A Method of Regulating Wireless Power Transfer Based on the Analysis of Power Communication

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Abstract— **Reducing the complexity of the wireless power transfer receiver while keeping high power transmission efficiency becomes more and more attractive these days. In this digest, a design method for high efficient resonant regulating wireless power transfer (RWPT) in the case of having load variation at the receiver presented, based on the power transferring theory of resonant wireless power transfer using Laplace analysis, is revealed. The proposed method opens a potential of independent design between power transmitter and power receiver of the RWPT system, and provides an option to reduce receiver area by reducing the need of information communication, without affecting power transmission efficiency of the system. In addition, the proposed method also contributes to the extension of battery lifetime of the power receiver.**

Keywords—power communication, resonant wireless power transfer

I. INTRODUCTION

Recently, wireless power transfer (WPT), especially RWPT, draws an intensive attention for its feasibility of charging electric devices over long distances without any burden of plugging wire, opening an era of wireless one-charger-fits-all design, and offering more flexibility to the portable devices. In order to reduce size, while keeping high power conversion efficiency at the receiver side, which is important in the portable device case, a resonant regulating rectifier based on switched-capacitor converter [1] was studied. To further enhance power conversion efficiency of the receiver, usually a wireless communication circuit is implemented to feedback the power condition of the receiver to the transmitter, and the transmitter will adapt its transferring power capacity accordingly, as illustrated in Fig. 1. In this digest, an analysis on the power transmission of the RWPT will show that, the transferring power can be obtained directly only based on the voltage/current state of the transmitter/receiver. Therefore, the system can be designed without the communication units.

Shown in Fig. 2 is the equivalent model for RWPT, where the transmitter involves an AC source V_S, with its equivalent series resistance R_S, an LC resonator composed a resonant coil L_1 with its self-inductance L_1, and a resonant cap C_1 whose equivalent series resistance is embedded in the R_S model, and the equivalent series resistance (DCR) of the inductor L_1 is R_{L1}; and the receiver includes an LC resonator composed a resonant coil L_2 with its self-inductance of L_2, and a resonant cap C_2, the

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This work was supported by Samsung Electronics.

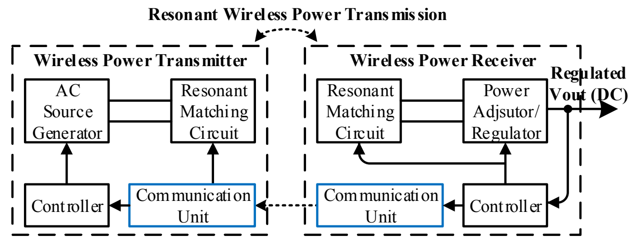

Fig. 1. Common Resonant Regulating WPT System

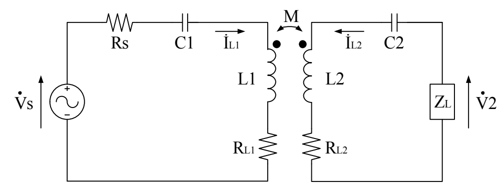

Fig. 2. Equivalent model for RWPT as a coupled resonator

equivalent series resistance of the inductor L_2 is R_{L2}, and the output impedance load (including the equivalent series resistance of C_2) Z_L. In the case of a rectifier loading after the impedance matching stage L_2, C_2, Z_L is the emulated resistance of the rectifier [2]. At the resonant condition, the mutual inductance of L_1 and L_2 is M. The coupling coefficient is $k = \frac{M}{\sqrt{L_1 L_2}}$, in which k is usually less than 0.2 in resonant LC coupling circuit.

The wireless power transfer theory is based on the Faraday's law of inductance: Once the mutual inductance occurs, the voltage across the coil L_1 and L_2 are:

$$V_{L1} = L_1 \frac{dI_{L1}}{dt} + M \frac{dI_{L2}}{dt} \quad (1)$$

$$V_{L2} = L_2 \frac{dI_{L2}}{dt} + M \frac{dI_{L1}}{dt} \quad (2)$$

Using Laplace transform, the equivalent equations in s-domain are:

$$\dot{V}_{L1} = sL_1 \dot{I}_{L1} + sM \dot{I}_{L2} = \dot{V}_{11} + \dot{V}_{12} \quad (3)$$

$$\dot{V}_{L2} = sL_2 \dot{I}_{L2} + sM \dot{I}_{L1} = \dot{V}_{22} + \dot{V}_{21} \quad (4)$$

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Where,

$\dot{A}$ denotes $A\angle\phi$, the polar form of a complex number .

