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Design and Performance Investigation of a Series Compensated Inductive Wireless Power Transfer System for Supplying a Low Power DC Load

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Abstract
In this study, a series compensated WPT system is presented for low power DC load applications. Series LC resonant circuits are applied for both transmitter and receiver sides of WPT system to reduce the impedance at a specified operation frequency, and thus, ensure low power losses. The operation frequency is chosen as 109 kHz for the series compensated WPT system. Then, the series resonant LC filter is designed according to the operation frequency and WPT rating values. In addition, the power electronics systems and their controllers and operation principles are demonstrated in depth. To investigate the performance of the proposed system, a 100 W series compensated WPT model is designed and constructed in a Matlab/Simulink environment. Different simulation results are provided to illustrate the performance of the proposed WPT model. The simulation results show the stable operation of the proposed system under the designed system parameters.

1. Introduction

Recently, wireless power transfer (WPT), also called contactless power transfer, has gained widespread development around the world. In a WPT system, electrical energy is transferred from an electric source to an electric load through the coupling of electromagnetic waves without any physical contact between the source and the load [1], [2].

The transfer of electrical energy without a physical connection provides some benefits such as isolation, more flexibility, mobility, reliability, and convenient operation for underwater or hazardous environment applications [1], [2]. The WPT system also has many utilization areas, such as battery charging of electric vehicles (EVs) and portable electronic devices, implantable medical devices, lighting, heating, etc. [3]-[5].

In literature, WPT systems are mainly divided into two categories: inductive WPT (I-WPT) and capacitive WPT (C-WPT) [6], [7]. Extensive work has been done by researchers and academicians for the I-WPT systems owing to their advantage of having more power transfer capability [8], [9]. It is noted in [10] that the market value of the I-WPT around the world has increased from a $1 billion budget in 1995 to an approximate $9.5 billion budget in 2020. It is obvious that the WPT market value has been growing day by day.

The I-WPT systems are classified into four main groups in terms of series or parallel compensation circuits [8], [11]. There are also hybrid compensation circuits. The compensation circuits in I-WPT systems resonate with inductive coils to perform almost zero impedance at a specified frequency [12], [13]. By this way, the efficiency of the system is enhanced. In addition, voltage drop is prevented with an approximate zero impedance.

This paper builds upon previous research in the fields of WPT and series compensation. For instance, Frechter et al. [14] investigated the use of series compensation in resonant inductive WPT systems and demonstrated improvements in efficiency and power delivery range. Similarly,

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Kuperman [15] proposed a novel series compensation technique for enhancing the voltage regulation of inductive WPT systems, particularly under variable load conditions. On the other hand, the article [16] discusses the topology of the secondary side rectifier while focusing on the operational analysis of the wireless power transfer system. While these studies have provided valuable insights into the potential benefits of series compensation, their focus has primarily been on general WPT applications rather than specifically targeting low-power DC loads. In this study, an I-WPT system is proposed for supplying a low-power DC load. The proposed system is based on series compensation circuits for the both energy sending and receiving sides of the WPT system. In this work, the design of the utilized WPT system is presented in detail. Besides, the power electronics interface for WPT is conducted. A simulation model of the proposed system is modelled and constructed in a simulation environment. The performance of the proposed system is also examined under different loading conditions.

2. I-WPT System: Operation Principles and Characteristics

The general structure representation of an I-WPT system for supplying a DC load is illustrated in Figure 1. An I-WPT system consists of a DC power supply, a DC load, coils, and electronics interfaces for both the transmitter and receiver sides. The energy is transferred from the power supply to the DC load through the inductive coils without a physical connection between the transmitter coils and receiver coils. To transfer the energy between the coils without connection, a high-frequency magnetic field is produced by a high frequency current flowing in the transmitter coils. To produce the high-frequency current and magnetic field, power electronics converters are utilized between the power supply and the transmitter coils. On the other hand, the magnetic field produces AC current flow at the receiver coils. Then, this current is rectified through power electronics circuits to supply the DC load.

