PWM-Less Utility Frequency Output Capacitive Wireless Power Transfer System

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Keywords

«Wireless Power Transfer», «Capacitive coupling», «On-board charger», «AC-AC converter», «Utility frequency output».

Abstract

This paper proposes a capacitive wireless power transfer (CPT) system designed to provide utility frequency output, specifically targeting onboard chargers (OBCs) for electric vehicles (EVs) in automated parking systems. The system functions by directly injecting high frequency into a fully rectified sinusoidal waveform, thus removing the need for DC link capacitors. On the secondary side, the waveform is converted back into a full-wave rectified sinusoid using a diode rectifier and filter. The unfolder on the secondary side provides the utility frequency output without pulse width modulation (PWM). This topology reduces switching losses and supports system miniaturization. Experimental results from a prototype show AC voltage output at a utility frequency of 50 Hz. The analysis reveals a total harmonic distortion (THD) of 4.10% for the input current and 5.43% for the output current.

Introduction

In recent years, the increasing adoption of electric vehicles (EVs) has driven the demand for efficient and convenient charging infrastructure. This demand is especially notable in urban areas, where automated parking systems are common due to their capacity to accommodate many vehicles within limited spaces. As EV adoption continues to rise, onboard chargers (OBCs) are expected to become more prevalent as a charging method [1–2]. However, challenges arise when integrating an OBC into an automated parking system. One such challenge is supplying power to the OBC, which requires a long cable connection from the grid due to the system's complexity. This may result in a higher risk of a cable disconnection.

A promising alternative to physical cables, Wireless power transfer (WPT) has emerged as a viable solution for supplying power to OBCs. WPT is a technology that allows the transfer of electrical energy between couplers without any physical connections. By eliminating the requirement for direct electrical contact, WPT offers enhanced convenience, improved safety, and greater flexibility in various applications. Demand for this technology is increasing with the spread of battery-powered mobile devices and EVs [3–5].

Currently, many of the WPT systems proposed in the previous research are designed for specific battery voltages and predominantly provide DC output [6–8]. As a result, these systems are not suitable for supplying power to OBCs, which usually require AC input. Solving this problem requires the development of WPT systems that can deliver AC output at utility frequencies.

For instance, in [9–10], WPT systems designed for utility frequency input are proposed. These systems rectify and smooth the grid voltage to DC before power transmission through high-frequency switching on the primary side. On the secondary side, the high-frequency AC is converted to the specific battery voltage by an AC/DC converter. Therefore, the proposed systems in these papers are not suitable for OBC applications, which typically assume an AC input as input. To achieve a utility frequency output in these systems, an inverter must be connected to the system output, which raises concerns regarding decreased power density and power losses.

In [11], a WPT system capable of utility frequency output is proposed. In this system, the received voltage from the transmission circuit is rectified and smoothed using a diode rectifier, and utility frequency output is achieved with PWM. However, the proposed system operates with a DC input. Therefore, AC-DC conversion, such as that described in [9–10], is required between the grid and the proposed system. Since the addition of power converters raises concerns about increased losses, this is not desirable.

Consequently, the DC links in the WPT systems discussed in [9–11] include large electrolytic capacitors for DC smoothing. This raises concerns about the overall increase in circuit size and a shorter system lifespan. Additionally, these papers utilize inductive WPT (IPT) systems, which incorporate coils and cores. IPT is a technology for transmitting power using magnetic fields. However, in IPT systems, when metals other than the coils are present nearby, the magnetic flux links with the metal, resulting in power transmission losses. In automated parking systems, numerous metal components, such as parking plates and support columns, are present, which makes IPT systems unsuitable for such environments.

In this paper, a capacitive coupler is used for a transmission circuit that utilizes an alternating electric field to transfer power wirelessly [12–14]. Compared to an inductive coupler that uses a magnetic field, a capacitive coupler provides several advantages: reduced cost, lighter weight, lower eddy-current loss, increased reliability, and decreased EMI [15–18]. Thus, CPT technology has been thoroughly researched in recent years across a broad spectrum of power levels, ranging from milliwatts to kilowatts.

This paper proposes a capacitively coupled AC-AC WPT system suitable for utility frequency output aimed at supplying power to the OBC as shown in Figure 1. Utilizing a high-frequency injection method eliminates the need for a DC link capacitor. Additionally, it employs an unfolder circuit to enable AC output. As a result, the system achieves low switching loss without needing the high switching frequency of PWM techniques. This paper's main contribution is providing a capacitive wireless power transfer system that outputs utility frequency without PWM on the secondary side.

