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Class-E Power Amplifier with Minimal Standby Power for Wireless Power Transfer System

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Abstract – This paper presents a method for minimizing standby power consumption in wireless power transfer (WPT) system via magnetic resonance coupling (MRC) that operates at 6.78 MHz. The proposed circuit controls the required capacitance according to operational condition in order to reduce standby power consumption. Based on an impedance characteristic of the class-E power amplifier, operational principles of the proposed circuit are analyzed. Moreover, to verify the effectiveness of the proposed class-E power amplifier, an 8 W prototype for WPT system is implemented. The measured input power of the proposed class-E power amplifier at standby condition is reduced from 5.81 W to 3.53 W.

Keywords: Class-E power amplifier, Impedance matching, Magnetic resonance coupling (MRC), Standby power, Wireless power transfer (WPT)

1. Introduction

With increasing the performance of high-end smartphone, the power consumption of the system is strongly increasing. To satisfy this requirement, a high capacity battery is needed. However, the downsizing trend in product strictly limits the available space of the system. Commercially used battery capacity in smartphone is generally higher than 2000 mAh but not exceed 4500 mAh [1]. This limitation in battery capacity produces the daily charging time of smartphone, which induces the inconvenience of battery charging. In order to solve this realistic issue in IT gadget, the needs of wireless charging system and the market of wireless power transfer (WPT) is continuously increasing [2].

There are three standards in the wireless charging industry: Wireless Power Consortium (WPC) [3], Power Matters Alliance (PMA) and Alliance for Wireless Power (A4WP). In 2016, A4WP signed a collaborative deal with PMA and rebrand as AirFuel [4]. Both WPC and PMA are based on inductive coupling technology, which has typically quite short power transfer range. A4WP has been based on magnetic resonance coupling (MRC) technology. The inductive coupling method is effective at comparatively short distance [5, 6]. However, the power transfer efficiency of inductive coupling is very low at long distance. Compared to inductive coupling, MRC technology is more effective at middle distance, up to several meters. Moreover, WPT system via MRC can simultaneously transfer power to multiple devices. Thus, WPT system via MRC has become an active subject [7, 8].

Normally, WPT system consists of a transmitter defined as Tx, serving a power transmitter stage and a receiver defined as Rx, doing as a power receiver stage as shown in Fig. 1 (a). In general, WPT system operates in two periods of mode, a charging mode and a standby mode. The power is transferred from Tx to Rx in the charging mode. Fig. 1 (b) shows the structure of WPT system at standby mode. The role of standby mode is detection of proper Rx within effective charging range. Even when Rx is located in unavailable charging circumstance, Tx of WPT system consumes power to communicate with Rx. For the most of time, Tx of WPT system is in the standby mode. In other words, the considerable quantity of power is wasted during the standby mode. To figure this inefficiency

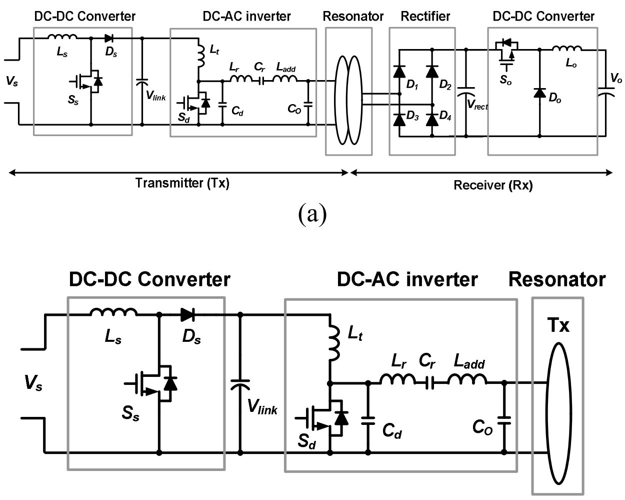

Fig. 1 The structure of the conventional WPT system : (a) At charging mode (b) At standby mode

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problem out in the WPT system, it is required to reduce the input voltage of DC-AC inverter [9]. With this voltage manipulation approach, it is possible to reduce the power consumption of DC-AC inverter. However, the DC-DC converter, used to vary the input voltage, generates additional power losses. Moreover, it is required additional components. Thus, it eventually faces the limitation of power transfer efficiency and that of power density.

