An Optimal Design of Series-Series Resonant Energy Link in Wireless Power Transfer

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***Abstract*— The resonant energy link plays a vital role in the performance of inductive wireless power transfer (IPT) system, whereas the effective design method has not been actively investigated from a perspective of power conversion circuit. This paper presents a new graphical design method based on FOM-rd plane which gives convenience as well as insight to circuit designers. The proposed FOM-rd plane can estimate the voltage gain and efficiency according to the variations of magnetic coupling coefficient and the load resistance. Furthermore, the gain bifurcation phenomenon which hampers soft-switching operation and complicates the output voltage control can be readily avoided from the operating region. An energy link for 200W wireless power transfer system in series-series configuration has been designed and constructed by the proposed method, and its hardware test result verifies the usefulness of the proposed method.**

Keywords— inductive wireless power transfer, figure of merit, graphical methodology, S-S configuration.

I. INTRODUCTION

Inductive wireless power transfer (IPT) technology improves both safety and convenience, and enables waterproofing by removing the metal contacts. Generally, IPT utilizes Faraday induction between two adjacent magnetically-coupled coils located apart. To increase the power transfer efficiency in a mid-range application, the coils are compensated by capacitors in series or parallel, which constitute a pair of resonant energy link structure. Such a resonant structure can be categorized into series-series(S-S), series-parallel(S-P), parallel-series(P-S), and parallel-parallel (P-P) configurations [1] and Fig. 1(a) shows a typical IPT system in S-S configuration.

It goes without saying that design of the resonant energy link structure is important because it determines the overall performance of wireless power transmission. Many researchers have studied the resonant energy transfer mechanism. However, systematic design method has not been thoroughly investigated from a perspective of power conversion circuit. The performance of the resonant link can be measured by a figure-of-merit (FOM) where it is obtained by coupling coefficient (k) multiplied by a quality factor (Q). The theoretical approach based on coupling theory in [2] only focuses on the resonant link, and the efficiency are represented by scattering parameters that are unfamiliar to power electronics engineers. In [3], more circuit-friendly design procedure has been suggested. However, the design equations are too complex to use and thus it is very difficult to estimate the performance according to the variations of the load resistance and the magnetic coupling coefficient caused by perturbations in coil alignment or distance. This paper presents a new graphical design method based on FOM-r_d plane which gives convenience as well as design insight to circuit engineers. A theoretical formulation is to be presented and followed by hardware verification to check validity and effectiveness of the proposed method.

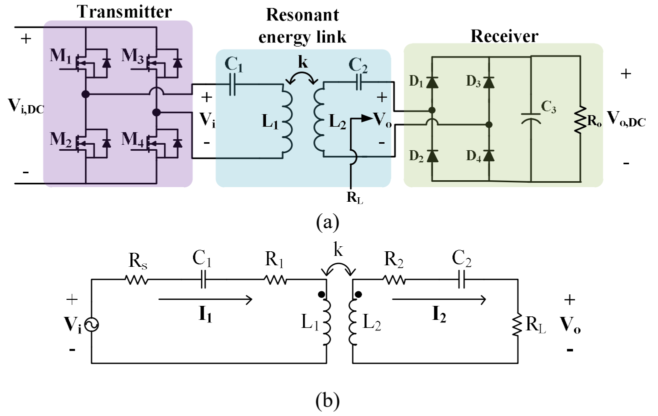


Fig. 1. System description. (a) IPT system in S-S configuration. (b) Equivalent ac circuit model.

II. THE PROPOSED DESIGN PLANE

A. *Theoretical derivation*

Fig. 1(b) is the AC equivalent circuit of the IPT system. In the figure, V_i, I_1, and I_2 are the phasor representations of the input voltage, the transmitter (Tx) current, the receiver (Rx) current, respectively. Circuit parameters used in the mathematical formulation are summarized in Table 1. It should be noted that the extra series resistance (ESR) such as R_1 and R_2 is the sum of individual ESR's in the coil and the compensation capacitor.

