

6.78MHz Capacitive Coupling Wireless Power Transfer System

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Abstract

Wireless power transfer technologies typically include inductive coupling, magnetic resonance, and capacitive coupling methods. Among these methods, capacitive coupling wireless power transfer (CCWPT) has been studied to overcome the drawbacks of other approaches. CCWPT has many advantages such as having a simple structure, low standing power loss, reduced electromagnetic interference (EMI) and the ability to transfer power through metal barriers. In this paper, the CCWPT system with 6.78MHz class D inverter is proposed and analyzed. The proposed system consists of a 6.78MHz class D inverter with a LC low pass filter, capacitor between a transmitter and a receiver, and impedance transformers. The system is verified with a prototype for charging mobile devices.

Key words: 6.78Mz, Capacitive Coupling Power Transfer, Class D inverter, Wireless Power Transfer

I. INTRODUCTION

Recently, the application of wireless power transfer (WPT) in charging mobile devices and the electric vehicles is widely researched. WPT are generally classified as magnetic resonance, inductive coupling, and capacitive coupling. Magnetic resonance WPT uses resonance with the transmitting coil and receiving coil. The method has many advantages such as long distance transfer and user convenience. However, the system has not been commercialized because of electromagnetic interference (EMI), human activity, and some imposed regulations [1], [2]. Inductive coupling WPT follows the same principle of a transformer in the power converter. Despite having good efficiency and developed commercialization techniques, inductive coupling WPT has disadvantages such as one position power transfer, heat dissipation in the metal barrier, and the large coil volume [3], [4]. The prior two approaches employ the magnetic field, hence the presence of radiation noise and power transfer metal interference. In contrast, capacitive coupling wireless power transfer (CCWPT) uses electric field and displacement current to transfer wirelessly power; this approach is also called contactless power

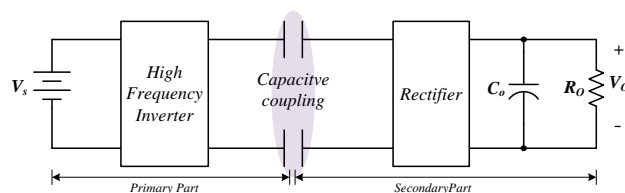


Fig. 1. The simple structure of the CPT system.

transfer [5], [6].

Fig. 1 shows the simple structure of the CCWPT system. Direct current (DC) voltage is converted to alternating current (AC) voltage that supplies two primary metal plates using a high-frequency inverter. Two secondary plates are located adjacent the structure and the electric field enables the displacement current to flow. The DC output voltage can be obtained with a rectifier. Coupling capacitance is an important factor in transferring energy and operation stability. However, the realized capacitance is limited by the available area of the device being used. The power conversion circuit is a series resonant type circuit that produces high frequency AC voltage. In the other approaches, a simple full bridge inverter is used to make the series resonance between the inductor and coupling capacitor [7]. If the obtained capacitance is very small, the simple resonant circuit limits the transferring. The quality factor is very high hence the operation is unstable.

A high-frequency operation and impedance transformation is a viable solution to overcome this drawback. Operation

Manuscript received Jul. 29, 2014; accepted Feb. 26, 2015
Recommended for publication by Associate Editor Hao Ma.