In order to overcome these drawbacks, a standby power reduction technique for WPT system via MCR is proposed. The characteristics of the proposed method are investigated and the operational principles of the proposed circuit are also studied. An 8 W prototype for the charging power of the smartphone is implemented and the validity of the proposed standby power reduction technique is verified.

2. Motivation

Fig. 1(a) shows the structure of the conventional WPT system at charging mode and it is composed with following parts: DC-AC inverter is needed to generate AC source from DC voltage. To generate AC source, a class-E amplifier is usually employed because of its simple structure and low cost [10-13]. Tx resonator for transferring power and Rx resonator for receiving power are used respectively. Both Tx resonator and Rx resonator can be implemented with either series-resonance or parallel-resonance [14, 15]. To achieve high power transfer efficiency, a high Q resonator design is required [16]. The bridge diode rectifier rectifies AC to DC voltage V_{rect}. The DC-DC converter for adjusting a level of the dc voltage V_O is usually employed.

In order to achieve high efficiency, the class-E power amplifier can be designed as following equations [10]:

$$C_d = \frac{P_O}{\pi \omega V_S^2} \tag{1}$$

$$R_{opt} = \frac{8}{\left(\pi^2+4\right)} \times \frac{V_S^2}{P_O} \tag{2}$$

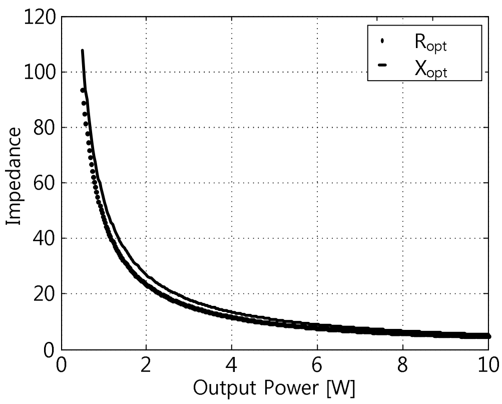

Fig. 2. R_{opt} and X_{opt} according to output power

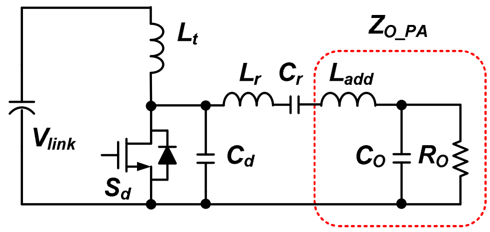

Fig. 3. Total output impedance of power amplifier

$$X_{opt} = \frac{\pi}{2} \times \frac{\pi^2-4}{\pi^2+4} \times \frac{V_S^2}{P_O} \tag{3}$$

where

C_d : capacitance of parallel connected to MOSFET S_d including output capacitance of S_d

P_O : output power of class-E power amplifier

ω : angular frequency of switching

V_S : input voltage of class-E power amplifier

R_{opt} : required optimal resistance

$X_{op}t$: required optimal reactance.

Since WPT system via MCR operates at constant 6.78 MHz, P_O is decided by V_S and C_d as described in (1). The required output impedance of the class-E power amplifier can be expressed by (2) and (3). Fig. 2 shows the required output impedance according to output power with constant 9 V input voltage. The required R_{opt} and X_{opt} for 9 V input voltage and 8 W output power transfer system are 5.84 and 6.72j, respectively.

The most of class-E power amplifiers are designed based on 50 ohm impedance matching, which generally produces the discrepancy between the required output impedance and 50 ohm impedance. To match the impedance, C_O and L_{add} are added between class-E power amplifier and Tx resonator as shown in Fig. 1 [13]. The total output impedance, Z_{O_PA}, associated with C_O and L_{add} as show in Fig. 3 can be expressed as follows:

$$Z_{O\_PA} = R_{opt} + jX_{opt} = sL_{add} + \frac{R}{1+sC_O R} \tag{4}$$

where R is an equivalent load impedance including Tx resonator. From (4), C_O and L_{add} can be obtained by (5) and (6) as follows:

$$C_O = \frac{1}{\omega R} \times \sqrt{\left(\frac{R}{R_{opt}} - 1\right)} \tag{5}$$

$$L_{add} = \frac{1}{\omega} \times \left\{ X_{opt} + \frac{\omega C_O R^2}{1+\left(\omega C_O R\right)^2} \right\}. \tag{6}$$

To minimize the discrepancy between 50 Ω and 5.84+j6.74, C_O and L_{add} are obtained as 1290 pF and 535 nH, respectively.

