A Small-scale Inductive Wireless Power Transmission Prototype for Charging Electric Vehicles

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***Abstract*— The continued commitment of the global community to alleviate the effects of climate change will result in widespread use of clean energy technologies including electric vehicles (EV). Safety and convenience are among the key features for successful and smooth transition to EV-based transportation. Therefore, wireless charging stations will become one of the emerging trends in the field of EV charging that has recently received considerable critical attention from researchers and practitioners to respond to the potential power and energy needs of EV fleets. Inductive wireless power transmission is widely adopted in wireless charging techniques in EV applications for its capability to efficiently transmit high power levels over long distances that can reach up to 40 cm. In this paper, a one-input one-output inductive wireless power transmission prototype is designed for EV charging and the efficiency under different charging distances is practically determined. The real voltage and current waveforms of the voltages and currents (in the transmitted and received sides) are presented to validate the robustness of the proposed prototype for battery charging under various airgap distances.**

Keywords*— *Wireless power charging, electrical vehicles, wireless inductive coupling.

I. Introduction

Transportation electrification is one of the most effective measures taken to reduce the impacts of climate change as transportation contributes to about 20% of global greenhouse gas emissions [1], [2]. The importance of decarbonizing the transportation sector was signified by the international community in the commitments made in the latest climate conference COP26 in 2022. Countries, automobile manufacturers and environmental organizations have cooperate to accelerate the transition to zero emission vehicles by pledging to achieve 100% electric vehicles (EV) sales within the next two decades [3]. The widespread use of EVs will require new infrastructure and technologies to facilitate efficient and reliable operation of EV fleets. The wire/wireless charging stations for EVs are one of the vital issues especially in smart grids. The main applications of wireless power transfer (WPT) systems in EVs are: (i) fixed battery charging system based on inductive wireless power transmission (IWPT) and (ii) variable wireless drive system for power feeding interior wheel motors (IWM) [4]. For the former applications, development of fast and efficient charging system is essential to achieve optimal energy from the source to load (e.g. battery) [5]. A wireless charging system is an emerging approach developed to meet the power needs of an EV besides wired charging. In fact, the advantages of wireless charging systems are suitability, safety in moist environments, no need for plugs and cables, and inherited galvanic isolation. Nikola Tesla was the first engineer in the world, who constructed a simple wireless power transmission system through his famous yet-overlooked Wardenclyffe Tower experiment in the early years of the 20th century. That experiment focused on transmitting electric power between two distant towers without cables. 100 years after Tesla's attempt, this concept was revived by a research group from MIT that succeeded in transmitting about 60 watts to a load located about 2 meters airgap from the transmitting source. Although the transfer efficiency was 40%, this achievement constituted challenges in modern wireless power transmission technologies [6]. The main concept of wireless charging system is transferring the power from an energy source to a battery without any means of physical connection based on the electromagnetic phenomena between passive elements. Depending on the electromagnetic coupling technique, there are two types of wireless power systems, which are inductive and capacitive.

In inductive wireless power transmission (IWPT), power is transferred from a primary coil (transmitter, Tx) to a secondary coil (receiver, Rx) via mutual electromagnetic induction. In reference [7], a new topology for improving the IWPT system has been demonstrated. The structure of the sending and receiving sides includes: (i) a transmitting coil, which is aligned with a transmitting resonator (i.e. parallel LC circuit), (ii) a receiving coil which is aligned with a second receiving resonator. This topology is called four-turn-winding system for protection issues. The weakness of this configuration is the huge size of the IWPT.

