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Decoupled control of wireless power transfer Eliminating the interdependence of load resistance and coupling to achieve a simple control framework with fast response times

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ABSTRACT

Wireless power transfer (WPT) is an exciting technology that attempts to transfer energy via loosely coupled inductors. This paper suggests an automated system in which load side impedance matching is utilized to regulate power to a variable load. Such a scheme requires proper selection of topology and component values so that reactance is not a function of load resistance or coupling. Since the maximum power point (MPP) and maximum efficiency point (MEP) do not arise at the same load resistance, careful selection of resistance must be made so efficiency is maximized while target power is maintained. The result is a system that is quick, accurate, simple, robust, and operates without the need of a backward communications link.

1. State of the art

Wireless power transfer control has been intensively studied since MIT's breakthrough in 2007 [1]. Most authors that studied power throughput and efficiency have noticed that tuning distance is key to optimizing wireless power transfer [2–4]. Surprisingly, distance optimization is a way of matching load resistance to source resistance (more on this later). Ideas have been introduced to optimize transfer efficiency in spite of distance variations. One idea is to dynamically insert different reactive matching components in order to compensate for distance variations [5]. This design involves switching capacitors and inductors in and out of the circuit which adds resistance and complication. On the positive side, it maintains a constant frequency operating within a thin ISM frequency band. Another suggestion utilizes frequency control coupled with an adjustable voltage source of the primary to control a charging battery [6]. This architecture assumes a constant voltage load which in many cases is not realistic. Also it relies heavily on a communication link between transmitter and receiver thus increasing the complexity and response time of the system. Another method is presented in [7] where frequency of the transmitter is varied to maintain a constant voltage over a constant load. The limitation of this idea is that load resistance is rarely constant in practical systems. Still others have suggested selecting topologies and component values that linearize the power per unit load resistance [8]. This method accepts small power losses for greater system control. But are these tradeoffs necessary? A closer analysis revealed in this paper suggest that they are not.

Thus, there is a need for a simple wireless power control methodology that is able to: (1) Compensate for variations in target output power, (2) Maintain maximum possible efficiency at targeted power, and (3) React quickly to changes in the coupling coefficient in order to maintain an uninterrupted flow of energy. This paper proposes a solution to meet these criteria.

2. Theory & solution

2.1. Architecture and topology

Wireless power transfer circuits come in many shapes and sizes. Usually, a source is coupled to the transmitter by an input matching network. When current flows through the transmitter it creates a magnetic field which is picked up by the receiver and connected to the load by an output matching network (see Fig. 1).

The secret to transferring power over loosely coupled inductors is to lower the reactance of the inductive coils by inserting capacitance to create a resonant system. Resonant coils increase the power transferred by a factor equal to the sum of the quality factors of the transmitter and receiver times the quality factor of the transmitter. Furthermore, they increase efficiency by half of the product of the quality factors of the transmitter and receiver [1,9].

Surveying current literature reveals varied perspectives on which matching topology is best. Since the quality factor, not the topology,

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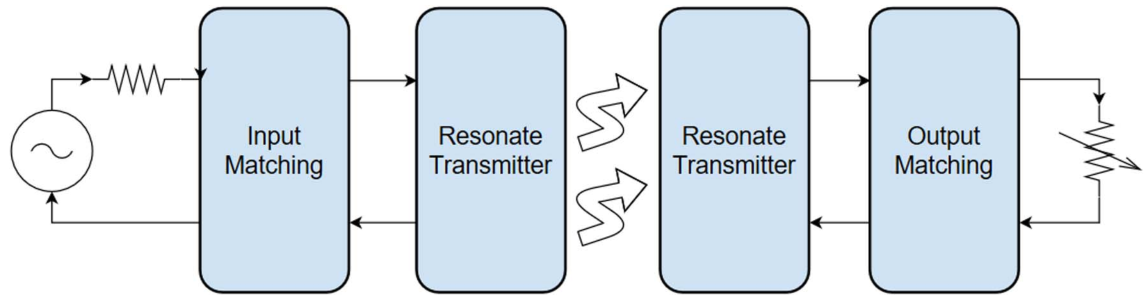

Fig. 1. Block diagram of wireless power transfer system.

determines the power and efficiency this decision should be made based on: (1) if the topology appropriately matches the load and (2) if the topology is easy to control. This paper will demonstrate that to eliminate the interdependence of variables, the series-series topology is the simplest choice.