3. Proposed Standby Mode Power Reduction Technique

3.1 Construction of the proposed Class-E power amplifier

The structure of the class-E power amplifier with a proposed technique is shown in Fig. 4. To realize the proposed technique, a power control block and an impedance matching block are added to the conventional class-E power amplifier. While the class-E power amplifier is connected to a load system like as smartphone, the operation of the class-E power amplifier with the proposed technique is exactly same as that of the conventional class-E power amplifier. Under standby condition, Tx including the class-E power amplifier and the Tx resonator is only existed and operated. The output power of the class-E power amplifier with the proposed technique is controlled by the power control block and the impedance matching block. The operational principle and the design equations are explained in the following subsections.

3.2 Construction of the proposed Class-E power amplifier

The output power of class-E power amplifier is a function of not only the input voltage V_S but also C_d, and the output power is directly proportional to the C_d according to (1). In Fig. 5, the output power is plotted as a function of the C_d with the design specifications and circuit parameters as described in Table 1 and Table 2, respectively. The output power can be regulated not by decreasing the input voltage but by decreasing the capacitance C_d as shown in Fig. 5. In case that the input voltage is constant as 9 V, the required C_d for 8 W maximum output power is 737 pF at charging mode, and it is decreased to 92 pF at standby mode for 1 W output power regulation. In order to control the required C_d as operating mode varies, a power control circuit is proposed as shown in Fig. 4. Since the power control switch S_{d2} maintains on-state in charging mode, the total power control capacitances C_d is expressed as (7).

$$C_d = C_{d1} + C_{d2} \tag{7}$$

Since S_{d2} is turned off at the standby mode, the total power control capacitance is C_{d1}. To achieve $P_{o,stby}$, C_{d1} is selected as 92 pF. Since output capacitance of S_d has to be considered to design C_{d1}, additional C_{d1} is finally selected as 47 pF in reference to specifications of S_d [17]. Moreover, since C_d for 8 W is 737 pF, C_{d2} for charging mode is designed as 645 pF.

The characteristics of the power switch are important to design power control block and to implement the

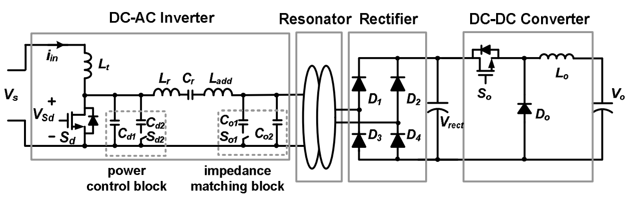

Fig. 4. The structure of the proposed WPT system

Table 1. System specifications

Part	Value
Input voltage, V_S	9 V
Maximum Output Power, $P_{o,max}$	8 W
Required Output Power at Standby Mode, $P_{o,stby}$	1 W
Switching Frequency, F_S	6.78 MHz

Table 2. Circuit parameters

Part	Value
Choke inductor, L_t	22 uH
Switch, S_d	FDMC86116LZ (V_{DS}=100V, I_{DS}=7.5A, C_{OSS}=45pF)
Parallel capacitor, C_d (= C_{d1} + C_{d2})	740 pF
Resonance inductor, L_r	165 nH
Resonance capacitor, C_r	3348 pF
Additional inductor, L_{add}	535 nH
Matching capacitor, Co (= C_{O1} + C_{O2})	1280 pF