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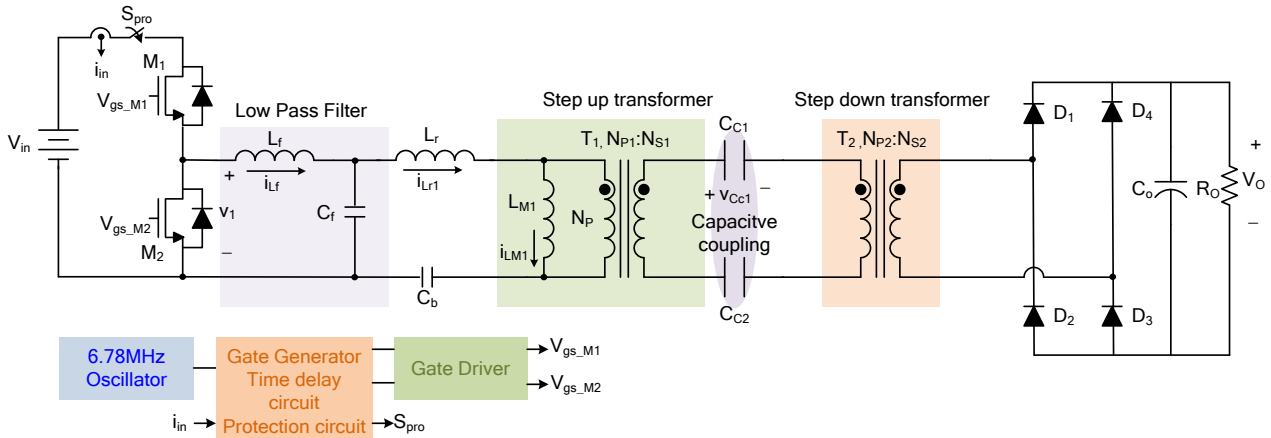


Fig. 2. A proposed 6.78 MHz CCWPT system.

frequency selection is necessary to meet wireless regulations in mobile wireless charger applications and standardize the operation frequency of industrial, scientific, and medical (ISM) band. A silicon power semiconductor cannot be driven with a very high frequency like the GHz operation. 6.78MHz and 13.56MHz ISM bands can drive the silicon power semiconductor, reducing the quality factor and meeting regulations. However, the 13.56MHz band is already used in other application. Hence 6.78MHz operation can meet wireless regulations without obstructing other devices and help transfer energy with a small capacitance in the CCWPT.

This paper is proposes a 6.78MHz CCWPT system with a Class D inverter, LC low pass filter, and impedance transformation circuit. A theoretical estimation of the capacitance is shown according to width of the plastic molding. Moreover, the design procedures of the LC filter and impedance transformation circuit are shown with the area of the electro metal plates and receiving power. The system is verified with the 5V and 800mA output for charging a mobile device.

II. A PROPOSED SYSTEM

Fig. 2 shows a proposed 6.78MHz CCWPT system. S_{pro} is a path switch that controls the input power by monitoring input current. Class D inverter and LC low pass filter are used for the transmitting circuit. The LC low pass filter suppresses EMI noise from the rectifier. A zero voltage switching (ZVS) can be achieved by below resonance operation of the L_f and C_f . L_r is the transferring power to the receiver by a resonance with coupling capacitors, C_{c1} and C_{c2} . C_b is a DC blocking capacitor for non-saturation of a step-up transformer. A step-up transformer is used to make the impedance of the coupling capacitance, C_{c1} and C_{c2} , whereas the small and step-down transformer reduces the quality-factor (Q-factor) of the series resonant circuit. The optimized Q-factor can be obtained by turn-ratios of the step-up and step-down transformers. Fig. 3 shows the waveforms of the resonance

