$ |

an inductive coupler (two rectangular coils), and a rectifier and a load resistive. A photograph of the experimental setup is shown in Figure 10. The key parameters used in the proposed prototype are summarized in Table 2. In order to limit losses due to skin and proximity effects, we will use Litz wire of 1.5 mm^2 section to construct the two rectangular coils of the coupler. The equivalent radius of the primary and secondary coils have been found, respectively, equal to $r_1 = 5.8 \text{ mm}$ and $r_2 = 6.9 \text{ mm}$ (Figure 2).

A dSpace DS1104 processor board generates the switch control signals to the inverter. For as witching operating frequency $f_s = 10 \text{ kHz}$, the compensation capacitors are calculated from equations (11) and (12). Figure 11 presents the scheme of the designed compensation capacitances, the primary C_p and the secondary C_s , which are used in this paper.

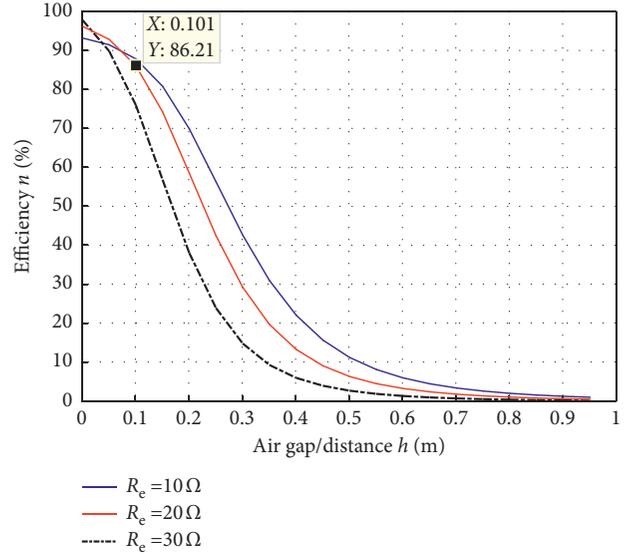


FIGURE 8: Simulation results showing a reduction of transmission efficiency with increased air gap between coils.

The experimental results are obtained using a digital oscilloscope during transfer power to optimally resistive load 20Ω with switching frequency $f_s = 10 \text{ kHz}$ and DC input voltage $V_{dc} = 60 \text{ V}$. The voltages and currents across input and output of the ICPT system are displayed in Figures 12-15. In the first experimental test, the receiver coil is placed at 10 cm gap from the transmitter coil. Figure 12 shows the input voltage V_1 (output voltage of the inverter bridge) and the output voltage V_2 (input voltage of the rectifier bridge), while Figure 13 presents the input current I_1 (transmitter coil current) and the output current I_2 (receiver coil current). However, the input and the output currents are nearly sinusoidal. According to these results, it is important to notice that the RMS value of output voltage V_2 and output current are equal to 50 V and 2.16 A, respectively, at 10 cm air gap, as shown in Figures 12 and 13. In addition, the load power P_L can be determined by the product of load voltage U_L and load current I_L . It is measured as 101 W. The power transfer efficiency (PTE), from DC input to DC output, is thereafter calculated as 80%. This value of the efficiency is compared to simulated result ($\eta = 86\%$) at 10 cm air gap shown in Figure 8. The obtained values show a good coherence between the simulated and experimental results.

In order to see the influence of air gap between coils in the proposed system, the receiver coil is placed at 15 cm gap. Therefore, Figure 14 demonstrates the input and the output voltages, and Figure 15 displays the input and the output currents. According to the observation of these curves, it can be noted that the RMS values of output voltage V_2 and output current I_2 are equal to 17 V and 0.85 A, respectively. From these experimental results, as the distance transmission increases, the output power and efficiency were reduced mainly, where the load power was at 14.45 W at 9.5% efficiency with 15 cm air gap. To summarize, as the distance between transmitter and receiver coils is increased, the power transfer capability of the ICPT system is rapidly decreased.

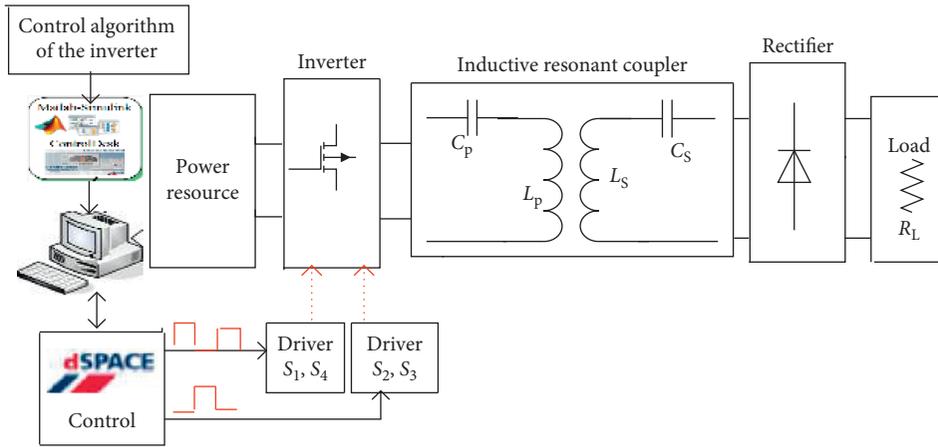


FIGURE 9: Scheme used for the experimental setup.