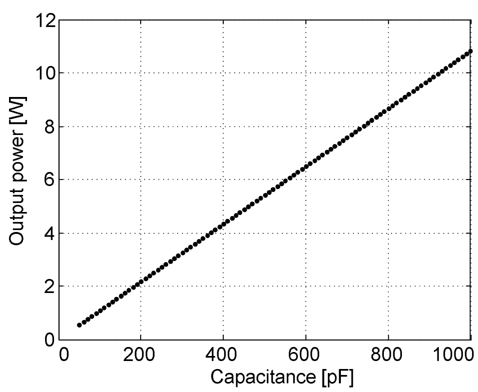

Fig. 5. The output power according to C_d

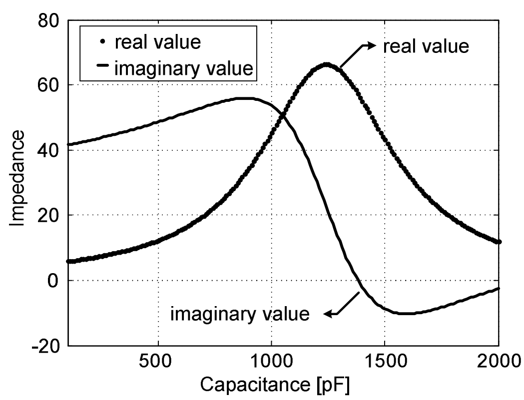

Fig. 6. The output impedance according to C_O

proposed class-E power amplifier. In this paper, the power switches are selected with following design criteria. First of all, for proper operation of class-E power amplifier, an output capacitance of power switch, C_{OSS} is smaller than the required capacitance C_d as plotted in Fig. 5. Since the required capacitances 92 pF, the maximum output capacitance of power switch has to be smaller than 92 pF. Secondly, rise/fall time has to be minimized due to 6.78 MHz high switching frequency operation. With 6.78 MHz switching frequency, on-time of power switch is approximately 70 nsec. In this paper, since the allowable rise/fall time is designed below 10~15 % of on-time of power switch, it is selected 7~10 nsec. Moreover, for high efficiency, gate power has also to be minimized. The maximum gate power is designed as 10 % of maximum output power. With these design criteria, the power switch of the proposed class-E power amplifier is selected as FDMC86116LZ.

3.3 Impedance matching block

Although the power control block reduces the power consumption of the class-E power amplifier, the power loss by impedance mismatch is still considerably large. In order to reduce the circulating power, the impedance matching block is analyzed with the circuit parameters in Table 2.

The output impedance of the class-E power amplifier with C_O and L_{add} is obtained from (4) ~ (6) and it is plotted as a function of C_O as shown in Fig. 6, based on the design specification and circuit parameters for the charging mode in Table 1 and Table 2, respectively. As shown in Fig. 6, both the real value and the imaginary value of Z_{O_PA} are varied according to C_O. Therefore, impedance difference between required impedance and Tx impedance can be minimized by controlling C_O. The proposed circuit is shown in Fig. 4. The total capacitance can be expressed as follow:

$$C_O = C_{O1} + C_{O2}\,. \tag{8}$$

The required capacitance at charging mode is 1290 pF. The required capacitance at standby mode is 1050 pF. Thus, the required capacitance for standby mode C_{O1} is selected as 1050 pF. Moreover, the additional capacitance for charging mode C_{O2} can be obtained from (8) and the value is 240 pF.

4. Experimental Results

To verify the validity of the proposed standby power reduction technique, an 8 W prototype of the class-E power amplifier is implemented for WPT system of smartphone and the proposed circuit is applied. The design specifications and circuit parameters of this prototype are same as presented in Table 1 and Table 2, respectively. Fig. 7(a) shows experimental waveforms of Tx at charging mode. The measured input current is 1.01 A and the measured input voltage is 8.97 V. Fig. 7(b) and Fig. 7(c) show input waveforms of the conventional WPT system and those of the proposed WPT system at the standby mode, respectively. In the conventional WPT system, the measured input current is 0.646 A and the measured input

