

Design Procedure of A Class E^2 DC-DC Converter for Megahertz Wireless Power Transfer Based on A Compact Class E Current-Driven Rectifier

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Abstract—This paper presents a design procedure of a Class E^2 DC-DC converter for megahertz wireless power transfer. The design formulas are analytically derived based on the input impedance of the Class E rectifier. A 6.78 MHz Class E^2 DC-DC converter is designed and implemented by means of those formulas. The power-level of the converter is 15W. The experiments are provided to verify the proposed design procedure and evaluate the performance of the converter. The experiment results show that the Class E^2 converter for loosely coupled wireless power transfer can achieve a very high efficiency, 85% for the best case, over a wide load and varying mutual inductance. Finally, the well agreement between the experimental results and design specifications indicates the validity of the proposed design procedure.

Index Terms—Wireless power transfer, Class E^2 DC-DC converter, Class E power amplifier, Compact Class E rectifier.

I. INTRODUCTION

In recent years, the wireless power transfer (WPT) becomes more and more attractive due to the convenient and safe non-contacting charging. Generally speaking, WPT system can be classified into two types: inductive coupling [1] and magnetic coupling [2]. The magnetic resonance coupling working at megahertz (MHz) is being widely considered a promising candidate for the mid-range transfer of a medium amount of power [2] [3]. It is because generally a higher operating frequency (such as several megahertz) is desirable for a more compact and lighter WPT system with a longer transfer distance. In order to build a well-performed MHz WPT system, most of researches focus on the design and optimization for the resonant coupling coils [4] [5] and the optimal load control for coupling coils [6] [7]. However, there are few works on high-efficiency power amplifiers and rectifiers for MHz WPT applications. Because the traditional hard-switching based inverters and rectifiers will have significant switching loss when working at MHz, it is desirable to apply the soft-switching techniques for MHz WPT system. Due to the resonant structures, the Class E power amplifier (PA) and Class E rectifier are suitable candidates to meet to the requirement.

The Class E PA was first introduced in [8]. It is attractive to be used in MHz WPT system for its high efficiency and simple structure [9]–[11]. The Class E PA achieves high efficiency, approaching 100% theoretically, when the circuit satisfies zero voltage switching (ZVS) condition and zero voltage derivative

(ZDS) condition. The Class E rectifier was first presented and used for very high frequency rectification in [12] at 1988. Then various Class E topologies have been developed, such as half-wave, full-wave, and mixed-mode rectifiers [13]. The application of the Class E rectifier in WPT system was first investigated and an efficiency of 94.43% was reported in [14] at 800 kHz operating frequency. Since the Class E PA and rectifier can achieve a high efficiency for the high frequency applications, it is attractive to introduce the Class E^2 DC-DC converter for MHz WPT, i.e., a Class E PA and a Class E rectifier. Paper [15] presents a state-space-based analysis of a Class E^2 converter for wireless power systems based on the inductive link. However, those systems are still working at frequencies below 1 MHz. Initial discussions about MHz Class E^2 converter for WPT can be found in [16], where the simulation-based analysis is introduced. Generally, the existence of the equivalent reactance of the rectifier will detune the receiving coil and lead to lower efficiency and weaker power transfer capacity. Meanwhile, the performance of Class E PA will be affected by the undesirable input impedance of coupling coils caused by the rectifier impedance. Thus, based on the rectifier's impedance, this paper proposed a design procedure for the MHz Class E^2 WPT system. In this procedure, the reactance of the rectifier is used to compensate the receiving coil. Then the input impedance of coupling coil is designed to be the optimal load for Class E PA by means of the resistance of the rectifier.

This paper is organized as follows. It first gives the circuit configuration of the proposed Class E^2 DC-DC converter and defines the efficiency of each part. Then the design procedure is shown with respect to the three subsystem, i.e., the Class E rectifier, coupling coils, and the Class E PA. A design case is provided to explain the design process of a Class E^2 WPT system using the proposed procedure. Finally, a 6.78 MHz Class E^2 WPT system is implemented and the experiments are carried out to verify the design procedure and evaluate its performance.