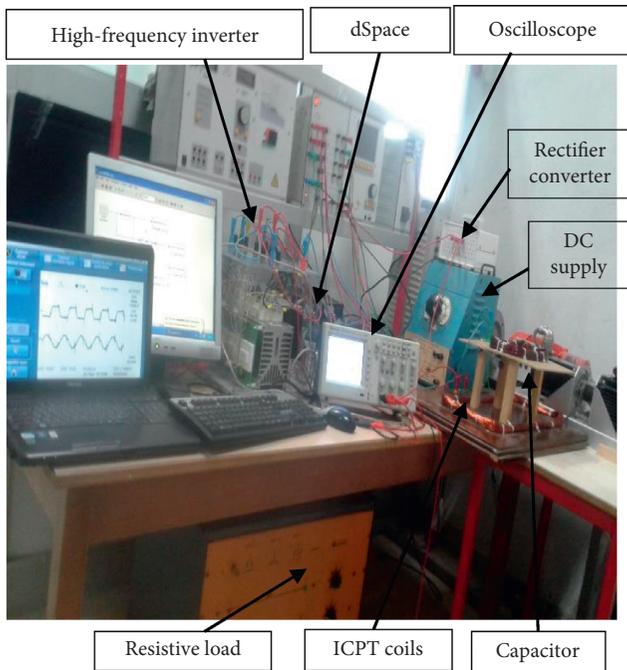


FIGURE 10: The experiment setup of the proposed wireless charging system.

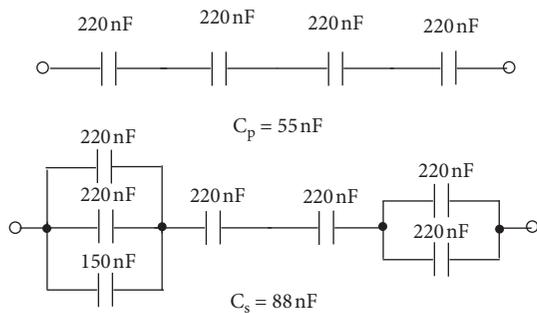


FIGURE 11: Association of the capacitor sets. (a) $C_p = 55$ nF. (b) $C_s = 88$ nF.

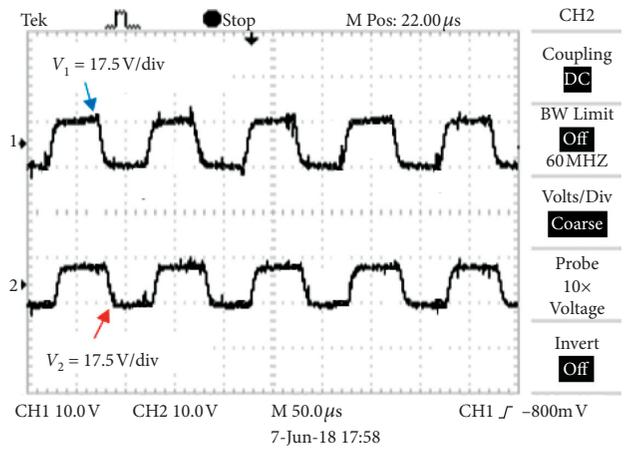


FIGURE 12: Input V_1 and output V_2 voltages of the ICPT system at 10 cm air gap.

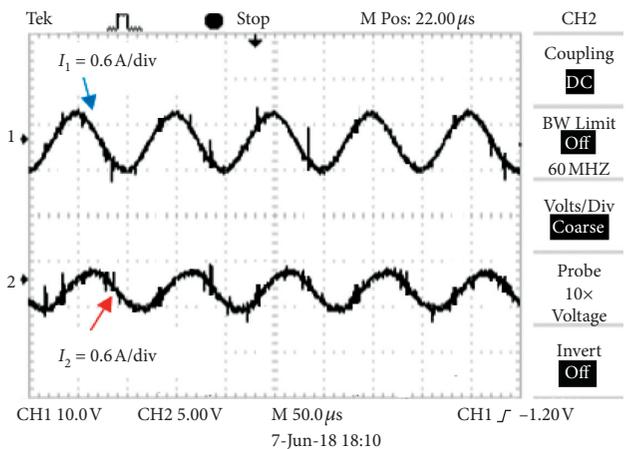


FIGURE 13: Input I_1 and output I_2 currents of the ICPT system at 10 cm air gap.