By circuit analysis, the linear relation between the phasors can be obtained as

TABLE I
NOMENCLATURES

Symbol	Quantity
L_1, L_2	self-inductances of Tx and Rx resonator
C_1, C_2	compensation capacitors for Tx and Rx resonator magnetic induction
R_1, R_2	total ESR's for Tx and Rx resonator
R_s	internal resistance of the voltage source
R_L	equivalent load resistance
k_1, k_2	coupling coefficients
k	geometric mean of k_1 and k_2
ω	operating angular frequency
ω_o	resonant angular frequency of resonator
Z_{o1}, Z_{o2}	characteristic impedances of Tx and Rx $Z_{o1}=(L_1/C_1)^{1/2}$, $Z_{o2}=(L_2/C_2)^{1/2}$
Q_1, Q_2	quality factors of Tx and Rx resonator $Q_1=Z_{o1}/R_1$, $Q_2=Z_{o2}/R_2$
Q	geometric mean of Q_1 and Q_2

$$\begin{bmatrix} V_i/(R_s+R_1) \\ 0 \end{bmatrix} = \begin{bmatrix} -j\frac{Q_1}{1+R_s/R_1}\left(\omega_N^{-1}-\omega_N\right)+1 & j\omega_N k_1\frac{Q_1}{1+R_s/R_1} \\ j\omega_N k_2\frac{Q_2}{1+R_s/R_1} & -j\frac{Q_2}{1+R_L/R_2}\left(\omega_N^{-1}-\omega_N\right)+1 \end{bmatrix}\begin{bmatrix} I_1 \\ I_2 \end{bmatrix}. \tag{1}$$

As it is necessary to simplify the subsequent formulation, three assumptions are made. First, transmitter and receiver energy link are symmetric: $L_1=L_2=L$, $C_1=C_2=C$, $R_1=R_2=R$, $k_1=k_2=k$, and $Q_1=Q_2=Q$. Secondly, switching devices are nearly ideal and thus the source impedance is small enough to be ignored: $R_s=0$. Lastly, the operating frequency of system is the same as the resonant frequency of circuit: $\omega_N=1$. Meanwhile, it is convenient to introduce two variables as in the following.

$$\mathrm{FOM} \equiv kQ, \quad r_d \equiv \frac{R_L}{R} \tag{2}$$

where the figure-of-merit (FOM) indicates the performance of the resonant link itself, and r_d is the ratio of the load resistance to the internal ESR of the resonant link.

Now, design equations are readily derived from (1). Power transfer efficiency of the resonant link is given by formula (3).

$$\eta = \frac{\frac{1}{2}R_L|I_2|^2}{\frac{1}{2}R_1|I_1|^2+\frac{1}{2}R_2|I_2|^2+\frac{1}{2}R_L|I_2|^2} = \frac{FOM^2 r_d}{(1+r_d)^2+FOM^2(1+r_d)} \equiv f(r_d,\ \mathrm{FOM}) \tag{3}$$

Similarly, AC voltage gain formula is formulated in (4)

$$M_{V,AC} \equiv \left|\frac{V_o}{V_i}\right| = \frac{\sqrt{R_L P_o}}{|V_i|} \approx \frac{FOM^2 r_d^{\,2}}{[FOM^2+(1+r_d)]^2} \equiv g(r_d, \mathrm{FOM}) \tag{4}$$

Because both (3) and (4) are functions of FOM and r_d, these two new parameters can be used as design variables. Fig. 2 is a plot representing the two performance indices at the same time and thus is useful in the resonant link design.