II. CLASS E^2 DC-DC CONVERTER FOR WPT

Fig. 1 (a) shows the circuit configuration of a MHz Class E^2 DC-DC converter for loosely coupled WPT. It consists of a Class E PA, series resonant coupling coils, and a compact Class E current-driven rectifier.

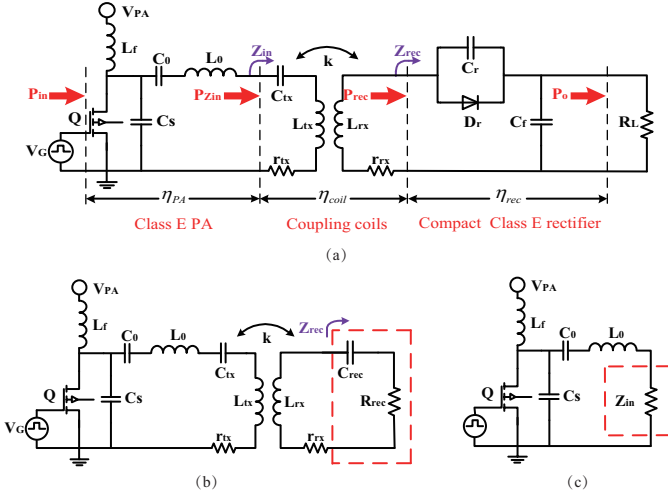


Fig. 1. Class E^2 DC-DC converter for WPT. (a) Circuit configuration. (b) Equivalent circuit with Z_{rec} . (c) Equivalent circuit with Z_{in} .

In this figure, P_{in} is the input power of PA, P_{Zin} is the input power of coupling coils, P_{rec} is the input power of the rectifier, and P_o is the output power of the rectifier. According to the circuit configuration, the efficiency of the system and the three parts are defined as:

$$\eta_{sys} = \eta_{pa} * \eta_{coil} * \eta_{rec} = \frac{P_o}{P_{in}}, \quad (1)$$

$$\eta_{pa} = \frac{P_{Zin}}{P_{in}}, \quad (2)$$

$$\eta_{coil} = \frac{P_{rec}}{P_{Zin}}, \quad (3)$$

$$\eta_{rec} = \frac{P_o}{P_{rec}}. \quad (4)$$

Fig. 1 (b) and (c) give two equivalent circuits of the Class E^2 WPT system. Here, Z_{rec} is the input impedance of the compact Class E rectifier and Z_{in} is the input impedance of coupling coils. Based on the input impedances, a design procedure of the Class E^2 WPT system is presented in the following section.

III. DESIGN PROCEDURE

A. The Current-Driven Model

Fig. 2 (a) shows a typical Class E current-driven rectifier. It consists of a diode D_r , a parallel capacitor C_r , a filter capacitor C_f , a DC feed inductor L_r and a DC load R_L . Here, i_{rec} is the input current, I_o is the output DC current, i_{D_r} is the current of diode, i_{C_r} is the current of capacitor, V_{D_r} is the diode voltage and D is the duty cycle of diode. In order to analyze the rectifier operation and derive the input impedance, assumptions are given as follows:

- 1) The rectifier is driven by a sinusoidal current source.
- 2) The current through the inductor L_r is constant and equal to the output current I_o .
- 3) The output-ripple-voltage is small enough so that the output voltage V_o is constant.

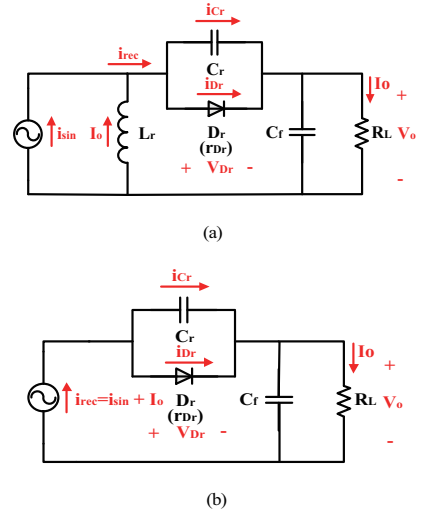


Fig. 2. Two Class E current-driven rectifiers. (a) Typical current-driven rectifier. (b) Compact current-driven rectifier.