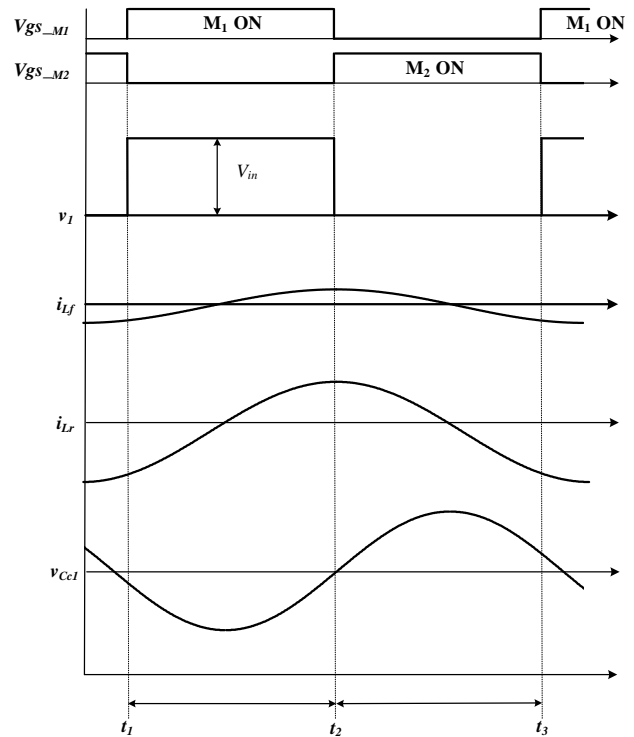


Fig. 3. Waveforms of the proposed system.

parts. The resonance with L_r , C_{c1} , and C_{c2} facilitates the energy transfer to the load. A driving stage consists of a 6.78MHz crystal oscillator, gate signal generator, time delay circuit, protection circuit, and gate driver. The proposed system works with high frequency, hence the time delay circuit design and gate driver are important. The driving block is applied with a general circuit.

III. DESIGN CONSIDERATIONS

A. Capacitance Estimation

Fig. 4 shows the simple structure of a capacitor in the transmitter and receiver. The capacitor can be made with

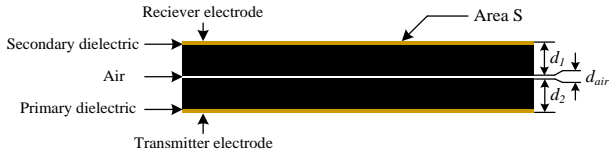


Fig. 4. Structure of capacitor between transmitter and receiver.

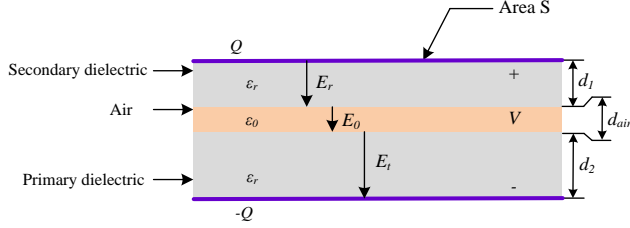


Fig. 5. Capacitance estimation by the Gauss' law.

electrodes and dielectric layers in the transmitter, receiver, and air. The capacitance can be derived using the Gauss' law, as shown in Fig. 5 [8]. Voltage, V , across the capacitor and capacitance can be expressed in the Gauss's law, as follows

$$V = E_r d_1 + E_0 d_{air} + E_t d_2$$

$$= \frac{Q/S}{\epsilon_r \epsilon_0} d_1 + \frac{Q/S}{\epsilon_0} d_{air} + \frac{Q/S}{\epsilon_r \epsilon_0} d_2 \quad (1)$$

$$C = \frac{Q}{V} = \frac{\epsilon_0 S}{(d_1 + d_2)/\epsilon_r + d_{air}} \quad (2)$$

where S is the area of the electrode, E_r is the electric field in the receiving substrate, E_0 is the electric field in the air part, E_t is the electric field in the transmitting substrate, ϵ_0 and ϵ_r are the permittivity of the air and dielectric substrate, and d_1 , d_{air} , and d_2 are the widths. The capacitance is critically determined by the width of the transmitting and receiving dielectric layer. The capacitance can be obtained according to the width of the dielectric layer if the dielectric layer is the acrylonitrile butadiene styrene (ABS) resin, the relative permittivity of the ABS resin is about 4, the d_0 is 0.00008 m, and the area of the electrode is 0.004m², as shown in Fig. 6. The capacitance is approximately 60pF in a 2mm-width dielectric layer.