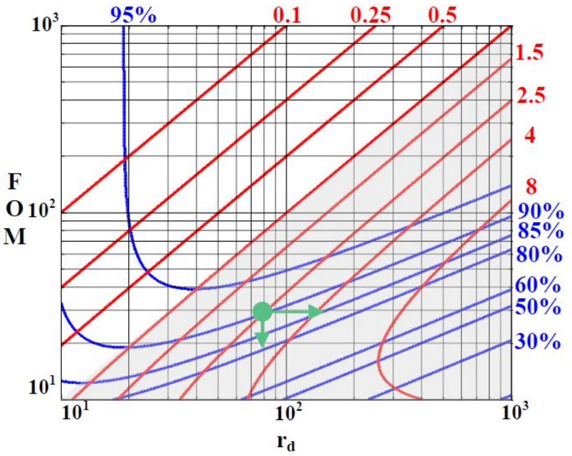


Fig. 2. FOM-r_d design plane.

B. *Operating Point Analysis in the FOM-r_d Plane*

It is possible to locate the operating point by calculating FOM and r_d for a ready-made energy link structure. In this case, the proposed FOM-r_d plane provides intuitive way of understanding of the performance dependency on the external conditions such as degree of misalignment, coil distance, and the load resistance effects.

Another advantage of the FOM-r_d plane analysis is that a peak splitting phenomenon called bifurcation can be graphically detected. The gain bifurcation makes challenge in a frequency-controlled output regulation mechanism and sometimes hampers soft-switching operation of the Tx inverter power switches. The criterion to prevent bifurcation from occur in S-S configuration has been studied in [5], and can be rewritten for the design space, FOM-r_d plane, as shown in (5).

$$\mathrm{FOM} < 1 + r_d \tag{5}$$

The above condition to guarantee the bifurcation-free operation can be mapped into the lower right shaded region in the Fig. 2.

C. *Energy Link Design in FOM-r_d Plane*

The FOM-r_d plane is convenient especially for energy link design process. An energy link can be designed by determining one operating point on the design plane through the target efficiency and voltage gain. Thereafter, with additional conditions such as a coupling coefficient, a load resistance, and a resonant frequency, all the circuit parameters for the resonant energy link can be calculated by the following equations.

$$Q = \frac{\mathrm{FOM}}{k}, \quad R = \frac{R_L}{r_d}, \quad L = \frac{QR}{\omega_o}, \quad C = \frac{1}{QR\omega_o} \tag{6}$$

As mentioned before, as the system approaches to the full load condition, the operating point tends to move further into the region of bifurcation. Likewise, as degree of coil misalignment or the distance between coils decreases, the energy link becomes more prone to bifurcation. Therefore, it is necessary to start the design in the full load and the maximum coupling coefficient to guarantee the uniqueness of the voltage gain peak.

III. VERIFICATION OF THE PROPOSED MEHOTD

A. Design Example

In this section, a 200W energy link structure for the IPT system in Fig. 1(a) has been designed. The target voltage gain is calculated as 2.5 from the voltage specification. The target efficiency is set to 90%, and the effective load resistance, R_L is calculated as 40.5Ω from the output power rating. According to Fig. 2, FOM=28 and r_d=78 are tried for the first design phase. The target coupling factor k is estimated as 0.04 and the resonant frequency of the system is set to 100KHz and the circuit parameters are calculated as Q=700, R=0.52Ω, L=579uH, and C=4.37nF. Tx-side capacitor stresses for the voltage, V_{C1} and the current, I_1 are 3.2KV and 8.8A in magnitude and Rx-side capacitor stresses for the voltage, V_{C2} and the current are 1.1KV and 3.1A in magnitude, respectively.