$\dot{V}_{ii}$, where i = 1, 2, denotes the induced voltage across L_i due to its own self-inductance L_i.

$\dot{V}_{jk,j\neq k}$, where j, k = 1, 2, denotes the induced voltage across L_j due to the mutual inductance *M*.

The transmitted power is the magnetic field power, which is the dot product of the induced voltage in one coil and the current crossing it:

$$P_{12} = \dot{V}_{12} \cdot \dot{I}_{L1} = sM\dot{I}_{L2} \cdot \dot{I}_{L1} = -P_{21} \quad (5)$$

$$\leftrightarrow \omega M I_{L2} I_{L1} \cos\left(sM\dot{I}_{L2}, \dot{I}_{L1}\right) = \omega M I_{L2} I_{L1} \sin\left(\dot{I}_{L2}, \dot{I}_{L1}\right) \quad (6)$$

Where, $P_{jk,j\neq k}$, where j, k = 1, 2, denotes the power induced in the coil L_j affected by the coil L_k

Therefore, by letting AC current flowing into two coils put near each other so that there is mutual inductance between the two coils, energy can be transferred wirelessly through the electromagnetic field. Furthermore, the transferred energy depends on the induced current through the two coils and their mutual inductance M. However, in the WPT point of view, the current of one coil cannot be measured directly from the other coil's circuit. Therefore, in the next section, we will see how these induced currents related to each other, and how the wireless power can be obtained without additional wireless information exchange.

II. Analysis of Power Transferring

In this section, a detailed analysis will reveal the relation between the induced inductor current of the two coils and relation of the transfer power and the transmitter's state. Based on that, direct and indirect methods to measure transfer power at the transmitter are suggested.

A. A Direct Formula for Transmitted Power Measurement

First of all, rewriting eq. (5) acknowledging eq. (3), the transmitted power is:

$$P_{12} = \dot{V}_{12} \cdot \dot{I}_{L1} = \left(\dot{V}_{L1} - sL_1\dot{I}_{L1}\right) \cdot \dot{I}_{L1} = \dot{V}_{L1} \cdot \dot{I}_{L1} \quad (7)$$

$$\rightarrow P_{12} = -P_{21} = V_{L1} I_{L1} \cos(\dot{V}_{L1}, \dot{I}_{L1}) \quad (8)$$

Therefore, by measuring the AC voltage and current of the inductor at the transmitter side, transmitted power can be calculated directly. However, this method may require expensive and massive AC measurement component. Therefore, another analysis to convey an indirect evaluation of the transmitted power will be derived in the next section.

B. An Indirect Formula for Transmitted Power Measurement

Assume the conduction loss due to inductor DCR is negligible, and because $P_{C2} = V_{C2} I_{C2} \cos\left(\frac{\dot{I}_{C2}}{sC_2}, \dot{I}_{C2}\right) = 0$, by the conservation law of energy, we have: $P_{21} + P_{Z_L} \approx 0$. Hence, P_{Z_L} is approximate to P_{21}, i.e. the output power of the receiver can be monitored based on the available information (voltage, current) of the resonant coil in the transmitter. Next, the Kirchhoff's voltage and current equations of the system in Fig. 1 are:

$$\begin{bmatrix} \dot{V}_s \\ \dot{V}_2 \end{bmatrix} = \begin{bmatrix} R_{L1} + R_s + sL_1 + \frac{1}{sC_1} & sM \\ sM & R_{L2} + sL_2 + \frac{1}{sC_2} \end{bmatrix} \begin{bmatrix} \dot{I}_{L1} \\ \dot{I}_{L2} \end{bmatrix} \quad (9)$$

