Active Class E Rectifier with Controlled Output Voltage for Megahertz Wireless Power Transfer

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***Abstract*—Wireless power transfer (WPT) is desirable for its elimination of direct electrical contact, i.e., safer charing solution, water-proof and dust-proof capability, sterile environment application, etc. However, the variable working conditions, such as the coupling coil relative position, can always lead to output voltage fluctuations. Therefore, output voltage regulation is especially necessary for the charging of electronic terminals. This paper proposes an active Class E rectifier that can perform both high frequency rectification and output voltage regulation. The basic working principle of the active rectifier is explained and design guidance is provided. Both simulations and experiments are done to demonstrate the proposed design and desired performance. With the duty cycle control of the active rectifier, an constant output voltage can be maintained under a varying coupling coefficients and final DC load.**

***Index Terms*—Wireless power transfer (WPT), active Class E rectifier, output voltage regulation, duty cycle control.**

I. INTRODUCTION

Wireless power transfer (WPT) has been considered as a promising candidate for the charging of daily-used equipments, from cell-phones to electric vehicles [1], [2]. WPT is desirable for its elimination of direct electrical contact, i.e., safer charing solution, water-proof and dust-proof capability, sterile environment application, etc. The general tendency of the WPT goes from low frequency (kilohertz) to high frequency (megahertz (MHz)) and from low power level (several watts) to high power levels (kilowatt or megawatt) [2], [3]. Improving the operating frequency (from kilohertz to megahertz) helps facilitate a lighter and more compact WPT system with enhanced spatial freedom [4]. Also, with loosely coupled coils, MHz WPT is able to charge multiple devices simultaneously [5]–[7]. Therefore, there is a great interest on MHz WPT in both academia and industry over the past several years.

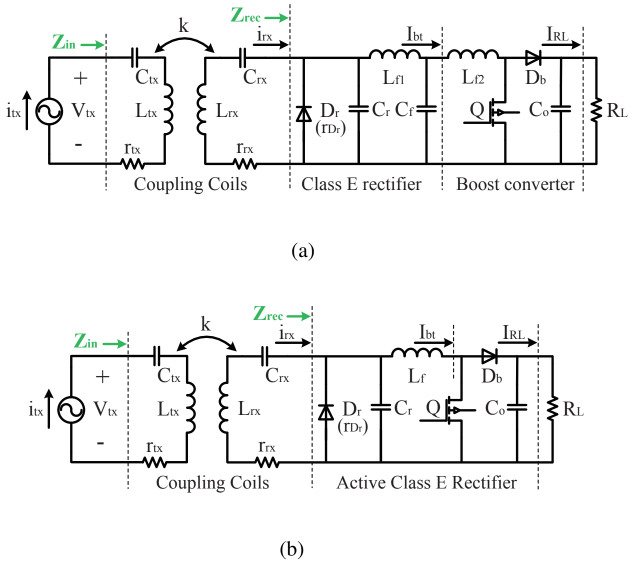
However, compared to the conventional plug-in charging, WPT still suffers some disadvantages, such as lower efficiency, severer EMI issues and heating problems. For the conventional plug-in charging, a constant DC voltage is supplied to the electronic terminals, such as 5 V for cell-phones. But for the WPT, the power received by the cell-phone is AC power and need to convert into constant DC voltage for the charging of Li-ion battery. Usually, a DC-DC converter is needed after the rectifier to provide a constant output voltage. This increases size, weight, and power dissipation, especially for the receiver side. Advanced solutions are expected to simplify the circuit configuration, while could provide output voltage regulation capability at the same time.

This paper proposes an active Class E rectifier to simultaneously perform high-efficiency rectification and DC output voltage regulation. The active Class E rectifier is proposed by combining Class E half-wave rectifier and boost converter together. The combined active Class E rectifier uses less components and can perform same functions as that of the Class E rectifier and boost converter. The regulation of output voltage can be achieved by turning the duty cycle of the switch in the active rectifier. Guidance is given for the design of the active Class E rectifier. Simulations results helps to better demonstrate the desired system performance. Finally an experimental 6.78 MHz WPT system is fabricated to validate the analytical derivations, high efficiency operation and output voltage regulation capability.