The typical frequency of IWPT lies between 100-300 kHz depending on the transmission distance which can be typically around 20-40 cm. In capacitive wireless power transmission (CWPT), two pairs of conductive plates are used as the transmitter and receiver. The transmitter pair of plates is supplied with high frequency voltage resulting in an induced electric field between the transmitter and the receiver. This transmitted electric field generates potential difference between the receiver's plates sensed as load voltage. The amount of power that can be transmitted in CWPT is proportional to the size of the system components, which makes CWPT systems cost effective in low power applications such as in portable electronic devices [8]. Hence, IWPT systems are more efficient and feasible for long-distance high power applications [9]. As a result, IWPT is widely adopted in EV applications and as reviewed and demonstrated in references [10-11]. Reference [12] has developed a 5 kW IWPT system for EV based on dual-sided controller, and the efficiency of the system has been determined at different operating conditions. With the expansion of smart grid technology including vehicle-to-grid (V2G) schemes, the bidirectional power flow has become a necessary feature in charging stations based on wired or wireless technologies [13], [14]. A multi-output bidirectional IWPT system for V2G application has been presented in Reference [15]. In that paper, the system has been tested for transmitting 1.5 kW over a 4 centimeters distance between Tx and Rx coils. Achieving high efficiency is one of the critical factors to implement efficient IWPT system. Thus, a considerable body of research has been carried out on development of high efficiency IWPT systems. In reference [16], the efficiency has been improved by adding a pair of intermediate coils with resonant capacitors in order to enhance the effective magnetizing impedance between the source and load-side windings. Evaluating the efficiency at which power is transferred from the source to the load is another imperative issue for designing an acceptable IWPT system. In reference [17], a modified mathematical approach has been developed to determine the efficiency of an IWPT system. In that paper, the derived model has been practically verified. Design the geometry of the magnetic coupler in IWPT system can be considered as a crucial aspect, that influences on the quality of mutual inductance between Tx and Rx coils and the efficiency. In reference [18], the effectiveness of square and circular planar spiral coils in loosely coupled WPT systems have been analyzed. The analytical models of the two geometries have been compared in terms of the self and the mutual inductances of the coils by considering the line spacing, coils misalignments and the semi-infinite substrate properties. Another research field dealt with another challenge that faces IWPT, which is the misalignment between Tx and Rx coils at wireless charging stations for EVs. Coil misalignment significantly affects on the efficiency of charging duration due to increase in airgap distance and magnetic flux leakage between the coils [19], [20]. The approaches to compensate efficiency reduction due to misalignment can be found in three categories [21] as following: (i) misalignment-tolerant coil design techniques [22]; (ii) frequency-tuning power electronic topologies [23]; and (iii) parking-assistant methods in which the driver is aided by sensors and monitoring systems to accurately align the EV with the charging plug [24].

The coupling coefficient between the coils of the IWPT system is a key parameter in the design of the system because it determines how much magnetic flux can be transmitted from the transmitter to the receiver through the air gap between Tx and Rx. Consequently, it defines the amount of the transmitted power. Therefore, it is essential to study the relation between the distance between the coils and the coupling coefficient and its effect on the efficiency of the IWPT system [25]. This paper presents an overview of a single-input single-output IWPT system for EV battery charging. A small-scale prototype is designed and the efficiency is practically determined under various airgap distances. The general block diagram of the fixed wireless power charging system is illustrated in Fig (1) [2].

The system performance is demonstrated at different transmission distances up to 4 cm. The remaining part of this paper proceeds as follows: in Section 2, a description of the IWPT prototype is presented including the design of the electronic circuits and the resonance inductive power transfer. Section 3 discusses the experimental results. Section 4 summarizes the main conclusion of this paper.

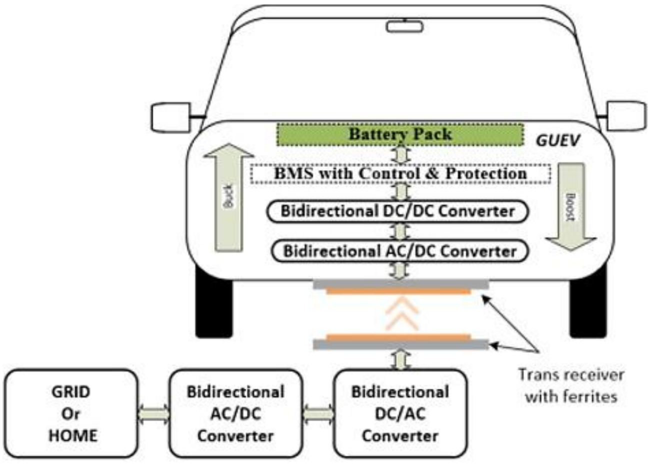


Fig. (1) Scheme of a static charging IWPT system for an electric vehicle [2].