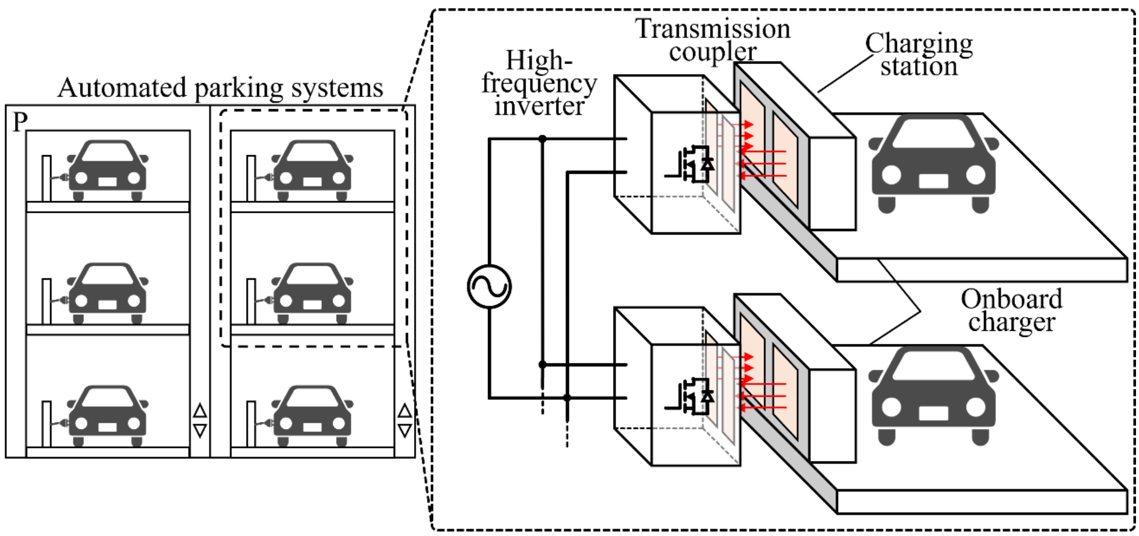

Figure 1. Concept of proposed CPT system for onboard chargers in the automated parking system.

CPT System Configuration

A. Basic CPT System Circuit Configuration

Figure 2 illustrates the circuit configuration of a conventional CPT system that delivers utility frequency output. The input AC voltage on the primary side is converted to DC via an AC-DC converter, followed by a smoothing stage. This DC voltage is fed into the inverter, which produces high-frequency output. The high-frequency inverter employs the displacement current within the coupler interface to supply AC excitation to the primary and secondary resonant networks.

The compensation network is designed to reduce the input impedance at resonance, thereby maximizing system efficiency. In recent years, interest in filter-based configurations utilizing series or parallel LC resonance has grown. A typical four-plate coupler consists of two plates that create the forward path and two additional plates that establish the return path for the resonant current. Materials such as copper, aluminum, and zinc are commonly selected for these couplers due to their properties. The high-frequency AC voltage is rectified and filtered to produce a DC voltage on the secondary side. This DC voltage is then modulated by an inverter through PWM to generate a utility frequency output.

This system highlights the concern of increased circuit volume. Because of their function, the AC-DC converters connected to both the primary and secondary sides require large electrolytic capacitors. As a result, this contributes to lower power density and a reduced circuit lifespan. To tackle this problem, it is essential to eliminate these DC link capacitors.

B. Proposed CPT System Configuration

Figure 3 illustrates the configuration of the proposed WPT system. The proposed system utilizes a high-frequency injection method. In this method, the AC voltage of the utility frequency is switched directly at a high frequency. Therefore,

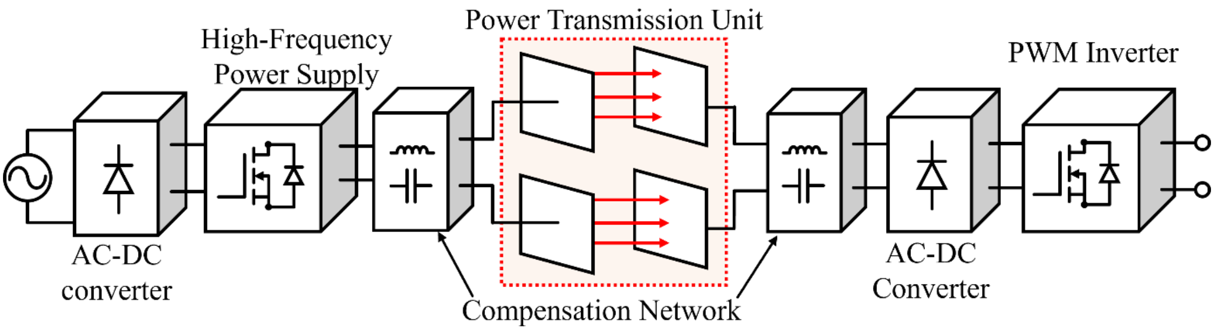

Figure 2: Basic CPT system with utility frequency output.