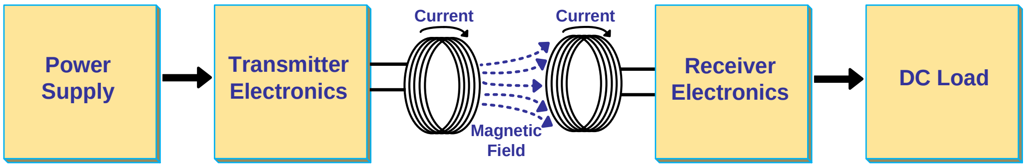

Figure 1. The general structure illustration of an I-WPT system for supplying a DC load.

In order to reduce impedances on both sides at the operating frequency and to enhance the efficiency of the WPT system, some compensation circuits are applied to the transmitter and receiver coils. Although there are various compensation circuits, a series compensation circuit is preferred in this study. The structure of the I-WPT with series compensation circuits for the transmitter and receiver sides is demonstrated in Figure 2. It can be seen from the figure that capacitors are used in series with the coils of the transmitter and receiver. Thus, zero impedances are ensured for both sides at a specified frequency, which results in low power losses.

The equivalent electric circuit of a series-compensated I-WPT system is shown in Figure 3. The series resistances of the coils are neglected for mathematical modelling simplicity. The source voltage is modelled as a square wave because the inverter transforms the DC voltage into a square wave ac voltage. Besides, the DC load can be directly added to the equivalent model on the receiver side.

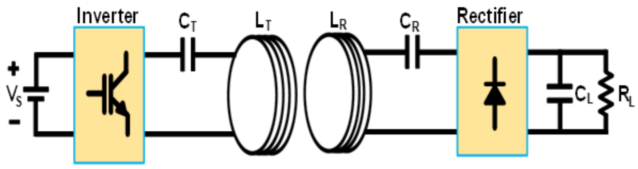

Figure 2. WPT system with series compensation circuits on the transmitter and receiver sides.

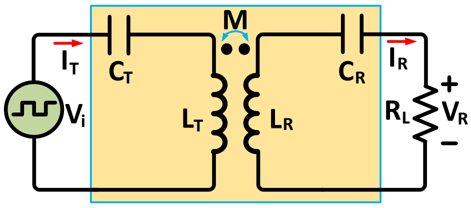

Figure 3. Equivalent electric circuit topology of a series-compensated I-WPT system.

The mathematical equations of the series compensated I-WPT system are given as equations (1) and (2). In these equations, the series resistances of the coil wires are neglected to simplify the calculations.

$$jX_T I_T - j\omega M I_R = V_i \tag{1}$$

$$j\omega M I_T - (R_L + jX_R) I_R = 0 \tag{2}$$

where, V_i is the output rms voltage of the inverter. I_T and I_R are the currents on the transmission and receiver sides, respectively. M is the mutual inductance between the transmitter and receiver. w is the angular frequency of the inverter voltage. Besides, X_T and X_R are the impedances of the transmission and receiver sides with series capacitances, respectively.

The series impedances X_T and X_R are zero at the specified operation frequency of the inverter (w). Thus, the induced voltage and current at the coil of the receiver side are acquired from equations (1) and (2) as below.

$$V_R = j\omega M I_T \tag{3}$$

$$I_R = \frac{j\omega M I_T}{R_L} \tag{4}$$

Therefore, the relationship between the inverter voltage and the load voltage can be deduced as equation (5). The ratio is also equal to the ratio between the transmission current and the receiver current.

$$\frac{V_R}{V_i} = \frac{I_T}{I_R} = \frac{R_L}{\omega M} \tag{5}$$

3. Electronic Circuit and Controller

The power electronic interface of the proposed WPT system consists of an inverter and a rectifier. The inverter is applied to convert the DC source voltage into a high-frequency AC voltage source [15], [16]. On the other hand, the rectifier system is used to transform the high-frequency AC signal into rectified DC voltage [17].