B. Low Pass Filter Design

A low pass filter design is important for the ZVS operation of the main switches and suppression of harmonic component. Fig. 7 shows the AC equivalent circuit for the LC filter design. R_{ac} is an equivalent AC resistance for the fundamental transfer gain for the resonant DC/DC converter and can be expressed as

$$R_{ac} = n_1 n_2 \frac{8}{\pi^2} R_o \quad (3)$$

where R_o is the output resistance [9]. The impedance of the LC low pass filter can be expressed as

$$Z_{ac} = j\omega L_r + \frac{1}{j\omega(C_{C1} + C_{C2})/C_{C1}C_{C2}/n_1^2} + R_{ac} \quad (4)$$

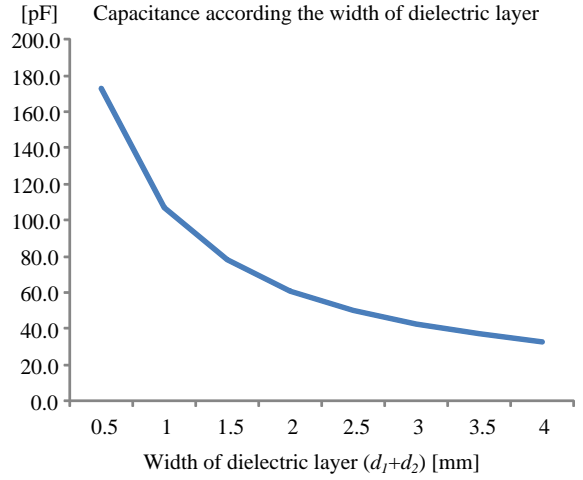


Fig. 6. Capacitance according the width of dielectric layer.

where ω is the angular frequency. The design of L_f and C_f can be obtained with the Butterworth low pass filter. The Butterworth filter can be designed using equation (5) and equation (6) to determine the L_f and C_f values

$$L_f = \frac{|Z_{ac,\omega_c}| \times \sqrt{2}}{\omega_c} \quad (5)$$

$$C_f = \frac{1}{|Z_{ac,\omega_c}| \times \omega_c \times \sqrt{2}} \quad (6)$$

where ω_c is the cutoff frequency and $|Z_{ac,\omega_c}|$ is the magnitude of the output impedance at the ω_c .

C. Voltage Gain Considering the Parasitic Component of the Step-Up and Step-Down Transformer

Ideally, the fundamental voltage gain of the CCWPT is part of the resonant frequency because the CCWPT is a series resonant converter, as shown in Fig. 8. The voltage gain can be expressed as

$$G_v = \frac{V_R^F}{V_{in}^F} = \frac{I}{\sqrt{I + Q^2 \left(\frac{f}{f_0} - \frac{f_0}{f} \right)^2}} \quad (7)$$

$$Q = \frac{\sqrt{\frac{L_r}{\left(\frac{C_{C1} + C_{C2}}{n_1^2 (C_{C1} \times C_{C2})} \right)}}}{R_{ac}} \quad (8)$$

$$f_0 = \frac{1}{\sqrt{L_r \left(\frac{C_{C1} + C_{C2}}{n_1^2 (C_{C1} \times C_{C2})} \right)}} \quad (9)$$

where V_R^F and V_{in}^F are the fundamental components of the input and output, Q is the quality factor, f_0 is the resonant frequency, and f is the switching frequency of the class D