Observing the typical Class E rectifier and the compact Class E rectifier in Fig. 2, it can be seen that the compact Class E rectifier can be built by adding the DC filter inductor current I_o to the current source. Then its driving current i_{rec} should be a sinusoidal current with a DC offset current I_o as shown in Fig. 2 (b). Thus, the compact rectifier can be designed using the following circuit equations of the typical Class E rectifier.

The current source i_{sin} is

$$i_{sin} = I_m \sin(\omega t + \phi_{rec}), \quad (5)$$

where I_m is the amplitude and ϕ_{rec} is the initial phase.

When the diode is off ($0 < \omega t \leq 2\pi(1 - D)$), the current through the capacitor C_r is

$$i_{C_r} = i_{sin} + I_o = I_m \sin(\omega t + \phi_{rec}) + I_o, \quad (6)$$

where I_o is the DC output current. Because i_{C_r} equals to zero when $\omega t = 0$, I_o can be expressed as

$$I_o = -I_m \sin \phi_{rec}. \quad (7)$$

Hence,

$$i_{C_r} = I_m (\sin(\omega t + \phi_{rec}) - \sin \phi_{rec}). \quad (8)$$

Using (8), the voltage cross the diode D_r is derived as

$$\begin{aligned} v_{D_{roff}} &= \frac{1}{\omega C} \int_0^{\omega t} i_{C_r} d\omega t \\ &= \frac{I_m}{\omega C} (\cos \phi_{rec} - \cos(\omega t + \phi_{rec}) - \omega t \sin \phi_{rec}) \end{aligned} \quad (9)$$

When $\omega t = 2\pi(1 - D)$, $v_{D_{roff}}$ reaches zero. Thus,

$$\cos \phi_{rec} - \cos(2\pi(1 - D) + \phi_{rec}) - 2\pi(1 - D) \sin \phi_{rec} = 0. \quad (10)$$

Rearranging (10), the relationship between ϕ_{rec} and D is obtained,

$$\tan \phi_{rec} = \frac{1 - \cos 2\pi D}{\sin 2\pi D + 2\pi(1 - D)}. \quad (11)$$

When the diode is on ($2\pi(1-D) < \omega t \leq 2\pi$), r_{D_r} is the on-resistance of diode, the current of diode is

$$i_{D_r} = i_{sin} + I_o = I_m \sin(\omega t + \phi_{rec}) + I_o. \quad (12)$$

As the current flows through the diode and the capacitor is shorted out, $v_{D_{ron}}$ can be represented as

$$v_{D_{ron}} = (I_m \sin(\omega t + \phi_{rec}) + I_o)r_{D_r}. \quad (13)$$

Based on $v_{D_{roff}}$ and $v_{D_{ron}}$, the average voltage cross the diode can be represented as

$$v_{D_r(avg)} = \frac{1}{2\pi} \left(\int_0^{2\pi(1-D)} v_{D_{roff}} d\omega t + \int_{2\pi(1-D)}^{2\pi} v_{D_{ron}} d\omega t \right), \quad (14)$$

substituting (9) and (13) to (14), $v_{D(avg)}$ is derived as

$$\begin{aligned} v_{D_r(avg)} = & -\frac{I_m}{2\pi\omega C} (2\pi(1-D) \cos \phi_{rec} \\ & + (1 - 2\pi^2(1-D)^2) \sin \phi_{rec} - \sin(\phi_{rec} - 2\pi D)) \\ & - \frac{I_m r_{D_r}}{2\pi} ((2\pi D - \sin 2\pi D) \sin \phi_{rec} + (1 - \cos 2\pi D) \cos \phi_{rec}) \end{aligned} \quad (15)$$