II. The Proposed IWPT Prototype

This section presents the configuration of the IWPT prototype including the design of the Tx and Rx electronic circuits especially the inductive coupling circuits. The essential power converter Tx circuit is the inverter to produce a sinusoidal signal from the DC supply. In this paper, class D inverter is implemented for the proposed IWPT due to its advantages, which are: (i) low voltage across power switches, that is equal to the input DC voltage; (ii) the control scheme for generating PWM signals is simple and the output power can be controlled in the wide range. The type Class D is also called a half-bridge inverter connected with a series resonance filter is used to generate a high-frequency voltage in Tx side. The frequency of the PWM control signal is adjusted to the wireless resonant frequency (f_{wpt}) for driving the MOSFETs. When the upper MOSFET is closed, the current follows from the DC supply to charge the capacitor but only the fundamental component can pass through the circuit. The capacitor is charged from zero to voltage up to the magnitude of input DC voltage. In the second period, the capacitor discharges through the lower MOSFET. This process repeats every cycle, where the upper MOSFET is closed from zero to ($1/2f_{wpt}$) and the lower MOSFET from ($1/2f_{wpt}$) to ($1/f_{wpt}$).

A. The Practical Circuit Design and Implementation

The proposed IWPT consists of four parts: (i) the transmitter side; (ii) the inductive coupling resonant circuit and (iii) the receiving side. In the transmitter side, a high-frequency inverter for converting the DC voltage from the source into an AC voltage is designed to generate a sinusoidal waveform. Therefore, the maximum amount of power that can be transfer to the load should be calculated to specify the rated of the power MOSFETs. It is worth to know that the type of the inverter is Class-D due to its features, which are the structure simplicity and the high efficiency at high frequencies. The high-frequency inverter is connected the inductive coupling circuit, which is composed of two tightly-wound coils aligned electromagnetically. The receiver and transmitter coils are made with planner spiral geometry for low self-inductance and improved efficiency. The compensation circuit, which is built with parallel capacitors, interfaces the inverter to the Tx coil. The compensation capacitors are necessary to compensate the leakage inductance in the airgap by providing the reactive power required to produce the compensating magnetic field. For the same purpose, a compensation circuit is needed on the Rx side. Therefore, a parallel capacitor is also used at the terminals of the Rx coil to improve the compensation efficiency. The high-frequency power at Rx is fed to a half-wave diode rectifier to generate DC power for charging the battery of the EV. Figures (2-5) show the schematic and real circuits of the IWPT prototype at Tx and Rx sides.

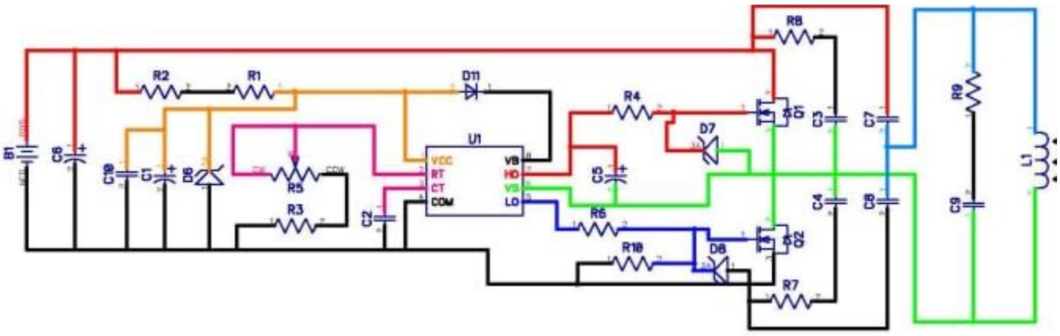


Figure 2. Schematic circuit of the IWPT system at the Tx side.

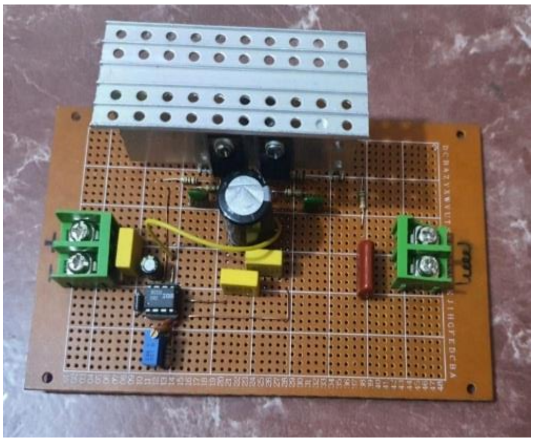


Figure 3. Real circuit of the IWPT system at the Tx side.