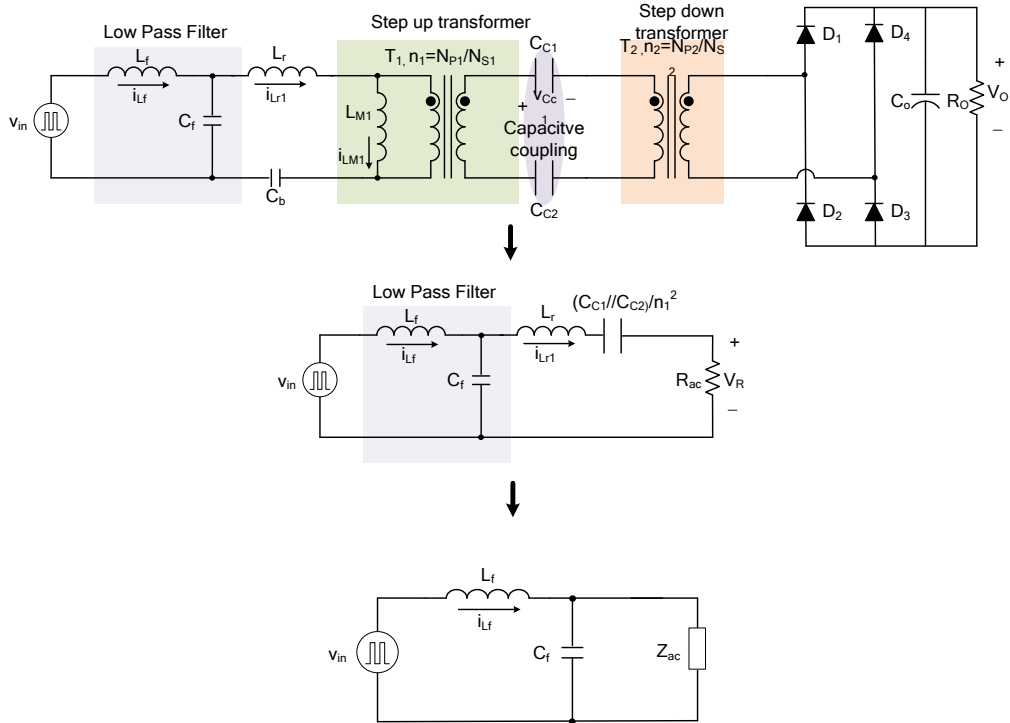


Fig. 7. AC equivalent circuit for the LC filter design.

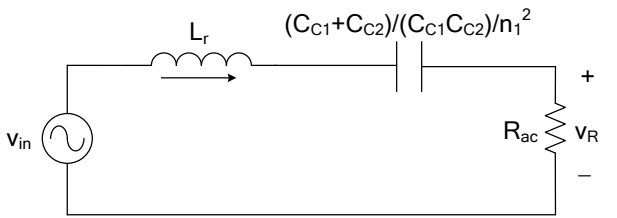


Fig. 8. Equivalent circuit for the voltage gain without the parasitic components.

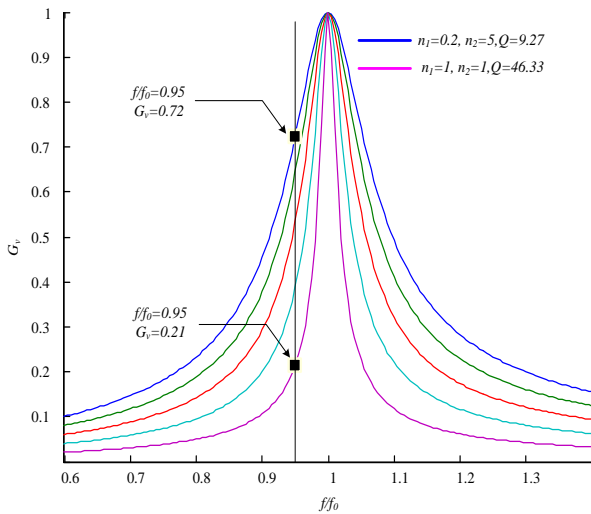


Fig. 9. Voltage gain curve without the parasitic components.

inverter. The Q is high and the voltage gain curve is sharp, hence the unstable operation. The output voltage feedback cannot control the CCWPT, thus a low Q is needed to obtain the constant output when the resonant frequency changes.