The applied inverter topology in this study and its control algorithm are demonstrated in Figure 4. As shown in the figure, a single-phase H-bridge inverter structure is preferred for the generation of the high frequency AC signal. The single-phase H-bridge inverter circuit includes four switching components, such as MOSFETs, IGBTs, etc. [18].

The switching components are triggered by a high-frequency square wave to obtain a high-frequency voltage for the WPT system [19]. The switching frequency of the inverter is selected so that the series capacitive-inductive components resonate at the selected frequency. As mentioned in the previous section, the resonance frequency of the proposed WPT system is equal to 109 kHz.

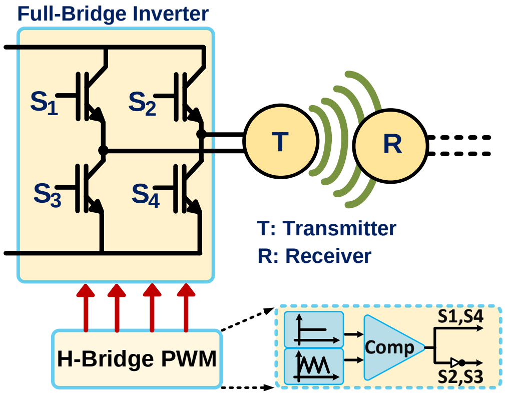

Figure 4. The single-phase H-bridge inverter structure and its switching control algorithm.

The other power electronics interface, which is used on the receiver side of the WPT, is a rectifier circuit. In this study, a single-phase uncontrolled rectifier is preferred to providing a suitable voltage form in order to supply the DC load. The structure of the single-phase uncontrolled rectifier is shown in Figure 5. As illustrated in the figure, the rectifier topology used in this work consists of four diodes for the rectification of AC voltage and one capacitor for the ripple reduction of the load voltage.

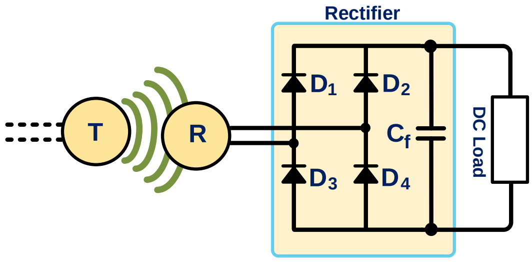

Figure 5. The single-phase uncontrolled rectifier circuit scheme.

4. Performance Results

In order to analyze and verify the proposed WPT system, a simulation model is designed and implemented in the Matlab/Simulink environment. The parameters of the constructed simulation model are given in Table 1.

Table 1. The parameters of the constructed simulation model for the proposed WPT system

Description (Symbol)	Value
Source Voltage (V_s)	100 V
Load Resistance (R_L)	100 Ohm
Inverter Operating Frequency (f_s)	109 kHz
Transmitter-side Conductance (C_T)	6.18 nF
Transmitter-side Inductance (L_T)	430 uH
Receiver-side Conductance (C_R)	6.18 nF
Receiver-side Inductance (L_R)	430 uH
Mutual Inductance (M)	85 uH

Figure 6 shows the waveforms of the source voltage and inverter output voltage. The source voltage is adjusted to 100 V level. The output voltage of the inverter is a square wave that is obtained by pulsing the switching components of the inverter. The frequency of the inverter output voltage is 109 kHz, where the series capacitance and transmitter inductance resonate. The inverter output voltage changes between 100 V and -100 V levels. In addition, the inverter output voltage and transmitter-side current are demonstrated in Figure 7. Similar to the inverter output voltage, the transmitter-side current has an AC signal with a frequency of 109 kHz. As seen from the figure, the transmitter-side current has a sinus waveform because of the output impedance of the inverter.