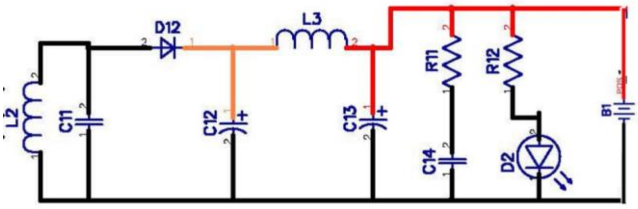


Figure 4. Schematic circuit of the IWPT system at the Rx side.

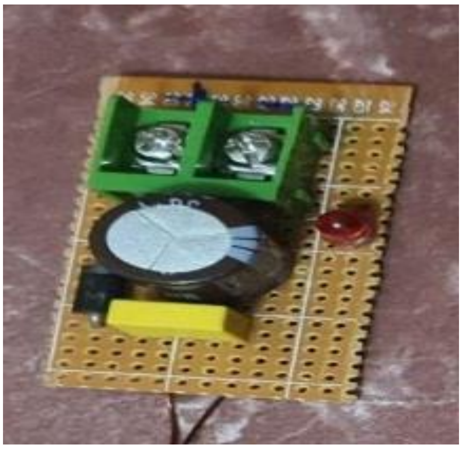


Figure 5. Real circuit of the IWPT system at the Rx side.

The parameters of the above electronic circuits are summarized in TABLE I.

TABLE I. The parameters of the designed circuits.

Parameter	Specification	Parameter	Specification
B1: Battery	16 V	C_5	100 µF
D7,D8,D6	Zener Diodes	C_6	2200 µF
Q1,Q2	IRFP460	C_7,C_8	100 nF
D11	UF 4007	C_9	6.8 nF
U1	IR2153	C_{10}	100 nF
R_1	3.3 kΩ	L_1	29 µH
R_2	2.2 kΩ	L_2	29 µH
R_3	9.9 kΩ	L_3	1 µH
R_4,R_5,R_6	10 Ω	C_{11}	100 nF
R_7,R_8	10 Ω	C_{12}	680 µF
R_9	6 Ω	C_{13}	10 µF
C_1	100 µF	C_{14}	1 nF
C_2	680 pF	D2	Red LED
C_3,C_4	22 nF	D12	HF A 159B60

B. Design of Inductive Coupling circuit

One of the key aspects to keep in mind when designing the IWPT coils is to achieve a high coupling coefficient between the receiver and the transmitter. The coupling coefficient can be improved by reducing the self-inductance of the coils; however, it is still required to keep a sufficient mutual inductance between them. In tightly-wound coils, the self-inductance can be decreased by increasing the distance between the two sides of the coil, i.e., increasing the coil pitch. Reducing the coil pitch will also downgrade the mutual inductance between the two coils but to a smaller extent compared to the extent to which the self-inductance is reduced. The challenge to estimate the optimal pitch is how to achieve the highest coupling coefficient. For circular type, the main empirical equations for designing the coupling coils are given below, which are based on modified Wheelers' formulae [9], where the result of Eq. (1) in (µH):

$$L = \frac{N^2\, a^2}{(30\, a - 11\, D_{in})} \tag{1}$$

$$a = \frac{D_{in} + N*(W+s)}{2} \tag{2}$$

The parameters in the above equations are defined as follows: D_{in} is the inner diameter in inches; s is the distance between turns in inches; w is the wire diameter in inches; N is the number of turns. In this paper, the self-inductance of the Tx and Rx coils are the same and equal, the mutual inductance is decreased by decreasing the coefficient of coupling as shown in Eq. (3).

$$M = k\,L \quad (3)$$

It is worth noting that the wireless resonant frequency, f_{wpt}, is estimated by varying different parameters affecting the gain of voltage produced within the coils. Parallel resonance or near-to-resonance circuits can be utilized to decrease the power losses. The use of the two types in parallel makes the inductor feed the capacitor, and vice versa, maintaining the same resonant current in the circuit, and converting all the current into useful energy. At f_{wpt}, the magnitude of inductive reactance and the capacitive reactance are equal as illustrated in Eq. 4.

$$f_{wpt} = \frac{1}{2\,\pi\,\sqrt{L\,C}} \quad (4)$$

The control circuit for the MOSFETs of the transmitter inverter is designed using IR2153 controller. It is based on self-oscillating, which includes a single resistor and a timing capacitor as shown in Fig. 4. This circuit exhibits 50% duty cycle and fixed frequency, which is determined by Eq. 5 [25]. It is clear that 75 Ohm term accounts for resistance of the oscillator output pin, RT.