TABLE I

EXPERIMENT SPECIFICATION AND PARTS

Specification/Components	Part	Value
Boost Input	V_s	10V~16V
Boost Output	V_{in}	22V
Inverter Switch	M_1 and M_2	FDS3601
Low Pass L	L_f	1.5 μ H
Low Pass C	C_f	220pF
Resonant Inductor	L_r	440nH
Step-up Transformer	$N_{p1}:N_{s1}$	1:4
Coupling Capacitor	C_{c1} and C_{c2}	200pF
Step-down Transformer	$N_{p2}:N_{s2}$	4:1
Rectifier	$D_1 \sim D_4$	BS630
Output Capacitor	C_o	2 μ F
Dielectric Layer Width	d_1+d_2	0.04mm
Charging Current	Buck output	800mA(5V)

Fig. 9 shows the voltage gain according to the n_1 and n_2 if the coupling capacitance is 30pF. The CCWPT can determine the output voltage gain with the design of the turn ratios of the step-up and step-down transformer. If the switching frequency only changes by 5%, the voltage gain is sharply reduced without the step-up and step-down transformers, as shown in Fig. 9. Therefore, the impedance transformation circuit is needed to obtain the small Q for a stable output voltage without feedback control.

The parasitic components will be in the step-up and step-down transformer, as shown in Fig. 10, hence a detailed analysis of the voltage gain is needed. L_{m1} and L_{m2} are the

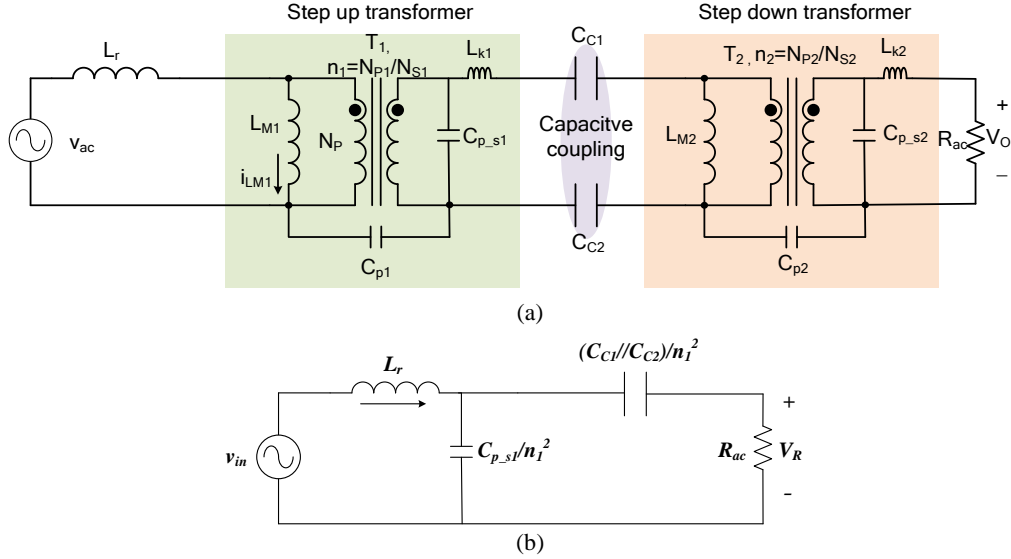


Fig. 10. Circuit diagram with the parasitic component. (a) Simplified circuit. (b) Equivalent circuit for the voltage gain.