By solving the linear equation system (9), inductor current in the two coils can be obtained:

$$\dot{I}_{L1} = \frac{\left(R_{L2} + sL_2 + \frac{1}{sC_2}\right)\dot{V}_s - sM\dot{V}_2}{\left(R_{L1} + R_s + sL_1 + \frac{1}{sC_1}\right)\left(R_{L2} + sL_2 + \frac{1}{sC_2}\right) - s^2M^2} \quad (10)$$

$$\dot{I}_{L2} = \frac{\left(R_{L1} + R_s + sL_1 + \frac{1}{sC_1}\right)\dot{V}_2 - sM\dot{V}_s}{\left(R_{L1} + R_s + sL_1 + \frac{1}{sC_1}\right)\left(R_{L2} + sL_2 + \frac{1}{sC_2}\right) - s^2M^2} \quad (11)$$

At fundamental frequency of $\dot{V}_2$ which is not the resonant frequency, $\dot{V}_s = \dot{0}$. Replace $\dot{V}_s = \dot{0}$ to the division of eq. (10) and (11), the transmitter and receiver current ratio is:

$$\frac{\dot{I}_{L1}}{\dot{I}_{L2}} = \frac{\left(R_{L2} + sL_2 + \frac{1}{sC_2}\right)\dot{V}_s - sM\dot{V}_2}{\left(R_{L1} + R_s + sL_1 + \frac{1}{sC_1}\right)\dot{V}_2 - sM\dot{V}_s} = -\frac{sM}{R_{L1} + R_s + sL_1 + \frac{1}{sC_1}} \quad (12)$$

This ratio of the two coil current is independent on the AC source voltage V_S of the transmitter, or the output voltage V_2 of the receiver. It means that, I_{L1} will vary according to I_{L2}, which also depends on the load current of the receiver. Hence, if output voltage of the receiver is regulated with some other switching frequency F_{SW} different from the resonant frequency, I_{L2} will also contains the F_{SW} frequency; and it can be detected in I_{L1} using a envelop detector or a simple low pass filter. Therefore, detecting the existence of the frequency spectrum other than the resonant frequency of I_{L1} or V_{L1} (according to eq. (3)) can tell that if the system is hungry of power or not. Then, by varying one of the parameters in the transmitter side, the system can be controlled to transmit just enough power and the current have only resonant frequency, to have higher efficiency, lower EMI noise, and smaller output ripple at the receiver side.

III. Simulation Results

Shown in Fig. 3 is the simulation result for such a resonant regulating WPT system shown in Fig. 1 with a resonant regulating rectifier at receiver implemented using a 0.35µm CMOS technology to verify the derived eq. (12) and (3). For the full power transfer case with load current of 1A, the regulating power is turned off, enabling the full-power transfer ability with no switching loss. In this case, the rectifier voltage contains only DC component and resonant frequency, hence, minimizing possible EMI noise. When the wireless power becomes redundant, output voltage is regulated using another switching frequency F_{SW} different from the resonant frequency so that it receives only its required power, and the output voltage is then kept constant. In this case, this switching frequency is also induced to the transmitted coil, as in the case

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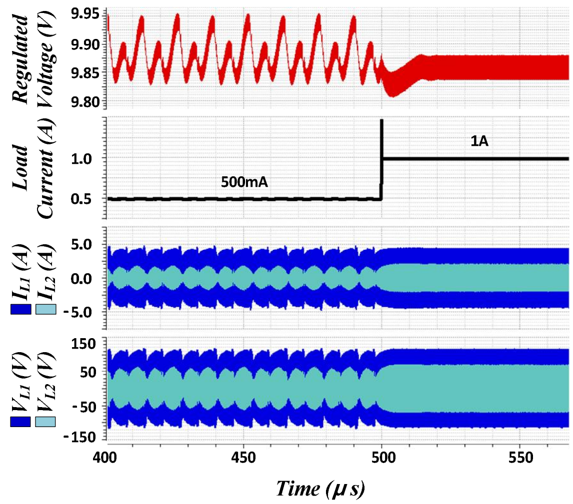

Fig. 3. Simulation for resonant regulating WPT system to verify the dependency of inductor current flowing in two coils

load current is 500mA in Fig. 3, which is also accordant to derived eq. (12) and (3): the current and voltage of the transmitted coil L_1 also include the switching frequency F_{SW} generated at the receiver side. Therefore, the transmitter can simply just detect the appearance of this frequency to evaluate receiver's power condition.