According to Kirchhoff's voltage law (KVL), the following equations can be obtained

$$v_{D_r(avg)} + V_o = 0, \quad (16)$$

where $V_o = I_o R$. Substituting (15) into (16), C_r can be obtained

$$C_r = \frac{1 + \frac{(\sin 2\pi D + 2\pi(1-D))^2}{1 - \cos 2\pi D} - 2\pi^2(1-D)^2 - \cos 2\pi D}{2\pi\omega(R_L + \frac{r_{D_r}}{2\pi} (2\pi D - \sin 2\pi D + (1 - \cos 2\pi D) \cot \phi_{rec}))}. \quad (17)$$

As shown in this equation, C_r and R_L can determine D . When R_L is determinate, C_r can be used to design the duty cycle of diode. It means C_r is the only design parameter for the rectifier. The input impedance of the rectifier can be derived based on the circuit analysis. As the input current is a sinusoidal wave, it is sufficient to determine the input impedance only at the operating frequency. The input impedance of the rectifier Z_{rec} can be represented as the series combination of the input resistance R_{rec} and the input reactance X_{rec} , both defined at the operating frequency. It can be expressed as

$$Z_{rec} = R_{rec} + jX_{rec}. \quad (18)$$

According to KVL, the input voltage of the rectifier v_{rec} is

$$v_{rec} = v_{D_r} + V_o, \quad (19)$$

where

$$v_{D_r} = \begin{cases} v_{D_{roff}} & (0 < \omega t \leq 2\pi(1-D)) \\ v_{D_{ron}} & (2\pi(1-D) < \omega t \leq 2\pi) \end{cases}. \quad (20)$$

The fundamental component of the input voltage is $v_{rec,fc}$, it can be expressed as

$$\begin{aligned} v_{rec,fc} = & v_{R_{rec}} + v_{X_{rec}} \\ = & V_{mR_{rec}} \sin(\omega t + \phi_{rec}) + V_{mX_{rec}} \cos(\omega t + \phi_{rec}) \end{aligned} \quad (21)$$

where $V_{mR_{rec}}$ and $V_{mX_{rec}}$ are the amplitudes of $V_{R_{rec}}$ and $V_{X_{rec}}$, respectively. Substituting (19) into Fourier series formula, $V_{mX_{rec}}$ can be given as

$$\begin{aligned} V_{mX_{rec}} = & \frac{1}{\pi} \left(\int_0^{2\pi(1-D)} \cos(\omega t + \phi_{rec}) v_{D_{roff}} d\omega t \right. \\ & + \int_{2\pi(1-D)}^{2\pi} \cos(\omega t + \phi_{rec}) v_{D_{ron}} d\omega t \\ & + \int_0^{2\pi} V_o \cos(\omega t + \phi_{rec}) d\omega t \left. \right) \\ = & -\frac{I_m}{\pi} \left(\frac{a+b}{\omega C} + r_{D_r}(c+d) \right) \end{aligned} \quad (22)$$

where

$$a = \pi(1-D) + 2\pi(1-D) \sin \phi_{rec} \sin(\phi_{rec} - 2\pi D), \quad (23)$$

$$b = \sin 2\pi D + \frac{1}{4} \sin(2\phi_{rec} - 4\pi D) - \frac{1}{4} \sin 2\phi_{rec}, \quad (24)$$

$$c = \frac{1}{2} - \frac{\cos 2\phi_{rec}}{4} - \frac{\cos(2\phi_{rec} - 4\pi D)}{4}, \quad (25)$$

$$d = -\sin \phi_{rec} \sin(\phi_{rec} - 2\pi D). \quad (26)$$

Therefore, X_{rec} is

$$X_{rec} = \frac{V_{mX_{rec}}}{I_m} = -\frac{1}{\pi} \left(\frac{a+b}{\omega C} + r_{D_r}(c+d) \right). \quad (27)$$

