A 13.56 MHz Wireless Power Transfer System Without Impedance Matching Networks

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***Abstract*—A 13.56 MHz wireless power transfer (WPT) system is analyzed and implemented in this paper. This system consists of five subsystems: a class-D power amplifier, a pair of resonant coils, a rectifier, a DC/DC converter and various loads. By analyzing the transfer characteristics of the resonant coils, an optimum impedance is derived in order to minimize the power reflection. This impedance requirement is fulfilled by designing the rectifier and the DC/DC converter properly. The power reflection due to impedance mismatch can be controlled at 5%. When the load is a resistor, the system efficiency can reach 73% . When the loads are batteries or supercapacitors, the system efficiency can reach 66%.**

***Index Terms*—wireless power transfer system, magnetic resonance, power reflection, impedance matching**

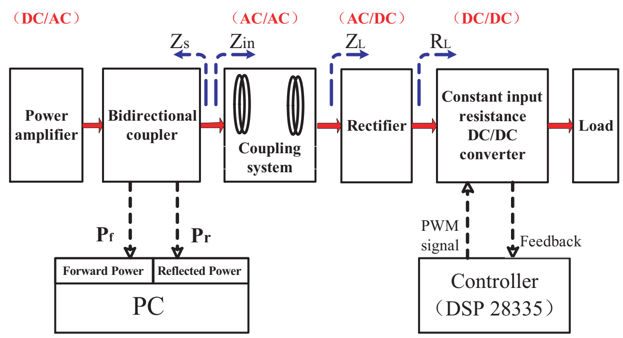

Fig. 1. System block diagram

I. Introduction

Nowadays, wireless power transfer technologies have attracted interest from industry and academic researchers [1] [2]. Among the popular WPT technologies, such as microwave [3], laser and inductive coupling, WPT using magnetic resonance coupling is a promising candidate for mid-range and high-efficiency wireless power transfer [4]. A general and complete power transfer path usually includes the following subsystems: power source, coupling system, rectifier, DC/DC converter and load. In order to maximize the system efficiency, one has to understand the origin of the power loss. One major origin of the power loss is the conversion loss, such as DC/AC loss in the power amplifier, AC/AC loss in the coupling coils and AC/DC loss in the rectifier. The other one is the power reflection between each subsystem due to impedance mismatch. To solve these difficulties, a conventional and straightforward method is to optimize each subsystem [5]- [8] to minimize conversion loss and use additional impedance matching networks to reduce power reflection [9]. An alternative method is to design each subsystem from a system perspective. It means one can design the subsystem from the requirement of the others, which can ensure a high efficiency by solving impedance mismatch instead of using impedance matching networks. After all, the impedance matching networks need extra components and inevitably cause additional power loss.

In this paper, a design methodology is given for high-efficiency wireless power transfer without using impedance matching networks. By analyzing the circuit model of the coupling system, the optimum impedance attached to the receiving coil is derived in order to achieve maximum transfer efficiency. This impedance represents the equivalent input impedance after the coupling system, which is the combination of rectifier, DC/DC converter and load. By designing the rectifier and DC/DC converter accordingly, the impedance requirement of the coupling system is fulfilled. A 13.56 MHz wireless power transfer system is demonstrated in this paper. When transmitting 50 watts power, it can achieve an efficiency of 73% for a resistive load and an efficiency of 66% for charging batteries or supercapacitors.

II. System Configuration

This section introduces the system configuration of the 13.56 MHz wireless power transfer system, whose block diagram is shown in Fig. 1. The WPT system consists of a power amplifier (AC source), a bidirectional coupler (power detection for forward power and reflected power), a coupling system (AC/AC), a full-bridge rectifier (AC/DC), a DC/DC converter and various loads (resistor, batteries or supercapacitors). To improve system efficiency, the goal is to minimize the reflected power (P_f). By analyzing coupling system, the optimum load impedance (Z_L) is first derived. Then optimum load of the rectifier (R_L) is determined by simulating the rectifier circuit, whose input impedance is ensured to be Z_L. At last, DC/DC converter is designed to fulfill the requirement of rectifier.

A. Power Amplifier

The power amplifier is 50 Ω matched Class-D type RF generator with an efficiency over 80%, based on Microsemi transistor (DRF1300). For maximum efficiency, conjugate impedance matching at the source port is required, which means $Z_{in} = 50\ \Omega$.