II. FUNDAMENTAL ANALYSIS

A. Active Class E Rectifier

The proposed active Class E rectifier can be considered combining half-wave Class E rectifier and boost converter together. As shown in Fig. 1 (a), the power receiver of the MHz WPT system originally composes of the receiving coil, the Class E rectifier, the boost converter, and the load. The Class E rectifier output is a DC current, which is equal to the input current of the boost converter. Therefore, the filter capacitor in Class E rectifier to facilitate a DC voltage, C_f, is not necessary at all. The three component, L_{f1}, C_f and L_{f2} can be combined as one DC filter inductor, L_f, as shown in Fig. 1 (b). L_f can facilitate DC output current for the



(a)

(b)

Fig. 1. Circuit configuration the proposed MHz WPT. (a) With Class E rectifier and boost converter. (b) With active Class E rectifier.

Class E rectifier while supplying DC input current for the boost converter, and the combined Class E rectifier and boost converter is designated as the active Class E rectifier in this paper.

In boost converter, the input output current relationship can be described as

$$I_{R_L} = I_{bt}\left(1-\alpha\right). \tag{1}$$

Here I_{R_L} and I_{bt} are the output and input current of boost converter, and α is the on duty cycle of the switch in boost converter.

In Class E rectifier, the input output current relationship can be denoted as

$$I_{bt} = \sin\phi_{rec} I_{rx}. \tag{2}$$

Here ϕ_{rec} and I_{rx} are the phase and amplitude of sinusoidal input current of the rectifier. ϕ is dependent on the shunt capacitor C_r and equivalent load of the rectifier. For the coupling coils, the receiving coil current can be represented with the transmitting coil current:

$$I_{rx} = \frac{\omega k\sqrt{L_{tx}L_{rx}}}{\sqrt{\left(r_{rx}+R_{rec}\right)^2+\left(\omega L_{rx}-\frac{1}{\omega C_{rx}}+X_{rec}\right)^2}} I_{tx}. \tag{3}$$

Here k is the coupling coefficient while I_{tx} is the amplitude of the transmitting coil current i_{tx}. R_{rec} and X_{rec} are the input resistance and reactance of the Class E rectifier (Z_{rec}=R_{rec} + X_{rec}), which is dependent on the shunt capacitor C_r and the DC load. Combining (1) (2) and (3), the load current I_{R_L} can be represented with the amplitude of transmitting coil current, I_{tx}. Then, the load power can be represented as

$$P_{R_L} = \frac{{I_{tx}}^2(1-\alpha)^2(\sin\phi_{rec})^2\omega^2k^2L_{tx}L_{rx}R_L}{\left(r_{rx}+R_{rec}\right)^2+\left(\omega L_{rx}-\frac{1}{\omega C_{rx}}+X_{rec}\right)^2}. \tag{4}$$

Note that in the about equation, ϕ_{rec}, R_{rec} and X_{rec} are all dependent on the load of Class E rectifier. The load of the rectifier is equivalent to the input resistance of boost converter, α. Therefore, ϕ_{rec}, R_{rec} and X_{rec} are all dependent on the α. Based on this equation, it can be seen that load power P_{R_L} can be adjusted by adjusting α.

B. Parameter Design

In this WPT system, the design parameters includes filter capacitor C_o, DC inductor L_f, shunt resonant capacitor C_r, receiving coil compensation capacitor C_{rx}, transmitting coil compensation capacitor C_{tx}. L_{tx}, L_{rx} and k are dependent on the transmitting coil, receiving coil and relative location between them, so its not considered as the design parameter here. The compensation capacitor C_{tx} is designed to be fully resonant with the transmitting coil at operating frequency.

$$j\omega L_{tx} + \frac{1}{j\omega C_{tx}}{=}0 \tag{5}$$

C_{rx} is designed to resonant with the receiving coil considering the input reactance of Class E rectifier.