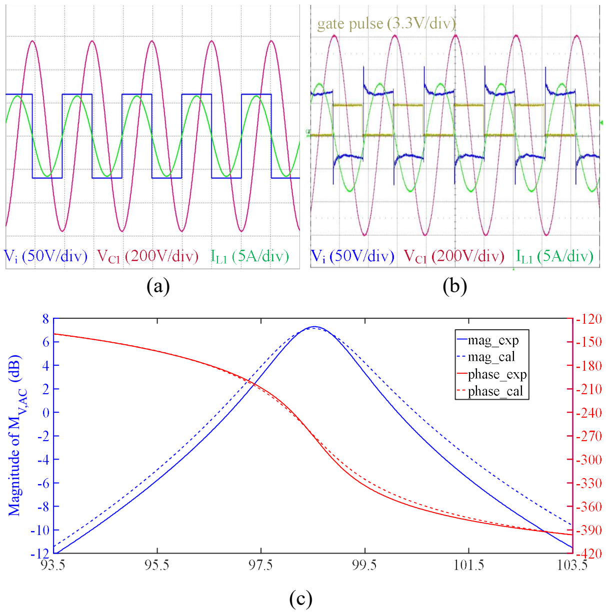
B. Experimental Results

The inductance formula in [4] has been utilized for implementing the practical coil structure whose value of inductance is 579uH. The center radius of the loop is chosen to 15cm. Litz wire in the diameter of 1.2mm has been used in the current carrying conductor. With the number of turns, N=30, the calculated values of inductance and DC resistance of the coil are 479uH and 0.4Ω. And Rx coil is designed identically. From mutual inductance formula achieving k=0.04, Tx and Rx coils are placed a part with the distance of 30 cm, which has been slightly adjusted experimentally.

For the implementation of Tx capacitor in 4.37nF, the capacitor bank structure is used with series as well as parallel connection, because the capacitor voltage and current stresses must be considered lower than 3.2kV and 8.3A. As a result, high voltage film capacitors (ICEL, PSB2301680KGS) are used in 6S-4P configuration. According to the datasheet, ESR of the capacitor bank at 100 KHz is found to be 112.5mΩ. The same configuration has been used for Rx capacitor bank.

The overall system which contains the resonant link has been tested with a full-bridge inverter for Tx-side and a passive rectifier for Rx-side. Fig. 4(a) and Fig. 4(b) show LTSPICE simulation and hardware waveforms and two operating waveforms match well with each other. When the input power is 231.9W (46.15V/5.03A), the output power is measured to be 182.80W (95.6/1.92A), and thus the overall dc to dc efficiency of the IPT system is 78.8%. To aid the efficiency analysis, PLECS thermal simulation considering the device datasheet shows the inverter efficiency and the rectifier efficiency are 98.1%, and 98%, and thus the energy link efficiency is estimated to be 85%. The actual measurement of the voltage gain in the resonant link is 2.32.

For further comparisons, some other measurements have been made. The LCR meter (Agilent, 4263B) reading says that the capacitance and the self-inductance are 4.12nF and 633uH. Using the impedance measurement set-up (AP Instruments, AP300), Tx-side total ESR is measured to 0.76Ω at the resonant frequency of 98.52 KHz. From these observations, the actual operating point should be re-located to (FOM, r_d)=(20.7, 53), which indicates the implemented efficiency and the voltage gain to be 87% and 2.27, respectively. Fig. 4(c) shows the magnitude-phase comparisons of the voltage gain and the measurement results matches well with the simulation.



(a) (b)

(c)

Fig. 4. Experimental results. (a) Simulation Waveforms (5us/div). (b) Hardware Waveforms (5us/div). (c) Voltage Gain Comparison.

IV. CONCLUSION

This paper presents a new graphical method based on FOM-r_d plane that can intuitively describes the energy link of the IPT system. Using the proposed method, the voltage gain as well as the efficiency can be designed together in terms of power conversion circuit. In addition, it is easy to estimate the performance and to check the bifurcation condition even with perturbations in the magnetic coupling or in the system load. By applying the proposed design method, a 200W energy link system has been constructed. The validity of the design is verified by comparing the simulation and the hardware results, and the differences are about 2.0% in the efficiency and about 2.2% in the voltage gain. To conclude, the suggested method is expected to be a powerful methodology in both analysis and design of IPT system.

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