Based on the energy conservation law, the following equation can be obtained

$$P_{rec} = P_o + P_{D_r}, \quad (28)$$

where P_{rec} is the input power of the rectifier, P_o is its output power. P_{rec} is

$$P_{rec} = I_m^2 R_{rec} / 2. \quad (29)$$

Since the current through R_L is the DC current I_o , P_o can be given as

$$P_o = I_o^2 R_L, \quad (30)$$

as the power loss on diode only occurs at the on-state, P_{D_r} is derived as

$$P_{D_r} = \frac{1}{2\pi} \int_{2\pi(1-D)}^{2\pi} i_{D_r}^2 r_{D_r} d\omega t = e I_m^2 r_{D_r}, \quad (31)$$

where,

$$\begin{aligned} e = & \frac{1}{2} + \sin^2 \phi_{rec} + \frac{1}{\pi} \sin \phi_{rec} \cos(\phi_{rec} - 2\pi D) \\ & + \frac{1}{8\pi} \sin(2\phi_{rec} - 4\pi D) - \frac{9}{8\pi} \sin 2\phi_{rec} \end{aligned} \quad (32)$$

Substituting (7) into (28), R_{rec} is

$$R_{rec} = 2\sin^2 \phi_{rec} R + 2er_{D_r}. \quad (33)$$

B. Coupling Coils

The coupling coils are compensated to operate at resonance frequency by the resonant capacitors in conventional design approaches, where the influence of rectifier is not taken into account. Actually, the coupling coils can be detuned by the input reactance of rectifiers. It leads to the lower efficiency and power transfer capacity for the coupling system, especially at MHz. Thus, in the proposed design procedure, the equivalent capacitor of the compact Class E rectifier is designed to retune the receiving coil as follows

$$\omega L_{rx} + X_{rec} = 0. \quad (34)$$

Using this compensation method, the load of the coupling coils can be viewed as a pure resistance, which is equal to the equivalent resistance of the compact rectifier R_{rec} . Then, the capacitor in transmitting side C_{tx} can be designed by the traditional method

$$j\omega L_{tx} + \frac{1}{j\omega C_{tx}} = 0. \quad (35)$$

Based on Fig. 1 (c), (34) and (35), the input impedance of the coupling coils Z_{in} can be derived as

$$Z_{in} = \frac{r_{tx}(R_{rec} + r_{rx}) + \omega^2 L_m^2}{R_{rec} + r_{rx}}, \quad (36)$$

where L_m is the mutual inductance and can be expressed by the mutual inductance coefficient k as

$$L_m = k\sqrt{L_{tx}L_{rx}}. \quad (37)$$

By substituting (37) into (36), Z_{in} can be expressed as

$$Z_{in} = \frac{r_{tx}(R_{rec} + r_{rx}) + \omega^2 k^2 L_{tx}L_{rx}}{R_{rec} + r_{rx}}. \quad (38)$$

It can be seen that, from (38), Z_{in} is a pure resistance, regardless of the value of k . In this design procedure, the receiving coil is compensated to improve the efficiency and power transfer capacity of the coupling coils. And the resistance of the rectifier is designed to match the optimal load of PA $Z_{in,opt}$. Then the optimal R_{rec} ($R_{rec,opt}$) can be obtained by rearranging (38),

$$R_{rec,opt} = \frac{\omega^2 k^2 L_{tx}L_{rx} + r_{tx}r_{rx} - Z_{in,opt}r_{rx}}{Z_{in,opt} - r_{tx}}. \quad (39)$$

According to (34), the optimal X_{rec} ($X_{rec,opt}$) is

$$X_{rec,opt} = -\omega L_{tx}. \quad (40)$$

Therefore, the optimal C_r ($C_{r,opt}$), and the optimal R_L ($R_{L,opt}$) can be calculated by substituting (33) into (39) and (27) into (40), respectively.