$$j\omega L_{rx} + \frac{1}{j\omega C_{rx}}{+}X_{rec}{=}0 \tag{6}$$

Note that rectifier input reactance X_{rec} would change according to the duty cycle α. Therefore, a specific α as the nominal case would be chosen to design C_{rx}. The shunt resonant capacitor C_r helps to realize soft switching for the diode D_r. The value of C_r have an effect on the on-duty cycle of diode. Normally C_r is chosen achieving an diode on-duty cycle around 50% to balance the voltage stress and current stress of the diode [8]. The relationship between C_r and diode duty cycle D is given as follows.

$$\begin{aligned} C_r \quad &= \quad \frac{\left[\sin(2\pi D)+2\pi(1-D)\right]^2}{2\pi\omega(R_{bt}+r_{L_f}+r_{D_r})\left[1-\cos(2\pi D)\right]} \\ &+ \quad \frac{1-2\pi^2(1-D)^2-\cos(2\pi D)}{2\pi\omega(R_L+r_{L_f}+r_{D_r})}. \end{aligned} \tag{7}$$

Here r_{L_f} and r_{D_r} are the parasitic resistance of inductance L_f and diode D_r, and R_{bt} is the input resistance of boost converter. In Fig. 1, L_f is the DC filter inductor used for both Class E rectifier and boost converter. L_f need to be large enough to facilitate DC current for both Class E rectifier and boost converter. Here boost converter works at much lower frequency than the Class E rectifier. Normally Class E rectifier works at the same frequency of WPT system, 6.78 or 13.56 MHz, while boost converter works at 100-500 kHz. In this case, the DC inductor required for boost converter would be larger than that required for Class E rectifier. Therefore, L_f would be chosen the same as L_{f_2}, and the design of L_{f_2} would be similar as that in boost converter.

From (4) we know the load power is affected by α, ϕ_{rec}, R_{rec} and X_{rec}. And ϕ_{rec}, R_{rec}, X_{rec} are all related with α. The expression of P_{R_L} with α would be complicated and redundant. Here a well-know radio frequency simulation tool, Advanced Design System (ADS), is used to verify the proposed design of active Class E rectifier. The parameters used in the simulation model are the same as that in the final experiment.

TABLE I
PARAMETERS OF SIMULATION MODEL

I_{tx}	C_{tx}	L_{tx}	r_{tx}	L_{rx}
2 A	375 pF	1.47 μH	0.3 Ω	1.47 μH
r_{rx}	k	L_f	C_o	R_L
0.3 Ω	0.12	10 μH	22 μF	10 Ω

According to (6), the compensation capacitor C_{rx} need to be designed to resonant with both the coil inductance L_{rx} and reactance X_{rec} under a specific duty cycle α. However, the C_{rx} to achieve the highest efficiency are different under different α. Here in the simulation, a group of C_{rx} and α are swept to show the system performance, i.e., the efficiencies and output power. The simulation results are given in Fig. 2 and Fig. 3.

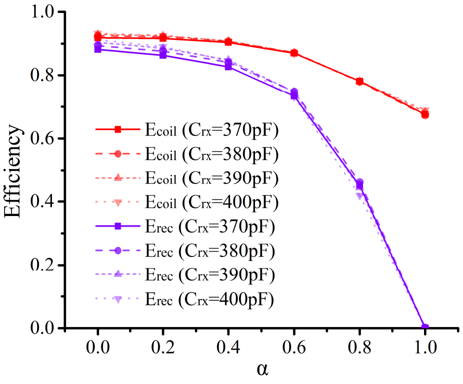


Fig. 2. Efficiencies of coupling coils and active rectifier versus duty cycle α in simulation.

Fig. 2 shows the efficiencies of coupling coils and active Class E rectifier when sweeping C_{rx} and α. It can be seen that C_{rx} has no obvious effects on the efficiencies of coupling coils and active rectifier. However, the efficiencies of couplings and rectifiers both drops when duty cycle α increases. When α equals one, the output power is shorted to ground and the rectifier efficiency drops to zero. Here the operating range of α is restricted below 60% to guarantee a good system efficiency.