$$f = \frac{1}{1.38\,(R_1 + 75\Omega)C_1} \quad (5)$$

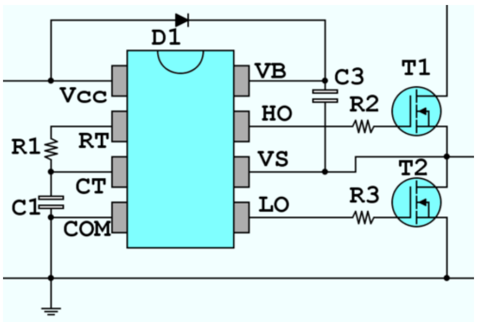


Figure 4. Circuit diagram of half-bridge driver (IR2153) for a Class-D inverter.

In this paper, the wireless resonance frequency f_{wpt} is determined using Eq. (4), which is about 95.113 kHz, where R_1 and C_1 are chosen respectively about 12.4 kΩ and 611 nF. The design parameters of the IWPT prototype are listed as follows: D_{out} = 2.560 inches; D_{in} = 1.457 inches; W = 0.024 inches; s = 0.029 inches; N = 20 turns.

The design results are found as follows: the self-inductance, L is about 28 μH and the wireless resonant capacitance, C is about 100 nf.

III. Experimental Results

The experimental setup of the developed IWPT prototype is shown in Fig. 5. The system was used to charge a 3.7 V, 2 Ah Lion battery of a smart robot car at different transmission distances between the transmitter side (Tx) and the receiver side (Rx). The distance was changed from 1 cm to 4 cm at a step of 1 cm. At each experimental step, the input and output voltage, current and power as well as the transmission efficiency were measured and calculated. The waveforms of voltage and current at Tx and Rx sides (e.g. at a transmission distance of 1 cm) are shown in Fig. 6 and Fig. 7, respectively.

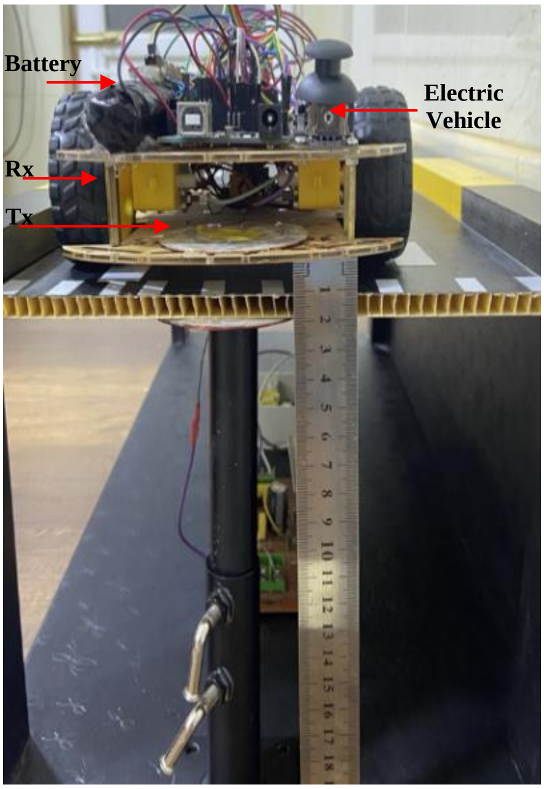
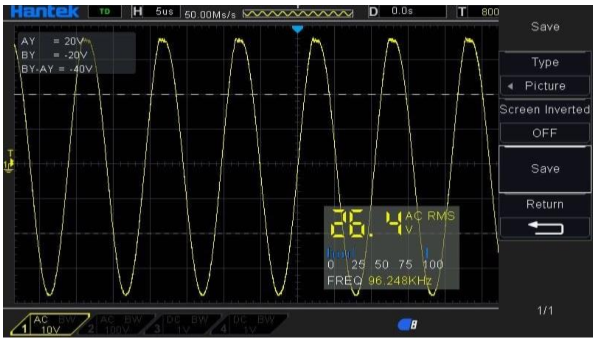
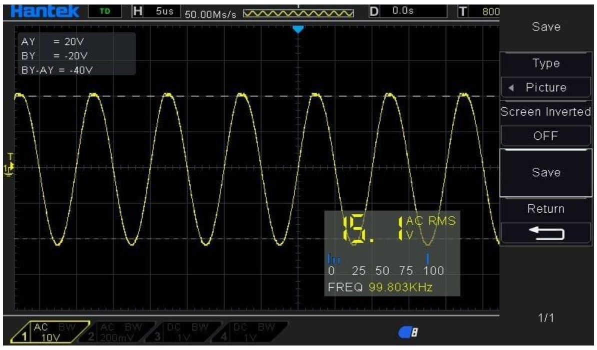


Figure 5. The implemented static charging IWPT prototype.