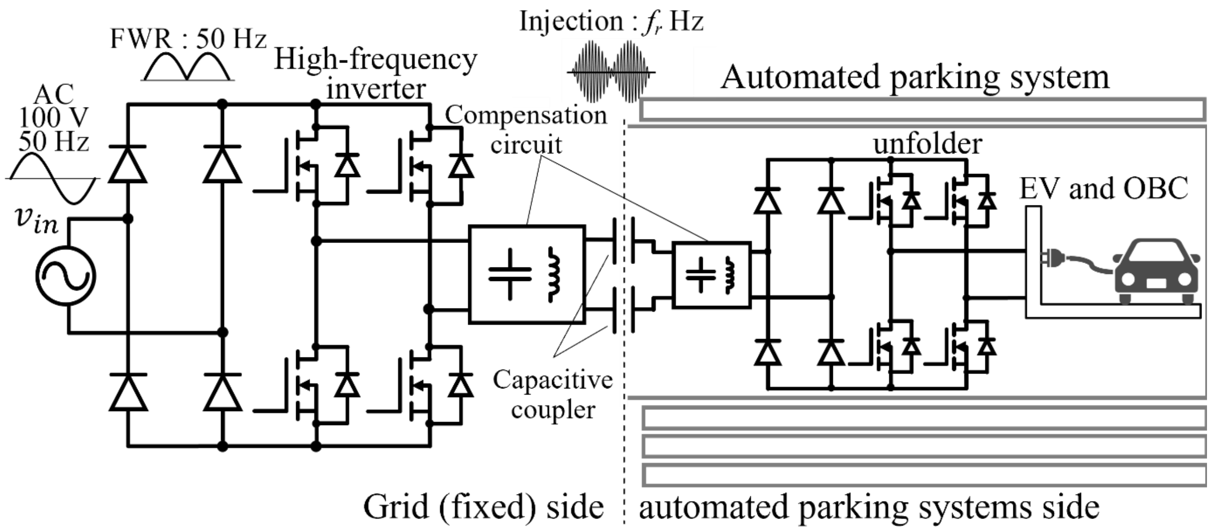

Figure 3: Proposed CPT system with utility frequency output.

high-frequency is injected directly on a full-wave rectified sinusoidal wave for power transmission. On the secondary side, the voltage is regenerated to a full-wave rectified sine wave through a diode rectifier and filter. The secondary-side inverter functions as an unfolder, generating utility frequency output voltage without high-frequency switching. Consequently, large-capacity DC link capacitors are not required on either the primary or secondary sides. Furthermore, conventional PWM with high-frequency switching is unnecessary, as the secondary-side inverter does not need control. This approach significantly reduces switching losses in the secondary-side inverter. As a result, the proposed circuit enables a more compact design.

Figure 4 illustrates the configuration of the compensation network in the proposed system. This system utilizes a CLC-S/S resonant topology that incorporates a series resonant structure with a series CL circuit connected to the primary side. The high-voltage stress between couplers in typical CPT systems results in dielectric breakdown. This method helps to reduce the voltage stress between couplers by allowing the series CL circuit to share part of this voltage stress.

Capacitive Coupler and Compensation Circuit

Figure 4 shows the resonance compensation circuit of a CPT coupler based on a series resonance compensation (S/S) topology, where the compensation inductor is connected in series. In this paper, the resonant frequency is 415 kHz. The resonance condition is

$$f_c = \frac{1}{2\pi\sqrt{LC(1-k)}}, \qquad (1)$$

where $L = L_1 = L_2$, $C = C_1 = C_2$, and k represents the coupling coefficient.