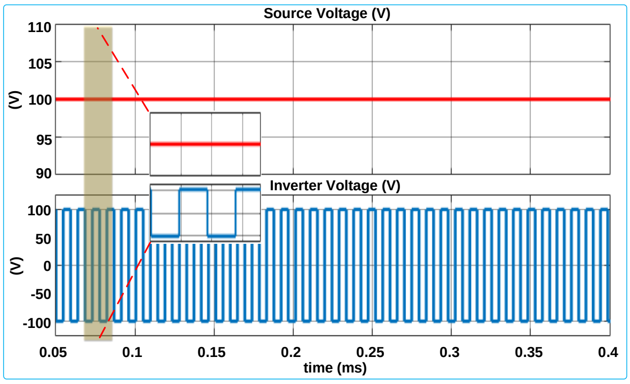

Figure 6. The waveforms of the source and inverter voltages.

On the other side, the induced voltage at WPT inductance and the receiver-side current are shown in Figure 8. The induced voltage, similar to the inverter output voltage, has a square wave form with the ranges of 100 V and -100 V levels. Besides, the receiver-side current has a sinusoidal waveform owing to the receiver-side impedance.

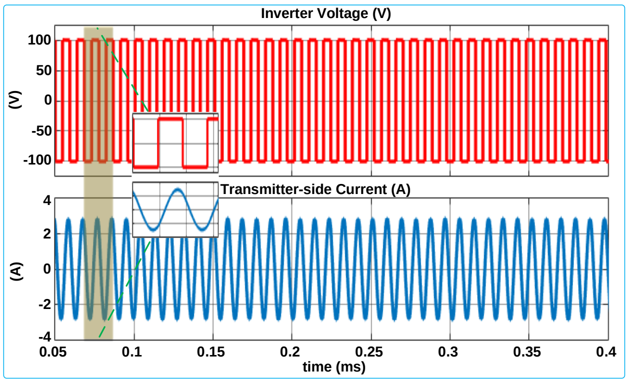

Figure 7. The waveforms of the inverter voltage and transmitter-side current.

Furthermore, the voltages of the source, the inverter, the induced voltage, and the load voltage are illustrated in Figure 9. It is obvious that the load voltage is adjusted to be the same as the source voltage through the designed system parameters. Moreover, the load voltage and current are shown in Figure 10. The load is designed to consume an approximate 100 W of power from the source. It can be seen from the simulation results that the WPT system ensures stable operation at the designed parameters.

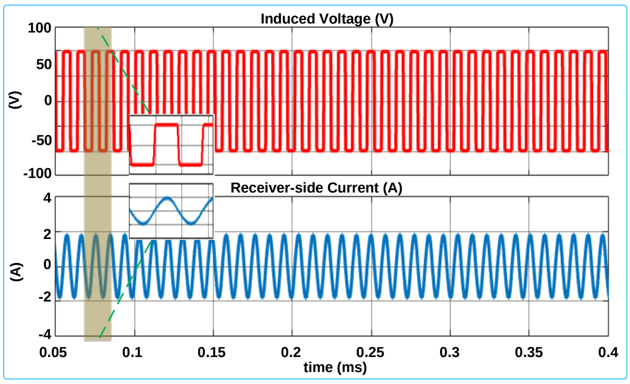

Figure 8. The waveforms of the induced voltage and receiver-side current.

