© November 2018 | IJIRT | Volume 5 Issue 6 | ISSN: 2349-6002

Optimal Coupling to Obtain Higher Output Power in a Wireless Power Transmission System

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***Abstract*- In a WPT system, if its system parameters are designed unreasonably, output power and transmission efficiency will be low. Practical WPT must be able to support complicated coil configurations and keep following magnetic resonant conditions with maximum power transfer capability during coupling distance variation. The main parameters affecting output power and transmission efficiency are the distance between the coils, coupling coefficient, the resonance frequency and the resistance of the load. The maximum output power can be obtained in over coupled state by changing capacitor value of the resonating system. The proposed technique is analyzed with an equivalent circuit model, and simulations are performed to evaluate the performance. The system is validated through experimental results.**

Index Terms- wireless power transmission, capacitance tuning, over coupled state.

1. INTRODUCTION

Two- and four-coil WPT systems have different topologies and are known by alternative names; for example, in the case of a two-coil WPT system, we have “inductive coupled WPT” or “inductively coupled power transfer” or “inductive WPT,” and in the case of a four-coil WPT system, we have “resonant coupled WPT” or “resonant WPT.” Additionally, the authors of through claimed that two-coil WPT systems are suitable for only short-range transmissions and that four-coil WPT systems are suitable for only mid-range transmissions. However, it was shown that there is no guarantee that both a two-coil WPT system and a four-coil WPT system will operate with identical primary and secondary coils, because the inductance either a two-coil, three-coil, or four-coil WPT system can be varied through an optimization process. As the coupling coefficient decreases, the real part of the input impedance for a two-coil WPT system was shown to decrease, whereas that of a four-coil WPT system was shown to contrarily increase. These give rise to different suitable transmission distances for two-coil and four-coil WPT systems; however, their explanation is unfortunately oblique for readers to clearly understand the relation between the real part of the input impedance and the transmission distance. To describe how autonomous WPT system obey to the self-organization theory, we present an analysis based on a circuit model of a two-resonance system consisting of a transmitter resonator coupled to a receiver resonator.

Previously demonstrated magnetically coupled resonators used for WPT has shown the potential to deliver power with more efficiency than far-field approaches, and at longer ranges than traditional inductively coupled schemes. However, it appears frequency splitting phenomenon which is a physical phenomenon in mid-range WPT system. It occurs when the conditions for the maximum power theorem cannot be met at the resonance frequency of the resonators within the over-coupled region.

We know that Frequency splitting results decrease in output power. The main parameters affecting output power and transmission efficiency are the distance between the coils, coupling coefficient, resonance frequency and the resistance of the load. Here, we are online tuning method is applied by adjusting capacitance of the input matching network, and maximum output power is obtained in over coupled state.

2. MAXIMUM OUTPUT POWER OF CONVENTIONALWPTSYSTEM

Applying kvl equations in fig. 1,

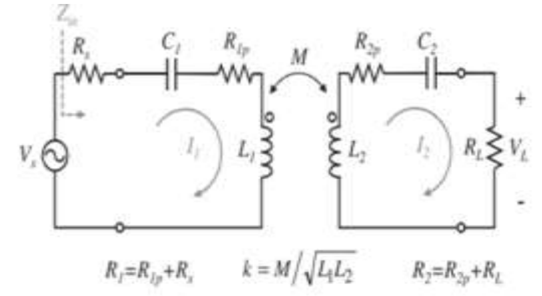


Fig. 1. Equivalent circuit model of a two-coil resonant WPT system.

$Vs=(j\omega L1+1/j\omega C1+R1)\cdot I1-j\omega M\cdot I2$ (1)

$0 =-j\omega M\cdot I1+(j\omega L2+1/j\omega C2+R2)\cdot I2$ (2)

The coupling coefficient k at critical coupling state become

$k\ critical=1/\sqrt{Q1Q2}$(3)where $Q1 = \omega L1 /(R1p + Rs) = \omega L1 /R1$ and $Q2 = \omega L2 /(R2p + RL) = \omega L2 /R2$ are the Q-factors of the primary coils and secondary coils. The free resonant angular frequencies are given by

$\omega 1=1\sqrt{L1C1}, \omega 2 = 1\sqrt{L2C2}$ (4)

The output power and input power ratio is called energy efficiency of the system.