The CPT technology generates a high-frequency electric field between multiple metal plates to transmit power. Therefore, the coupler in a CPT system behaves as a capacitor. However, the capacitance of a pair of metal plates over a short distance in the air is relatively small, typically in the range of a few pico-farads to a few nano-farads. To transmit sufficient power, resonant compensation using an inductor is necessary. Since a large inductance is required for the compensation inductor, CPT systems are typically driven at frequencies from several hundred kHz to several MHz to enable the miniaturization of the transmission circuit [19].

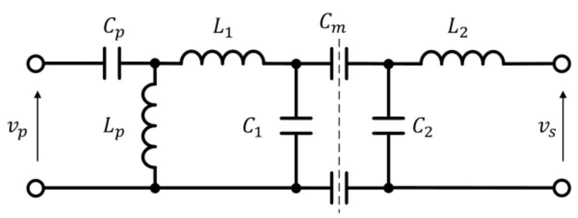

Figure 4: Transmission circuits for CPT systems.

A key feature of CPT systems is their capability to utilize a lightweight coupler constructed from metal plates for power transmission. As a result, there is minimal eddy current, and the system possesses unique properties, such as compatibility with foreign metallic objects [15]. However, the metal plates in a CPT coupler generate a potential difference of several kV. In the topology used in this paper, an *LC* resonant circuit is added to the primary side of the standard S/S topology. This configuration bears some voltage stress, reducing the potential difference between the metal plates.

Simulation Results

Figure 5 displays the simulation circuit, and Table 1 shows the simulation conditions. A 100-W linear load is connected to the system output in the simulation. The primary-side inverter operates at the resonant frequency of the resonant network, whereas the secondary-side inverter operates at the utility frequency (50 Hz). Furthermore, snubber capacitors are attached to both inverters to mitigate a switching surge.

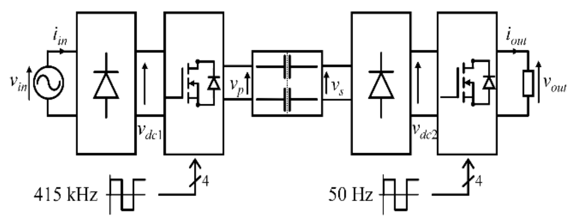

Figure 5: Simulation circuit model.

Table 1: Simulation conditions for the CPT system.

Parameters	Symbol	Value
Input voltage	v_{in}	100 [V]
Output voltage	v_{out}	100 [V]
Output power	P_{out}	100 [W]
Utility frequency	f_s	50 [Hz]
Resonant frequency	f_c	415 [kHz]

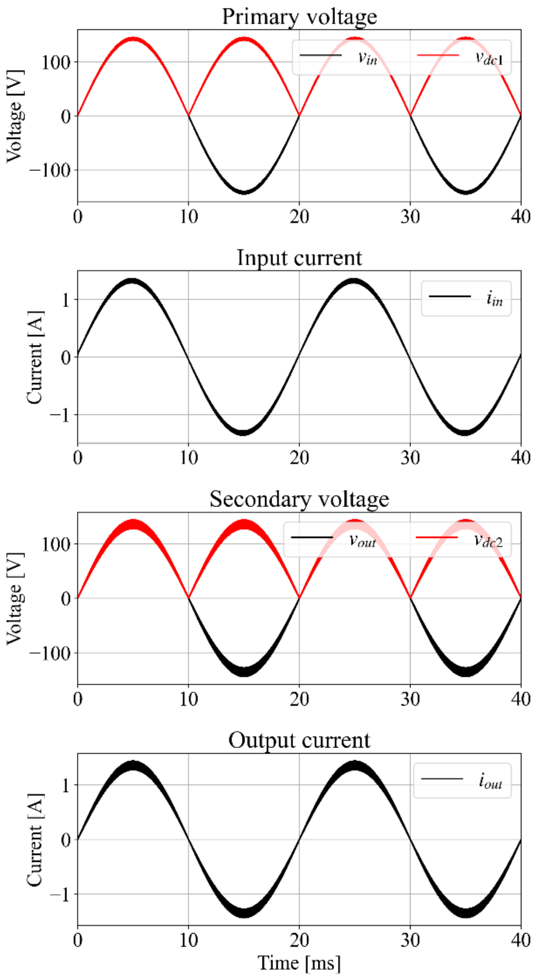

Figure 6: Simulation results of input/output voltages and currents in a CPT system with AC output.