IV. Recommended Method to Reduce Communication Units

Shown in Fig. 4 is the proposed method to reduce the communication units on both power transmitter and power receiver sides for the case receiver output voltage is regulated by the receiver itself. The proposed WPT system employs the receiver power information embedded in the transferred power of the resonant matching LC devices of the transmitter: At the transmitter side, inductor voltage or current can be sensed, and input to the envelope detector. In the case of too much power transferred to the receiver, assumed that the regulating receiver will regulate output voltage with a frequency F_{SW}, this switching frequency will also be induced into the voltage and current of the resonant inductor. Usually, this frequency is at the range of kHz to MHz; therefore, it can be detected by a low pass filter without any difficulty. Based on that information of the low pass filter, the controller can regulate input transferred power at the transmitter as summary in Fig. 5.

V. Conclusions

In this digest, resonant wireless power communicating was examined using simple Laplace analysis, and verified by simulation result of a RWPT system with regulating rectifier implemented by a 0.35um CMOS. According to the analysis and the simulation result, wireless power at the receiver can be evaluated directly or indirectly at the transmitter without acknowledging the receiver's condition. The analysis result provides a potential of independent design of wireless power transfer transmitter and receiver, each of which is able to regulate the its own transmitting and receiving power so that the system are always working at its maximum power conversion

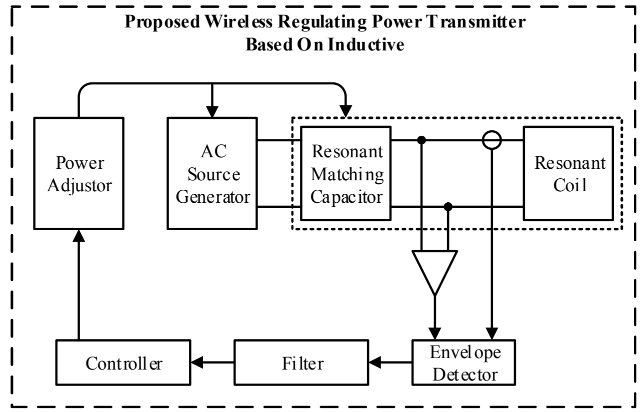

Fig. 4. Proposed Power Transmitter

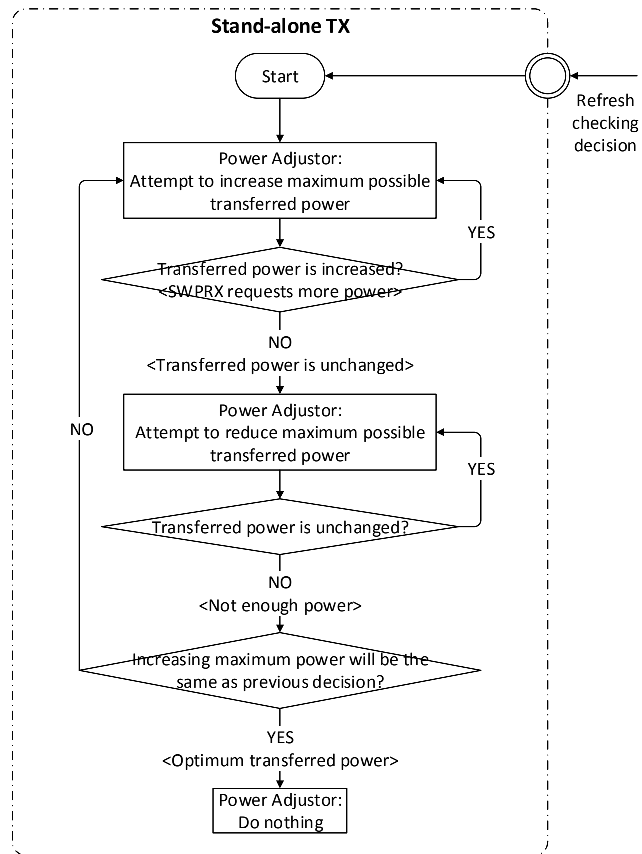

Fig. 5. Proposed Algorithm to Control the Power Transmitter

efficiency, without EMI disturbance.

References

[1] Jun-Han Choi et. al., "A resonant regulating rectifier (3R) operating at 6.78 MHz for a 6W wireless charger with 86% efficiency," *IEEE ISSCC*, vol., no., pp.64,65, 17-21 Feb. 2013.

[2] R.W. Erickson, and D. Maksimovic. Fundamentals of Power Electronics. Springer, 2001.

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