Fig. 2. Coupling system

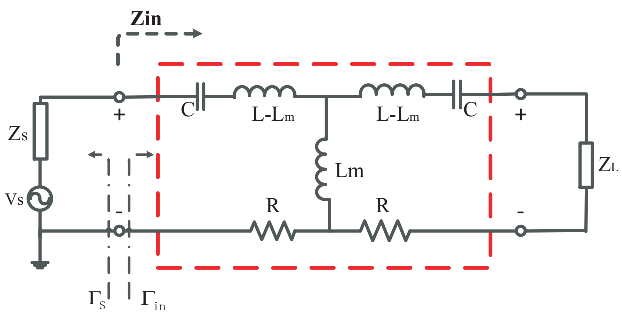

Fig. 3. Equivalent circuit model for the coupling system

B. Coupling system

The coupling system in Fig. 2 consists of two identical helical open circuit coils. The resonance is achieved by its self-inductance and parasitic capacitance. Therefore, no external lumped capacitor is needed. The coupling system is represented by its equivalent circuit model shown in Fig. 3, in which L is the self-inductance, C is the parasitic capacitance, R is the parasitic resistance and L_m is the mutual inductance. All the circuit model parameters are given in Table I.

With the help of circuit model, several parameters of the coupling system can be derived. The input impedance of the coupling system is

$$Z_{in} = \frac{(R + jwL + \frac{1}{jwC})(Z_L + R + jwL + \frac{1}{jwC}) + w^2 L_m^2}{Z_L + R + jwL + \frac{1}{jwC}}. \quad (1)$$

TABLE I
COUPLING SYSTEM CIRCUIT PARAMETERS

Inductance L [μH]	7.8
Capacitance C [pF]	17.6
Internal resistance R [Ω]	3.4
Mutual inductance L_m [μH]	0.7
Characteristic impedance Z_0[Ω]	50
Source impedance Z_s[Ω]	50
Coil diameter [mm]	320
Coils gap [mm]	150

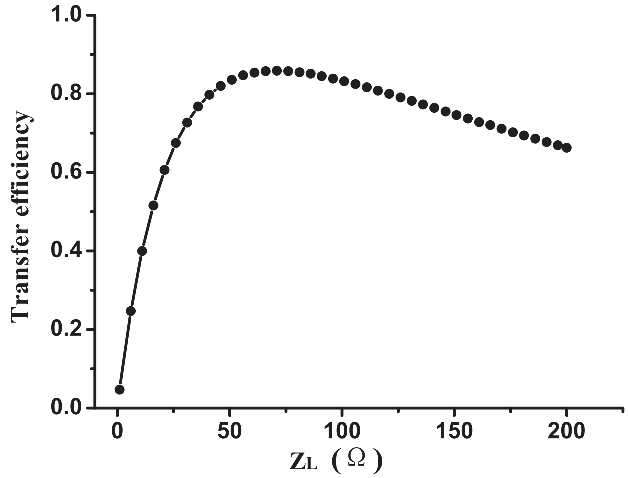

Fig. 4. Transfer efficiency for different Z_L

Under the resonance condition ($jwL + \frac{1}{jwC} = 0$),

$$Z_{in} = R + \frac{w^2 L_m^2}{Z_L + R}. \quad (2)$$

The maximum transfer efficiency requires no power reflection at the transmitting side, i.e. $\Gamma_{in} = \Gamma_s^*$, which equally means

$$Z_{in} = Z_s^*. \quad (3)$$

For a specific coupling system, which means that L, C and R are known. When the transfer distance is fixed, which means L_m is fixed. If the source impedance is predefined, for maximum efficiency, the only controllable variable is Z_L. In this paper, Z_S is 50 Ω. Combining Eq. 2 and Eq. 3, it gives

$$Z_L = \frac{w^2 L_m^2}{50 - R} - R. \quad (4)$$

Taking the parameters in Table I into Eq. 4, the calculated optimum value for Z_L is 73 Ω. By sweeping Z_L, the transfer efficiency curve is shown in Fig. 4.