C. Class E Power Amplifier

Fig. 1 (c) shows the circuit model of the Class E power amplifier used in this Class E^2 WPT system. It consists of a DC power supply V_{pa} , a RF choke L_f , a switch Q, a shunt capacitor C_s , a series capacitor C_0 , and a series inductor L_0 . Since Z_{in} has been derived in the above subsection, the Class E PA can be designed by the following equations to achieve its optimal operating condition (zero-voltage switching) and maximize its efficiency at a 50% duty cycle of switch Q, which has been proposed in [17],

$$Z_{in,opt} = 0.5768 \frac{V_{pa}^2}{P_{in}}, \quad (41)$$

$$C_{s,opt} = \frac{0.1836}{\omega Z_{in,opt}}, \quad (42)$$

$$C_{0,opt} = \frac{1}{\omega^2 L_0 - 1.1525\omega Z_{in,opt}}. \quad (43)$$

D. Design Case

Based on the proposed procedure, a Class E^2 DC-DC converter for wireless power transfer is designed and the design process is given in the following. The Class E^2 WPT system operates at 6.78 MHz. Based on Fig. 1 (a), the circuit parameters of the WPT system is given in Table I.

TABLE I
CIRCUIT PARAMETERS OF WPT SYSTEM

V_{pa}	P_{in}	L_f	L_0	C_{tx}	L_{tx}
23 V	15 W	68 uH	1.465 uH	203 pF	2.705 uH
r_{tx}	L_{rx}	r_{rx}	r_{Dr}	C_f	k
0.6 Ω	2.71 uH	0.6 Ω	1.4 Ω	44 uF	0.31

According to the parameters in Table I, $Z_{in,opt}$ is evaluated to 20 Ω by (41). Then $R_{rec,opt}$ and $X_{rec,opt}$ are 62 Ω and -110 Ω , calculated by (39) and (40). In order to achieve a maximum efficiency of coupling coils, the calculated results of $R_{rec,opt}$ and $X_{rec,opt}$ are substituted into (33) and (27), respectively. Then the optimal R_L ($R_{L,opt}$) and the optimal C_r ($C_{r,opt}$) are evaluated to 220 Ω and 92 pF, respectively. Here the duty cycle of the compact Class E rectifier D equals to 0.395. Table II lists the ratio of diode peak voltage to rectifier output voltage ($V_{Dr,p}/V_o$), the ratio of diode peak current to rectifier output current ($I_{Dr,p}/I_o$), and the ratio of rectifier output current to RMS of rectifier input current ($I_o/I_{rec,rms}$) to show the diode voltage stress, diode current stress, and the AC/DC current transfer function of the rectifier by using the design procedure. Where the formulas of $V_{Dr,p}/V_o$, $I_{Dr,p}/I_o$, and $I_o/I_{rec,rms}$ can be found in [18].

TABLE II
PERFORMANCE OF RECTIFIER AT D=0.395

D	$V_{Dr,p}/V_o$	$I_{Dr,p}/I_o$	$I_o/I_{rec,rms}$
0.395	2.9498	3.7156	0.8826

After finishing the design of coupling coils and the rectifier, the parameters of PA can be calculated based on $Z_{in,opt}$. Using (42) and (43), $C_{s,opt}$ and $C_{0,opt}$ are obtained as 212

pF and 602 pF, respectively. And the calculated values of the optimal parameters are given in Table III. Then, the design process of the Class E^2 DC-DC converter is completed and its performance will be evaluated experimentally in the next section.

TABLE III
CALCULATED RESULTS OF OPTIMAL PARAMETERS

$R_{L,opt}$	$C_{r,opt}$	$C_{s,opt}$	$C_{0,opt}$
220 Ω	92 pF	212 pF	602 pF

IV. EXPERIMENT

A 6.78 MHz Class E^2 DC-DC converter for wireless power transfer is implemented to verify the system analysis and show its performance. The experiment setup is shown in Fig. 3. It includes a Class E PA, coupling coils, a compact Class E rectifier and an electrical load. Here SUD06N10 is the switch of PA and STPSC406 is the rectifying diode of rectifier. The parasitic capacitance of the switch and diode are about 50pF and 30 pF, which are included in the calculated results of C_s and C_r . The distance of coils is 20 mm ($k=0.31$). Based on the circuit parameters in Table I and the design parameters in Table III, the experiments are given in the following to verify the validation of the proposed design procedure.