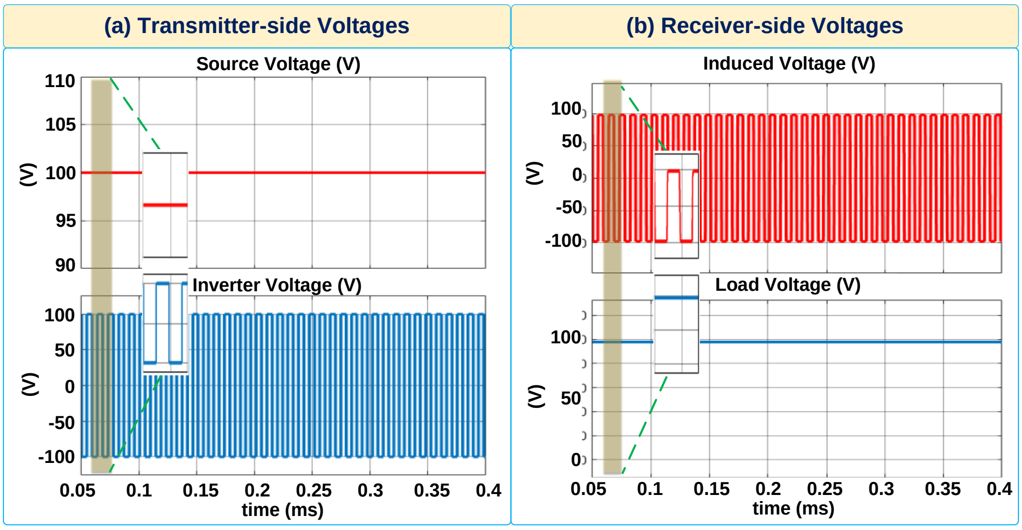

Figure 9. The waveforms of the transmitter-side and receiver-side voltages.

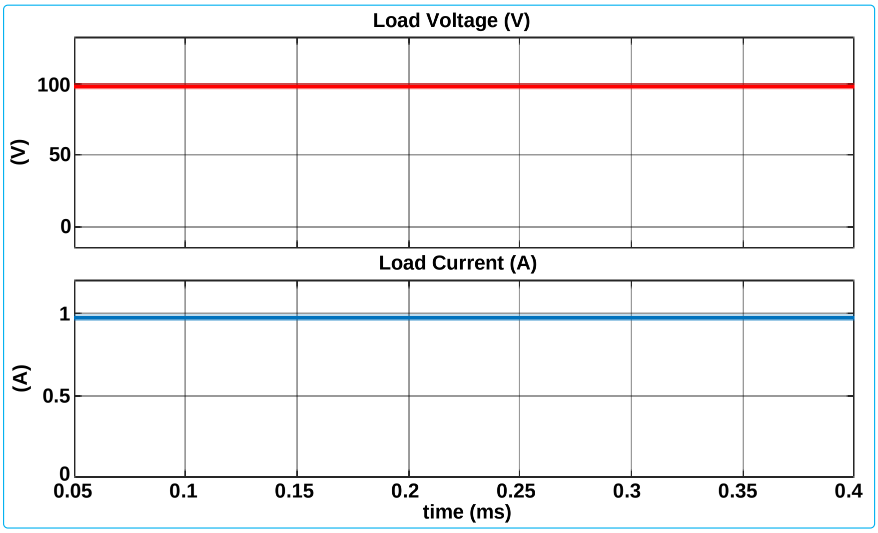

Figure 10 The waveforms of load voltage and current.

5. Conclusions

In this study, we have presented the design and investigation of a series compensated Wireless Power Transfer (WPT) system tailored for low-power DC loads. The operational characteristics of the proposed WPT system have been meticulously introduced, focusing on its series-compensated configuration and resonant operation. The series-compensated WPT system comprises series resonant LC circuits at both the transmitter and receiver sides, with the resonant frequency carefully adjusted to 109 kHz. Through detailed design procedures, the series LC components have been sized and configured to resonate at the specified frequency, ensuring optimal power transfer efficiency.

Moreover, we have provided an in-depth exploration of the electrical equivalent circuit and mathematical equations governing the proposed WPT model. This analytical framework offers valuable insights into the underlying principles driving the system's operation, facilitating a deeper understanding of its behavior. Furthermore, the power electronics interface systems, along with their associated control algorithms and operational characteristics, have been thoroughly presented. These interface systems play a crucial role in regulating the power transfer process and ensuring the stability and efficiency of the WPT system.

To validate the performance of the proposed system, we have modeled and constructed it in the MATLAB/Simulink simulation environment. The designed system parameters have been meticulously configured, and extensive simulations have been conducted to assess its performance under various operating conditions. Our simulation results demonstrate that the proposed WPT system exhibits stable and efficient operation within the designed model and parameters.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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