Finally, as we compare our work system to other works, the authors have described an advanced wireless charging system for real electric vehicle in [4], where the efficiency of

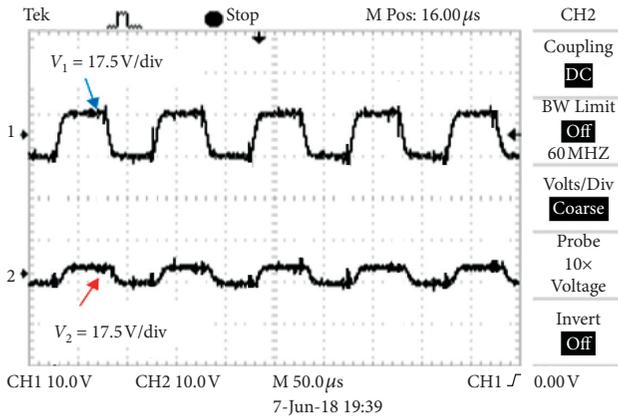


FIGURE 14: Input V_1 and output V_2 voltages of the ICPT system at 15 cm air gap.

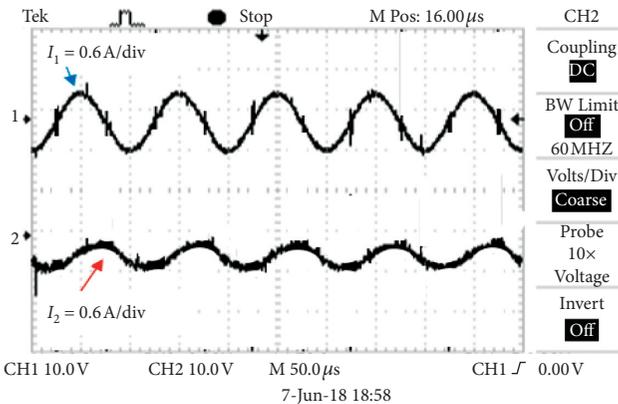


FIGURE 15: Input and output currents of the ICPT system at 15 cm air gap.

wireless charging system is not determined. However, a mathematical modeling and simulation of a wireless charging system based on the ICPT method have been studied and analyzed in our work with experimental validation. This paper also investigates the optimal load resistance corresponding to the maximum transmission efficiency in the series-series compensated WPT system.

4. Conclusion

In this paper, a novel wireless charging system based on equivalent electrical circuit of ICPT technology was studied. Thus, the input impedance of ICPT with a series-series compensation circuit, their phases, and the power factor are calculated and plotted by using Matlab scripts programming for different air gap values between the transmitter coil and receiver coil. Furthermore, a prototype of the wireless charging system has been built by optimizing the coils and compensating capacitance parameters. The experimental results were presented, and it was also demonstrated that the power transfer capability of the system is decreased if the air gap between coils increases. Finally, the presented system can be a good solution for electric vehicle battery charge and can be installed on highways to increase the EV usages.

Abbreviations

| | |
|--------------|---|
| EV: | Electrical vehicle |
| WPT: | Wireless power transfer |
| ICPT: | Inductively coupled power transfer |
| SS: | Series-series topology |
| f_s : | Switching frequency (circuit operating frequency) |
| ω_s : | Switching angular frequency ($\omega_s = 2\pi f_s$) |
| ω_r : | Operating resonant pulsation ($\omega_r = 2\pi f_0$) |
| R_p : | Resistance value of the transmitter coil |
| L_p : | Self-inductance value of the transmitter coil |
| R_s : | Resistance value of the receiver coil |
| L_s : | Self-inductance value of the receiver coil |
| M : | Mutual inductance value between coils |
| d : | Distance between coils |
| C_p : | Capacitance value of the primary sides |
| C_s : | Capacitance value of the secondary sides |
| C_F : | Output filter capacitance |
| N_1 : | Number of turns in the transmitter coil |
| N_2 : | Number of turns in the receiver coil |
| V_{dc} : | Input DC voltage of the wireless charging system |
| V_1 : | ICPT circuit input voltage (AC) (output voltages of the inverter) |
| V_2 : | ICPT circuit output voltage (AC) (input voltage of the rectifier) |
| i_1 : | Transmitter (primary) coil current |
| i_2 : | Receiver (secondary) coil current |
| V_L : | Load voltages |
| I_0 : | Load currents |
| R_L : | Load resistance |
| RFRC: | Rectifier, filter, and resistive load circuit. |

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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