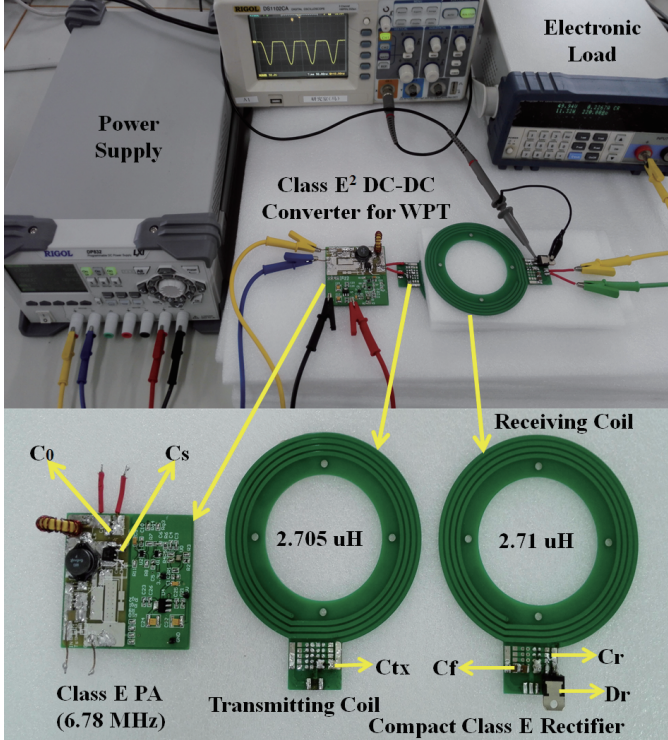


Fig. 3. System setup.

Fig. 4 and Fig. 5 give the switch's Drain-Source Voltage of the Class E PA (V_{drain}) and the diode's voltage of the Class E rectifier (V_{Dr}), respectively. It can be seen that V_{drain} and V_{Dr} are the typical waveforms for Class E PA/rectifier and are essentially sinusoidal at off-state of switch and diode. Fig. 6 gives the output voltage of the Class E^2 DC-DC converter

V_o versus the input voltage of PA (V_{PA}). It shows that V_o is a linear function of V_{PA} and increases with V_{PA} . The voltage conversion ratio of the Class E^2 DC-DC converter (V_o/V_{PA}) is equal to 2 using the optimal parameters in Table III.

Fig. 7 and Fig. 8 show the efficiency of the Class E^2 DC-DC converter by sweeping R_L from 50-300 Ω and k from 0.2 - 0.4, respectively. It can be seen that, from Fig. 7, the Class E^2 WPT system can achieve a very high efficiency over a wide load R_L and the optimal efficiency (85%) occurs on 200 Ω , which is close to the calculated value 220 Ω . Similarly, by using the proposed design procedure, the Class E^2 WPT system can also achieve a high efficiency with a varying k as shown in Fig. 8.

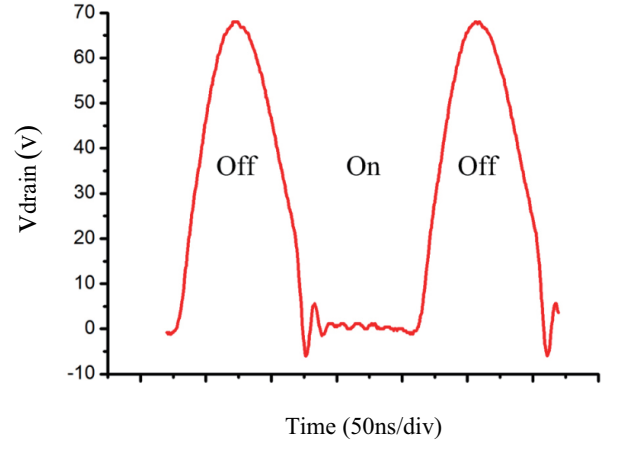


Fig. 4. The switch's Drain-Source Voltage of the Class E PA.