Fig. 3 shows the load power P_{R_L} versus different C_{rx} and α. It can be seen that the load power varies versus α, but the variation tendency under different C_{rx} is different. Since α is restricted below 60%, it can be seen that P_{R_L} increases with respect to α when C_{rx} equals 370 pF, 380 pF and 390 pF. Here C_{rx} equaling 380 pF can facilitate relatively large adjusting range for P_{R_L}, i.e., from 6.7 W to 24.9 W. The system can achieve desired overall efficiency performance as well in this case.

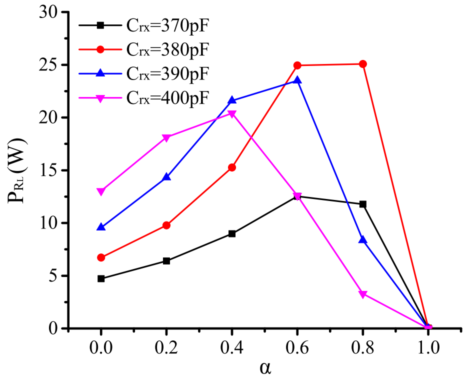


Fig. 3. Load power P_{R_L} versus duty cycle α in simulation.

III. EXPERIMENTAL VERIFICATION

An example 6.78-MHz WPT system is built up with the proposed active Class E rectifier [see Fig. 4]. Here the active Class E rectifier is fabricated with Schottky diode DFLS240 and GaN transistor GS61004B. The schematic of the coupling coils and active Class E rectifier is the same as that shown in Fig. 1 (b). A current-mode (CM) Class E power amplifier (PA) is employed to output desired sinusoidal current driving the transmitting coil. The output of CM Class E PA can keep constant against the variation of the Z_{in}, i.e., the load seen by the Class E PA [9]. Electronic load is employed to emulate the final dc load and measure the output power in the experiment. Due to the commercially available capacitors, C_{rx} equaling 377 pF is chosen as the receiving coil compensation capacitor. All other parameters of the WPT system are the same as that in the ADS simulation [see Table I]. To demonstrate the desired performance of the proposed active Class E rectifier, a group of experiments are done and the results are given as follows.

Fig. 5 shows the load voltage and power versus duty cycle α. It can be seen that, as α increases, both the output voltage and output power increases. As α increases from 0% to 60%, the output power P_{R_L} increases from 6.69 W to 19.33 W, as predict by the simulation in Fig. 3. Since C_{rx} equals 377 pF in the experiment, the variation tendency of P_{R_L} is just between the case when C_{rx} equals 370 pF and 380 pF in the simulation.

Fig. 6 shows the system efficiency E_{sys} and rectifier efficiency E_{rec} versus duty cycle α. The system efficiency E_{sys} means the DC-DC power transfer efficiency. The rectifier efficiency E_{rec} drops with respect to α, as predict in the simulation.

Fig. 7 shows the experimental duty cycle α during the output voltage regulation. The coupling coefficient is changed from 0.221 to 0.135 by changing the power transfer distances from 2 cm to 2.96 cm. At the same time, the duty cycle α is turned

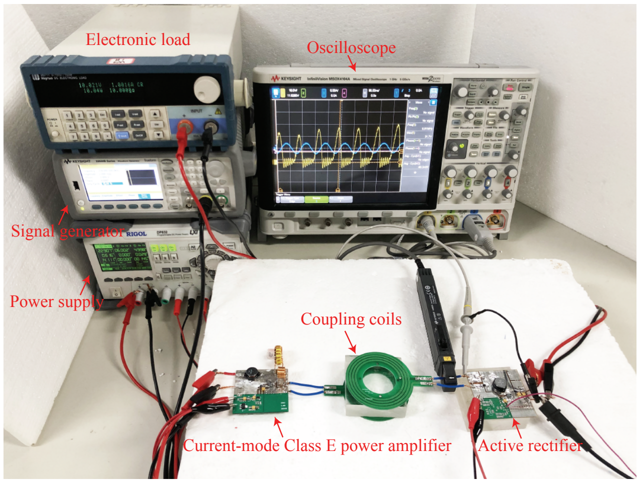


Fig. 4. Experimental setup of MHz WPT system with proposed active rectifier.