C. Rectifier

At the receiving part of the coupling coils, a rectifier is used to convert AC power to DC. Usually, a full-bridge topology is used. However, most high power diodes are incapable in a 13.56 MHz system because of their low switching speed. In this paper, SiC diodes (STPSC406) are used to build a full-bridge rectifier with ceramic capacitors as the low-pass filter. The design target here is to find the optimum value of the rectifier load (R_L in Fig. 1) which minimizes the power reflection. Because of the non-linearity of the diodes, it is difficult to derive the system transfer characteristics like the coupling system. Instead, the rectifier is analyzed in a commercially available simulation package, Advance Design System (ADS) by Agilent Technologies.

By sweeping the load resistance in Fig. 5, the system efficiency curve and power reflection coefficient are plotted in Fig. 6. The simulation results show that when the load resistance equals to 95 Ω, a maximum efficiency of 76% can be achieved, and the power reflection can be reduced to 5%.

In the impedance analysis for coupling system, it is required that $Z_L = 73\ \Omega$, which is the input impedance of the rectifier. However when $R_L = 95\ \Omega$, Z_L equals to (55-27*j) Ω, which means the mismatch between rectifier and coupling system cannot be completely resolved by adjusting R_L. If an ideal impedance matching network is added to tune Z_L from (55-27*j) Ω to 73 Ω in ADS, the system efficiency can be improved from 76% to 81%. However when the impedance matching network is simulated using practical inductor and capacitor model, the system efficiency drops to 78%. Because impedance matching networks require extra components and will inevitably cause power loss, it is a trade-off between system efficiency and system complexity. In this paper, a wireless power transfer without impedance matching networks is proposed.

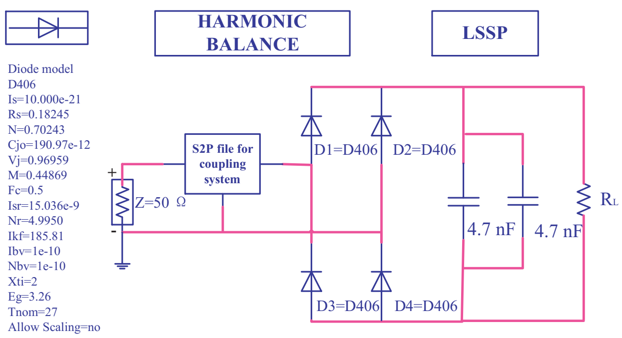

Fig. 5. Simulation setup

D. DC/DC converter

A DC/DC converter serves as a bridge between the load and the rectifier. It serves to convert the output DC voltage from rectifier to another DC voltage level, which suits the load voltage requirement. Actually, it can also convert the load impedance to another value, which is the input impedance of the DC/DC converter. Thus a DC/DC converter can be used to achieve the optimum value of R_L in a WPT system. A cascaded Boost-Buck converter is used in this paper, whose topology is shown in Fig. 7. It is a combination of two classical DC/DC converters (boost and buck) in power electronics. The control method is shown in Fig. 8. By controlling the ratio of the input voltage (V_{in}) to the input current (I_{in}), the input resistance value can be controlled at R_{ref}. V_{bf} represents the