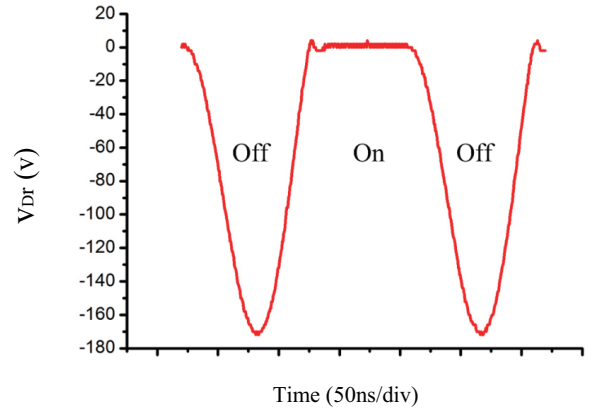


Fig. 5. The diode's voltage of the Class E rectifier.

V. CONCLUSION

This paper proposes a design procedure of a Class E^2 DC-DC converter for megahertz wireless power transfer. The design formulas are derived based on the input impedance of the compact Class E rectifier. Then the experiments are given for verification. It can be seen that the Class E^2 WPT system can achieve a very high efficiency with varying load and mutual inductance coefficient by using the design procedure and the efficiency is about 85% for the best case.

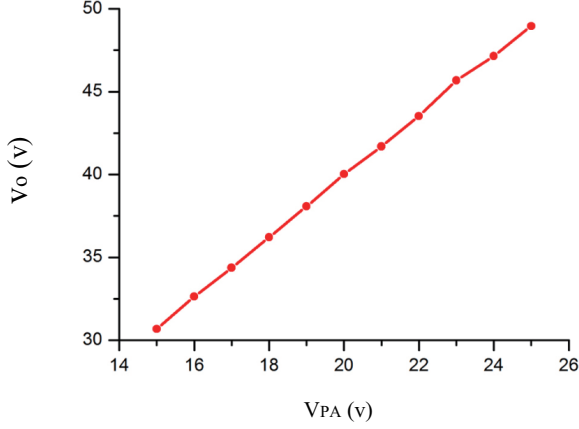


Fig. 6. The output voltage of the Class E^2 DC-DC converter.

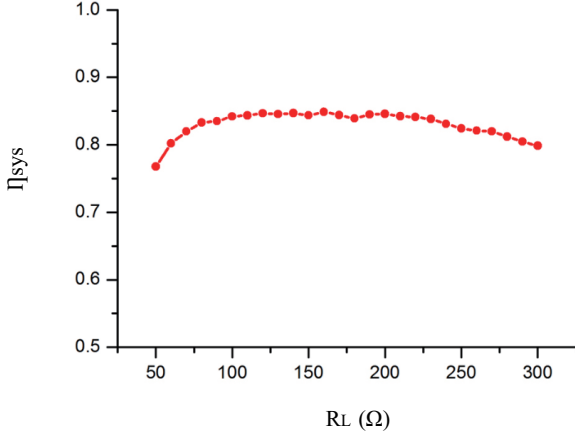


Fig. 7. The system efficiency at $k=0.31$ under a varying R_L .

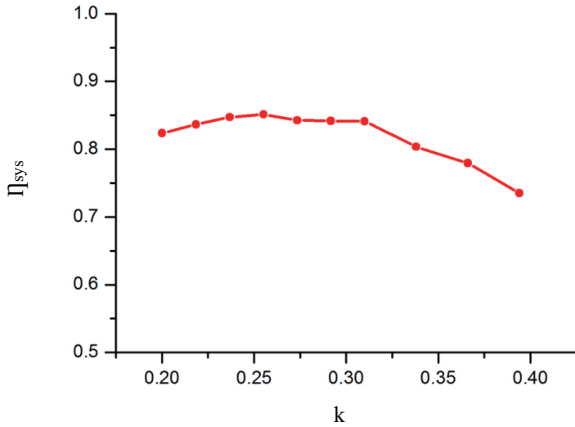


Fig. 8. The system efficiency at $R_L=220 \Omega$ under a varying k .

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