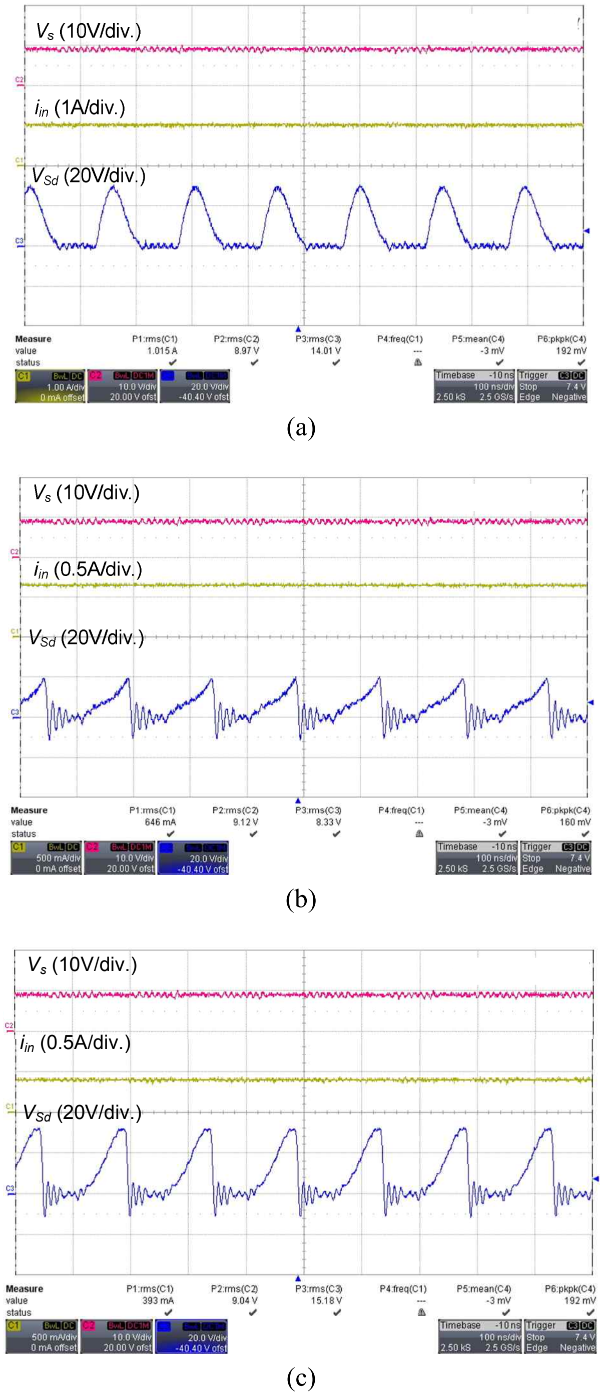

Fig. 7. Experimental waveforms of the WPT system: (a) At charging mode; (b) Conventional WPT system at standby mode; (c) Proposed WPT system at standby mode

Table 3. Comparison of power loss

Part	Conventional	Proposed	Note
Choke inductor, Ls	18 mW	6 mW	$P_{loss} = I_{rms}^2 \times R_{on}$
Power Switch, S_d	130 mW	109 mW	$P_{loss} = I_{rms}^2 \times R_{on} + Q_{gate} \times V \times F_S + C_{OSS} \times V_{ds} \times F_S$
Total Loss	148 mW	115 mW	Δ=33mW

voltage is 9 V at standby mode as shown in Fig. 7(b). In employing the proposed circuit with the decreased C_d and C_O, the input voltage is the same as 9 V, but the measured input current is reduced 0.393 A as shown in Fig. 7(c). Therefore, the input power decreased from 5.81 W to 3.53 W at standby mode by adopting the proposed techniques. Table 3 shows comparison of the estimated power loss. Since the power reduction of the proposed comes from the power control for required 1 W output power, the reduction of power loss is not considerable compared to that of the input power. However, the proposed system can reduce the power consumption under standby mode and control output power without the additional DC/DC converter.

5. Conclusion

In this paper, to minimize standby power of the class-E power amplifier for WPT system, the power control block and the impedance matching block are proposed. The proposed circuit reduces the input power at the standby mode. Based on the characteristics of the class-E power amplifier, the operational principles of the proposed circuit are analyzed. Furthermore, the design equations are derived. By implementing the 8 W prototype for the transfer power supply of wireless power system, the operational principles of the proposed circuit are confirmed. By employing the proposed circuit, the input power of class-E power amplifier is greatly reduced from 5.81 W to 3.53 W at standby mode. Moreover, since the proposed circuit is simple and cost effective, it is expected to be widely applied to various WPT systems for standby power reduction.

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