2.2. Reflected impedance

The concept of reflected impedance is well known for ideal transformers. It can be extended to non-ideal transformers such as the model pictured below (see Fig. 2).

In this circuit M represents the mutual inductance between the transmitter and receiver. Mutual inductance is related to the self-inductance of each coil, L_t and L_r, by the coupling coefficient, k.

$$M = k\sqrt{L_t L_r} \tag{1}$$

The aim of this work is not to analyze the impact the coils' separation distance and orientations but instead focus on modeling the reactive coupling characteristics to develop a simple control strategy. It should be noted that as the receiver and transmitter are moved away from each other, the magnitude of the coupling coefficient decreases from unity (a perfect transformer) to zero (no interaction of magnetic fields).

Using Kirchhoff's Laws one can show that:

$$Z_{in} = Z_t + \frac{\omega^2 M^2}{Z_r + Z_l} \tag{2}$$

$$Z_{out} = Z_r + \frac{\omega^2 M^2}{Z_t + Z_s} \tag{3}$$

$$A \overset{\text{def}}{=} \left.\frac{V_l}{V_s}\right|_{I_r=0} = \frac{-j\omega M}{Z_t + Z_s} \tag{4}$$

The impedances of the transmitter and receiver coils, Z_t and Z_r, include resistive as well as reactive components. V_l and Z_l are the load voltage and impedance while V_s and Z_s are the source voltage and impedance.

2.3. Impedance matching

According to Jacobi's law, maximum power is transferred when the load resistance equals the conjugate of the source resistance. To achieve maximum power transfer, the output impedance would have to be equal to the conjugate of the load impedance. However as mutual inductance varies, it affects the perceived impedance of components on the opposite side of the coupled inductors. Thus either the circuit must be able to compensate for the changes in impedance or the circuit must be designed so there is no change in impedance when mutual inductance varies. A third approach is a hybrid of these two approaches. If a circuit is designed to exhibit changes in only resistance not reactance as distance fluctuates, then load resistance can compensate for variations in distance while the resonant frequency remains constant. In this way, mutual inductance would have no effect on the equivalent reactance while it would have a noticeable effect on the equivalent resistance. This idea is key to the control strategy that will be presented in this paper and will be referred to as the decoupled reactance requirement (DRR).

2.4. Series topologies

The series-series topology can meet the DRR. To prove this consider the circuit in Fig. 3.

By applying the previously derived reflected impedance formula, the input impedance can be expressed:

$$Z_{in} = \frac{1}{j\omega C_t} + j\omega L_t + R_t + \frac{\omega^2 M^2}{j\omega L_r + R_r + \frac{1}{j\omega C_r} + R_l} \tag{5}$$

If a smart selection of the inductances, capacitances, and operating frequency is made such that:

$$\omega_0 = \frac{1}{\sqrt{L_t C_t}} = \frac{1}{\sqrt{L_r C_r}} \tag{6}$$

Then Z_{in} simplifies to:

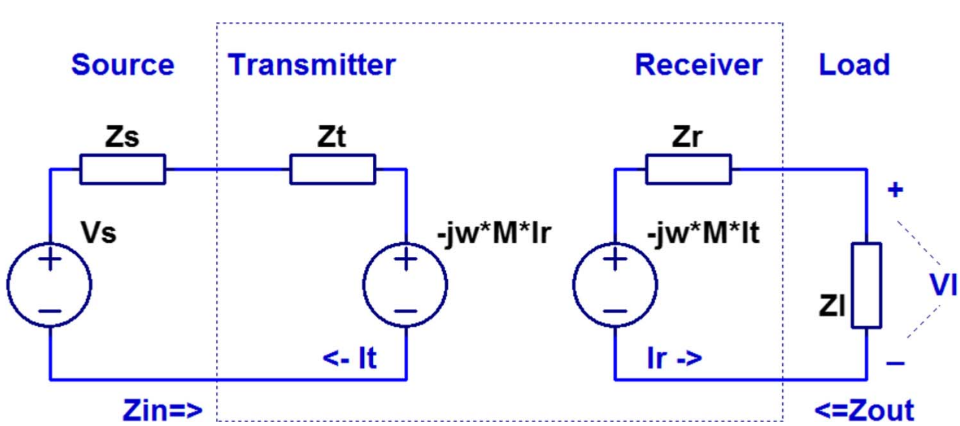

Fig. 2. Circuit model of coupled inductors.