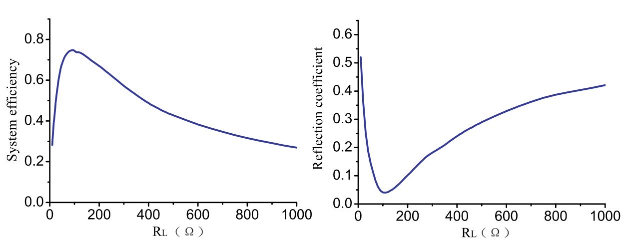

Fig. 6. System efficiency and reflection coefficient for different R_L

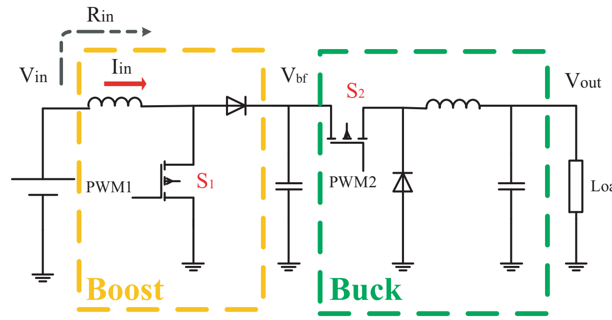

Fig. 7. Cascade Boost-Buck converter

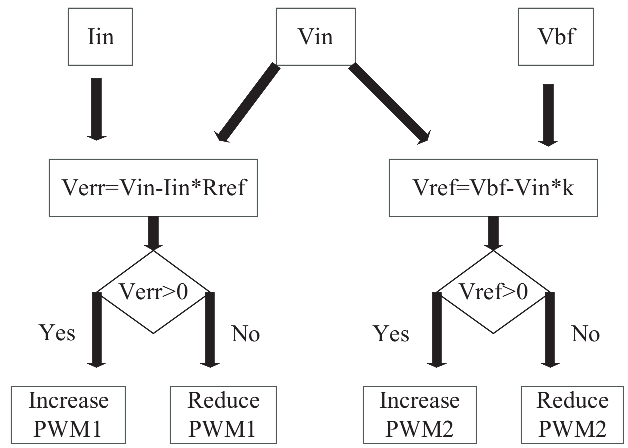

Fig. 8. Control block for the DC/DC converter

voltage of the buffer capacitor. In order to make sure boost converter can work and the power conservation is satisfied. V_{bf} should be controlled at a constant value, which is higher than V_{in}, i.e. k (refer to Fig. 8) should be larger than one.

III. Experiments Results

The experiment setup is shown in Fig. 9, which includes all the subsystems described above. In the following experiments, the setup of the DC/DC controller is $R_{ref} = 100\ \Omega$ and $k = 1.2$, which means R_{in} is controlled at 100 Ω and V_{bf} is controlled at 1.2*V_{in} in Fig. 7. And the forward power (P_f in Fig. 1) is 50 watts. The system efficiency is defined as the ratio of the power absorbed by the load to the forward power.

When the load is an electrical load, by sweeping the load resistance, the input resistance of the DC/DC is maintained at 100 Ω to keep track with the optimum operation condition and minimize the system power reflection. Fig. 10 shows the system efficiency and power reflection coefficient.

When the load is batteries or supercapacitors, whose terminal voltage rises during the charging process. It means the final load impedance changes over time. The charging efficiency for batteries is 67% and that for supercapacitors is 66%. It shows that the system can work at a stable condition even for large load impedance variation.

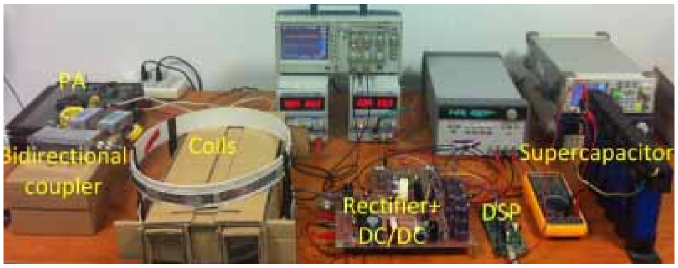

Fig. 9. System configuration

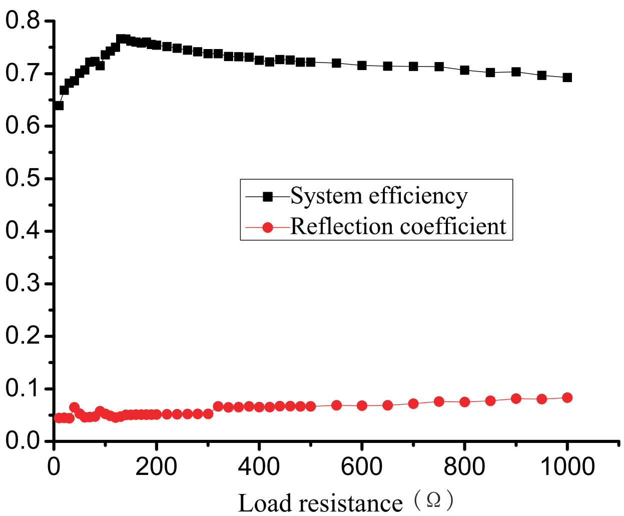

Fig. 10. System efficiency and reflection coefficient

IV. Conclusion

In this paper, a high-efficiency 13.56 MHz wireless power transfer system is demonstrated without using impedance matching network. The power reflection due to impedance mismatch can be greatly reduced by deriving the requirement of each subsystem and properly designing them from a system perspective. This system can supply power for various loads. The system efficiency can achieve 73% when load is resistor and 66% when charging batteries or supercapacitors.

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