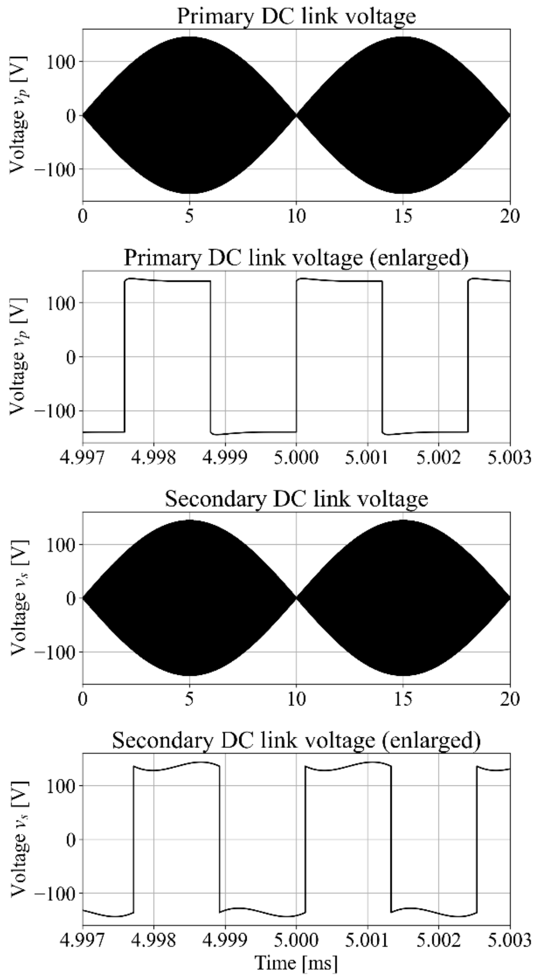

Figure 7: Simulation results of transmission voltage in a CPT system with AC output.

Figure 6 shows the input and output voltages, the DC link voltages on both the primary and secondary sides, and the system input and output currents. The results indicate that the proposed system generates a utility-frequency output. The measured DC link voltages of the proposed system represent a full-wave rectified commercial frequency sinusoidal wave with no DC smoothing applied. The total harmonic distortion (THD) of the input current is 1.71%, while the output current THD is 4.15%. Therefore, in theory, the proposed system does not degrade the grid current THD.
Figure 7 shows the transmission voltages on both the primary and secondary sides. In the proposed system, without DC smoothing, the envelope of the transmission voltage forms a full-wave rectified utility frequency sinusoidal wave. Additionally, the square wave switches at a resonant frequency of 415 kHz. Therefore, the voltage is transmitted with the resonant frequency directly superimposed on the full-wave rectified utility-frequency sinusoidal wave.

Experimental Results

Figure 8 shows the prototype of the proposed CPT system and CPT coupler. The parameters are also detailed in Table 2. Prototype experiments were carried out to verify the functionality of the suggested system. The input voltage and frequency are 100 V and 50 Hz, respectively. In addition, snubber capacitors are implemented in the DC link of the prototype to absorb switching surges.
Figure 9 shows the input/output voltage and current waveforms, and Table 2 shows the prototype conditions. The sinusoidal output voltage and current indicate that the proposed system generates utility frequency output. Furthermore, the output current THD is confirmed, and the results indicate that the input

current THD is 4.10%, while the output current THD is 5.43%.

Figure 10(a) shows the transmission voltage waveforms of the system. The input and output voltage envelopes are both observed at 100 Hz, which is consistent with the proposed system's operation of directly switching the commercial frequency full-wave rectified voltage without DC

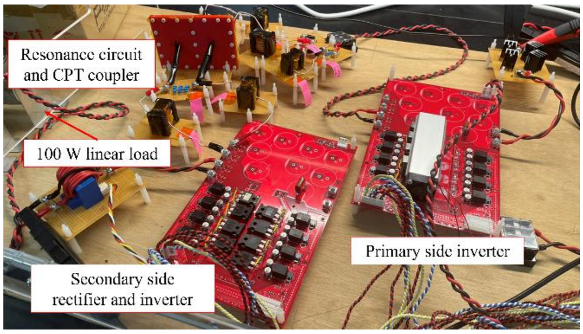

Figure 8(a): Experimental setup.

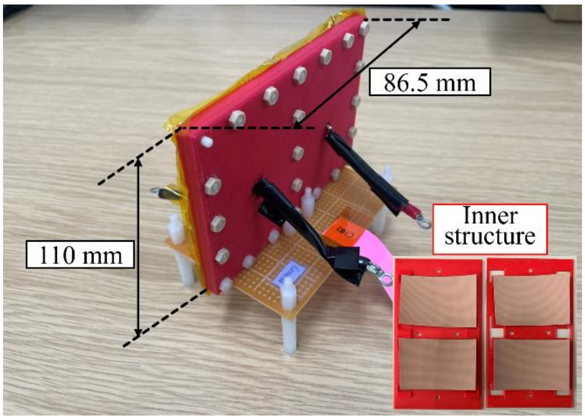

Figure 8(b): Coupler structure.