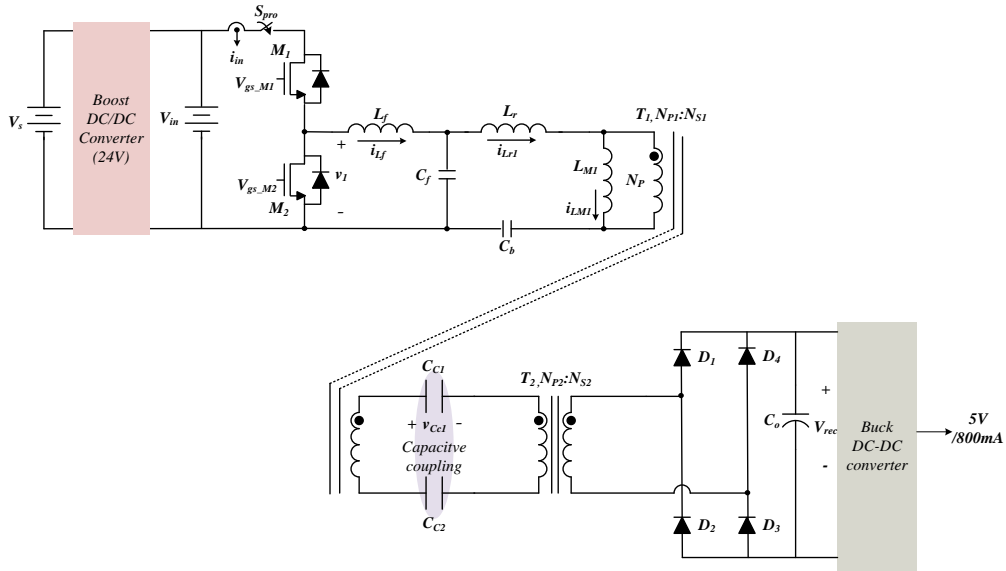


Fig. 11. Prototype system for the experiment.

magnetized inductors with a large inductance, thus these inductors cannot be considered in the voltage gain. The turn ratio of the step-up transformer is small and turn ratio of the step-down transformer is large hence a parasitic capacitor is placed between the copper wires [10]. The capacitor in the secondary step-up transformer is dominant, and the equivalent circuit for voltage gain can be obtained, as shown in Fig. 10(b). The voltage gain with the parasitic components is expressed as

$$G_v = \frac{V_R^F}{V_{in}^F} = \frac{I}{\sqrt{\left(\frac{2\pi f L_r}{R_{ac}}\right)^2 + \left(L_r \times \frac{C_{p-s1}}{n_1^2} + 1\right)}} \quad (10)$$

This equation shows that the output voltage cannot be obtained if the C_{p-s1} is large. This implies that the very small turn ratio of the step-up transformer to make a small Q has a

large parasitic capacitor, C_{p-s1} , and the power is not transferred to the load.

IV. EXPERIMENTAL RESULTS

A prototype system is implemented to verify the design. The parts used and parameters are shown in Table 1. The turn ratio of the step-up and step-down transformers is designed to obtain the low quality factor below one, and the RF carbonyl core is used to reduce the core loss in the 6.78MHz operation. The prototype is made for a mobile charger for many electronic systems such as standalone, automotive, and consumer electronic devices. The prototype system has a boost converter in the input stage and buck converter for the charger in the receiver system such as a mobile device, tablet, personal computer, or other hand-held devices, as shown in