It can be noticed that the experimental voltage waveforms are corresponding to the duty cycle and switching sequences of the Class-D inverter achieving sufficiently sinusoidal waveforms. The observed current waveforms were also fairly sinusoidal following the voltage waveforms.

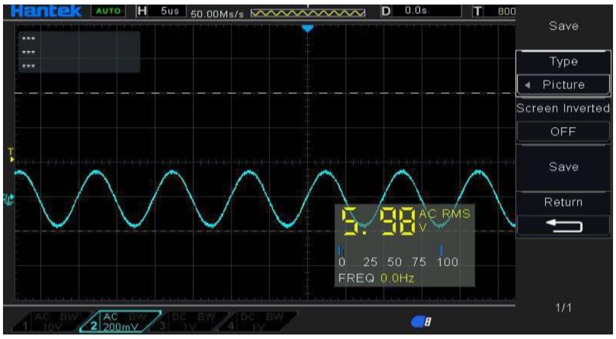


(a) Tx side.

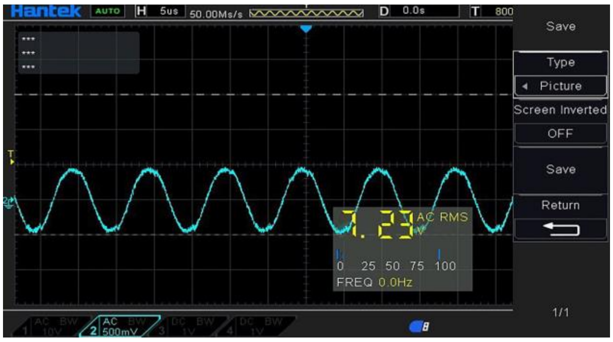


(b) Rx side.

Figure 6. Voltage waveforms at 1cm.



(a) Tx side.



(b) Rx side.

Figure 7. Current waveforms at 1cm (the scale shunt resistance is 10 Ohms).

The experimental measurements of the Tx and Rx voltage and current as well as the transmission efficiency at different distances are listed in Table II. It can be observed that when the distance between the transmitter coil and the receiver coil is increased the RMS voltage decreases. This decrease is attributed to the drop in the air gap flux between the coils. The highest efficiency achieved was at a distance of 1cm and it was about 69%. The efficiency declined with the distance and dropped drastically at 4 cm. The drop in the efficiency is self-explanatory and attributed to the deterioration of the wireless power transmission process at distances longer than 1 cm.

IV. TABLE II. EXPERIMENTAL RESULTS.

D (cm)	**Tx**		**Rx**		**Power (W)**		**Eff. (%)**
	***V_{Tx}* RMS (V)**	***I_{Tx}* RMS (A)**	***V_{Rx}* RMS (V)**	***I_{Rx}* RMS (A)**	***Tx***	***Rx***	
1	26.4	0.598	15.1	0.723	15.8	10.9	69.0
2	24.6	0.515	13.6	0.559	12.6	7.60	60.3
3	13.6	0.459	10.6	0.331	6.20	3.50	56.6
4	13	0.42	5.58	0.245	5.50	1.40	25.5

V. CONCLUSION

A wireless power transmission system is built and experimented for wireless charging applications. The system is based on inductive coupling technique where two spiral coils are used for transmission and receiving ends. A Class-D inverter is used as the power converter for high-frequency voltage transformation. A small-scale prototype of the system is tested to charge a 3.7 V, 2 Ah Lion battery of a smart robot car. The experimental results confirmed the functionality of the system in transmitting 15.8 W at a 69% efficiency. The efficiency dropped at distances longer than 1 cm because the voltage and current decreased. Although the system presented in this work is a small-scale experimental prototype, it provides useful practical insights on the design and operation of inductive wireless power transmission systems for EV.

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