Table 2: Actual experimental conditions.

Parameters	Symbol	Value
Input voltage	v_{in}	100 [V]
Output power	P_{out}	94 [W]
Utility frequency	f_s	50 [Hz]
Resonant frequency	f_c	415 [kHz]
DC link capacitor	$C_{dc1,2}$	22 [nF]
Unit capacitance constant	H_{dc}	4.4 [μJ/VA]
Boost stage capacitor	C_p	2696 [pF]
Boost stage inductor	L_p	57.28 [μH]
Primary side compensation inductor	L_1	818.4 [μH]
Primary side external capacitor	C_1	141.6 [pF]
Secondary side compensation inductor	L_2	423.4 [μH]
Secondary side external capacitor	C_2	348.6 [pF]
Coupling capacitor	C_m	115.1 [pF]

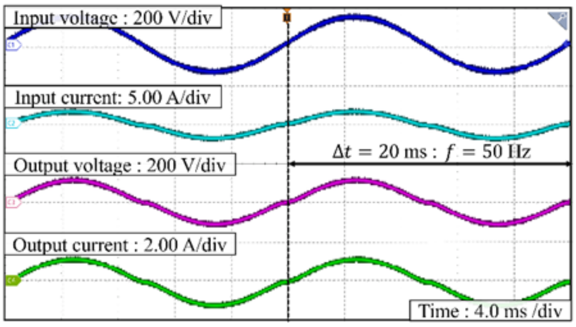

Figure 9: Experimental results of transmission voltage in a CPT system with AC output.

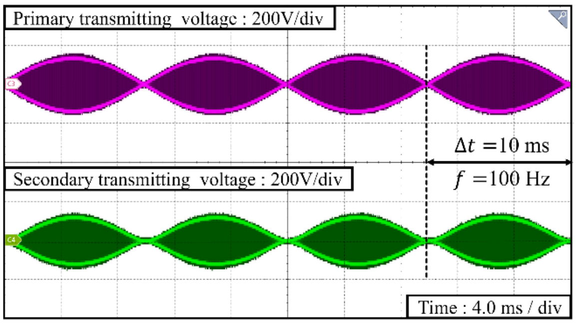

Figure 10(a): Experimental results of transmission voltage in a CPT system with AC output.

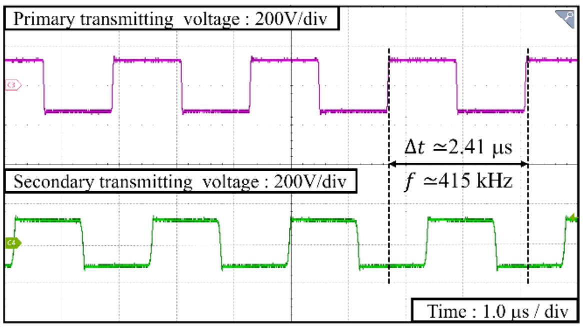

Figure 10(b): Experimental results of enlarged transmission voltage in a CPT system with AC output.

smoothing. Figure 10(b) presents an enlarged view of Figure 10(a). A 415-kHz square wave voltage is observed on both the primary and secondary sides. This frequency matches the switching frequency of the primary-side inverter and the resonance frequency of the compensation circuit. As a result, the resonance frequency component is introduced into the full-wave rectified voltage of the utility frequency.

This outcome aligns with the expected operation of the proposed system. Therefore, the proposed system achieves power transmission by employing the high-frequency injection method.

Conclusion

This paper presents a CPT system optimized for utility frequency output, supplying power to OBCs in automated parking systems. By utilizing a high-frequency injection method, the system eliminates the need for a large DC link capacitor by bypassing traditional DC smoothing. The secondary-side inverter acts as an unfolder, producing a utility frequency output with minimal switching losses, thereby reducing the overall circuit volume. Experiments with the prototype system confirm that it outputs a constant voltage at utility frequency. At the rated power, the total harmonic distortion (THD) was 4.10% for the input current and 5.43% for the output current. Future work will focus on designing the parameters of the transmission and compensation circuits, as well as redesigning the power conversion circuit to support high-power capacities.

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