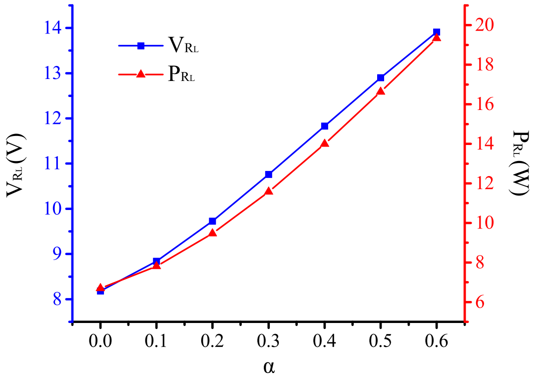


Fig. 5. Load voltage V_{R_L} and power P_{R_L} versus duty cycle α.

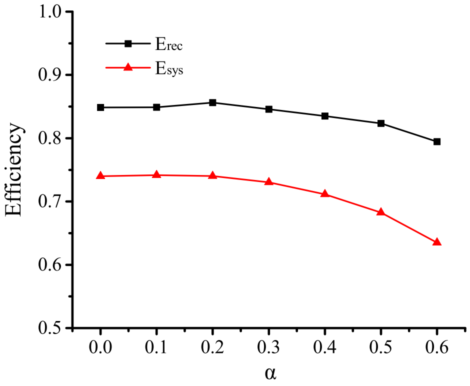


Fig. 6. System efficiency E_{sys} and rectifier efficiency E_{rec} versus duty cycle α.

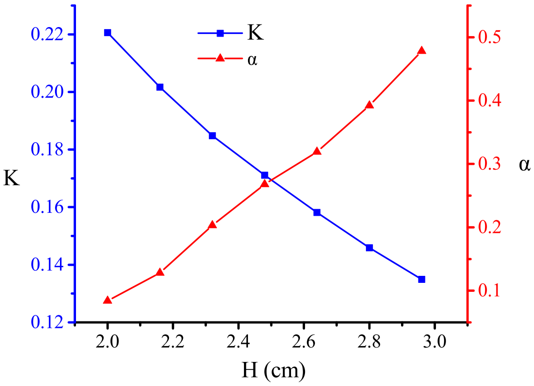


Fig. 7. Coupling coefficient K and duty cycle α versus power transfer distance H for 10 V output voltage regulation.

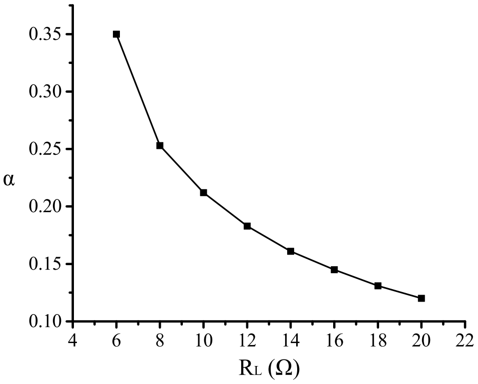


Fig. 8. Duty cycle α versus load R_L for 10 V output voltage regulation.

accordingly to facilitate a target constant output voltage, 10 V. It can be seen that, just by turning the duty cycle of the active rectifier, the constant output voltage can be maintained to counteract the variation of coil coupling. Fig. 8 demonstrate the voltage regulation capability of the active rectifier under the varying load. As the load changes from 6 Ω to 20 Ω, the duty cycle α drops from 0.35 to 0.12 gradually to maintain a 10 V output voltage. The voltage and power regulation capability of the active rectifier is well demonstrated by the experimental results in Fig. 7 and Fig. 8.

IV. CONCLUSIONS

This paper proposes an active Class E rectifier that can perform both high frequency rectification and output voltage regulation. The active rectifier comes from the combination of half-wave Class E rectifier and boost converter and elimination of DC power stage between them. By controlling the duty cycle of the switch in the active rectifier, the output voltage can be well regulated. The desired performance of the active rectifier is well demonstrated in ADS and further verified with real experimental WPT system.

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