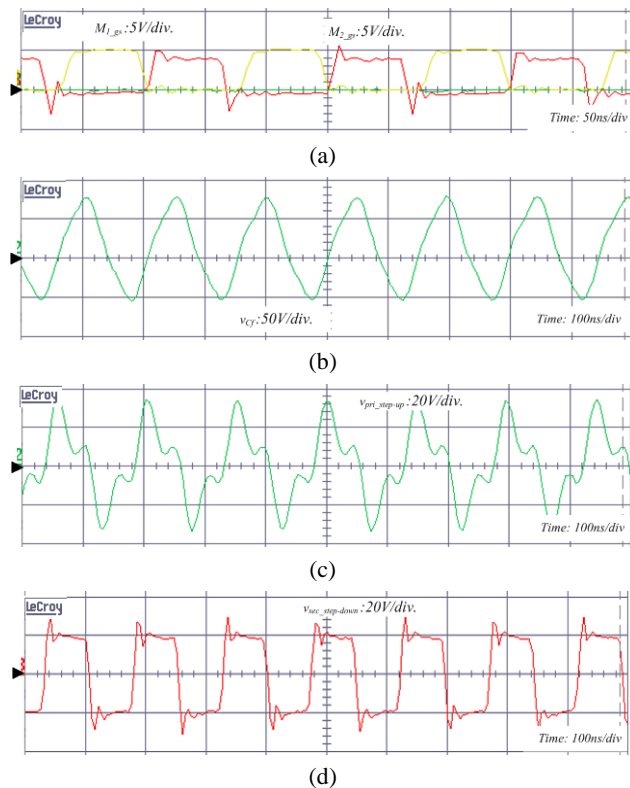


Fig. 12. Experimental waveforms. (a) Gate signals of M_1 and M_2 . (b) Low Pass filter output. (c) The primary voltage of the step-up transformer. (d) The secondary voltage of the step-down transformer.

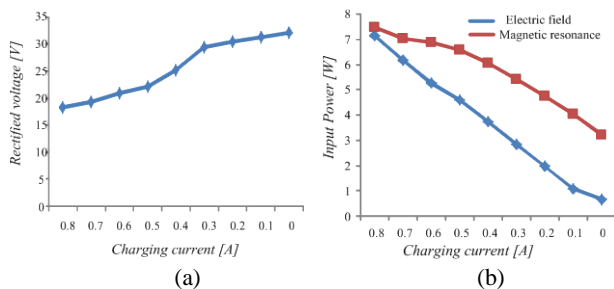


Fig. 13. Experimental results. (a) Rectified voltage according to charging current. (b) Input power according to charging current.

Fig. 11. Fig. 12 shows the experimental waveforms of the prototype CCWPT. Fig. 12(a) shows the gate signal for the Class D inverter switches. The gate signal is not simultaneously turned on. The output voltage is a 6.78 MHz sinusoidal waveform, as shown in Fig. 12(b). The measured capacitance of the coupling capacitor is approximately 200pF with an area of 100 cm^2 in the 6.78MHz operation. The cut-off frequency of the LC low pass filter is designed with the 9MHz operation, and the waveform of the LC low pass output is shown in Fig. 12(c). The excellent rectification of the received voltage is shown in Fig. 12(d). The rectified voltage is 18.6 V in the 5V/800mA charging, as shown in Fig 13(a). The rectified voltage increases with decreasing charging current because the quality factor reduces with a

large output voltage at the light load condition in the series resonance DC/DC converter. The 17 V output voltage is obtained when the position of the receiver is changed and the capacitance is 120pF. The efficiency is about 76% from the boost output stage to the rectified stage in a full charging current. Power loss mostly occurs in semiconductor devices because of the high frequency switching loss and conduction loss in the rectifier. The magnetic resonance WPT is utilized to compare the efficiency with the proposed system. The prototype of the magnetic resonance WPT used the same 6.78MHz transmitting and receiving circuit in Fig. 11 and has two coils with impedance matching. The efficiency of the proposed CCWPT and magnetic resonance WPT are almost identical at a full charging current condition, as shown in Fig. 13(b). However, the proposed CCWPT has higher efficiency in the light load condition, and the standby power consumption is significantly less than that of the magnetic resonance WPT.

V. CONCLUSION

In this paper, a new CCWPT system is proposed for a mobile device charger. The system consists of a class D inverter, LC filter, and impedance transformation circuit such as the step-up and step-down transformers. The coupling capacitance is primarily determined by the width and permittivity of the dielectric layers. The step-up and step-down transformers increase the coupling capacitance and reduce the Q-factor, hence output power can be obtained in the resonant frequency variation. The characteristics are verified with the prototype for the 4W mobile device charger, and the proposed system has better efficiency than that of the magnetic resonance WPT with full load and no load. The proposed system has a very low standby power consumption, particularly at the zero charging current. Therefore, the proposed CCWPT system can be applied in the WPT for mobile chargers and contactless power transfer for other electric devices.

ACKNOWLEDGMENT

This research was supported by the Daegu University Research Grant, 2013.

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