$\eta=PL/Pin=(RL|I2/I1|^2)/(R1+R2|I2/I1|^2)$ (5)

Where I1 is the primary RMS current and I2 is the secondary RMS current. From the equation (2),

$|I2/I1|=|(j\omega 0k\sqrt{L1L2})/(j\omega 0L2+1/j\omega 0C2+R2)|$ (6)

Here, $\omega 1=\omega 2=\omega 0$ substituting the equation (3) into equations (6) yields

$|I2/I1| = \sqrt{R1}/\sqrt{R2}$ (7)

From (1) and (2),

$|I2/Vs| = | j\omega M /((j\omega 0L1+1/j\omega 0C1 + R1)(j\omega 0L2+ 1/j\omega 0 C2 + R2) + \omega 2M2) |$ (8)

Substitute equation(3) into (8),

$|I2/Vs| = 1 /(2\sqrt{R1R2})$ (9)

Critical coupling is the degree of coupling that provides maximum transfer of signal energy from one radio-frequency resonant circuit to another when both are tuned to the same frequency. Also known as optimum coupling.It can be represented only by using resistance parameters of resonating system.

The impedance input Z in,

$Z\ in = Rs+(R1p + j\omega L1+1/j\omega C1) + [(\omega M)^2 /(R2 + j\omega L2 + 1/j\omega C2)]$

$= R1 + Z\ reflected$ (10)

Fig. 2 is the equivalent circuit diagram using the reflected impedance.

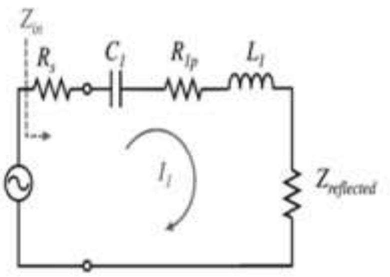


Fig. 2. Equivalent circuit model of Fig. 1 using reflected impedance.

$Z\ reflected=R1.k^2 .Q1Q2$ (11)

Substituting (3) into (11), the reflected impedance R1 = (Rs + R1p), and the input impedance is 2R1 . By doing this we get that the maximum power is transfers secondary resonator.

Substituting equation (7) to equation (5), we get the efficiency as

$\eta = RL / 2(R2p + RL)$ (12)

3. CRITICAL COUPLED STATE CONDITIONS FORMATION

If wireless power transfer system is over coupled at ω0,ω1 and ω2,

$|I2/I1| = \sqrt{(k^2L1 /L2)} / \sqrt{((\omega 2^2/\omega 0^2 -1)^2 + 1/Q2^2)}$ (13)

Comparing (7) with (13) gives

$\omega 2=\omega 0\sqrt{(1\pm\sqrt{(k^2.Q2^{-1}.Q1-Q2^{-2})})}$ (14)

Similarly, the free resonant angular frequency of the primary resonator is also expressed as

$\omega 1=\omega 0\sqrt{(1\pm\sqrt{(k^2.Q1^{-1}.Q2-Q1^{-2})})}$ (15)

If Q1 = Q2 and Q1,2>> 1,then equation (14) and (15) can be approximated as

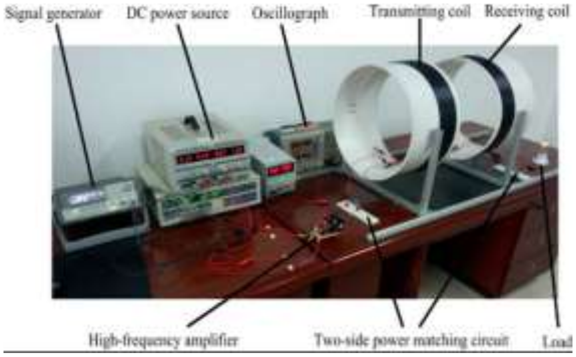
$\omega 1,2\sim=\omega 0\sqrt{(1\pm k)}$ (16)

This is the frequency splitting by over coupling.

4. SIMULATION AND EXPERIMENTAL RESULTS

An experimental test rig whose measured circuit parameters are listed in Table 1 is set up in the laboratory. Both Tx and Rx sides have the same inductance and capacitance, so they share the same resonant frequency. For the resistance part there will be a flexibility for the change in parameter. All the resistance values such as r1, r2, Rc1, and Rc2 are the practical measurement from the test rig.

Fig. 3 experimentation of two coil WPT system



Normally the distance between the two coils can be several times of the coil radius, which makes the coupling coefficient a very small value around 0.001 to 0.01.

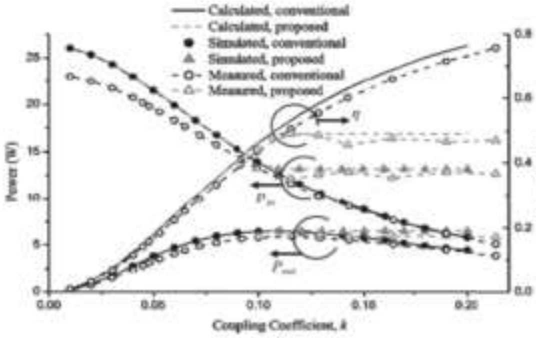


Fig. 4 Pout, Pin and efficiency with respect to k

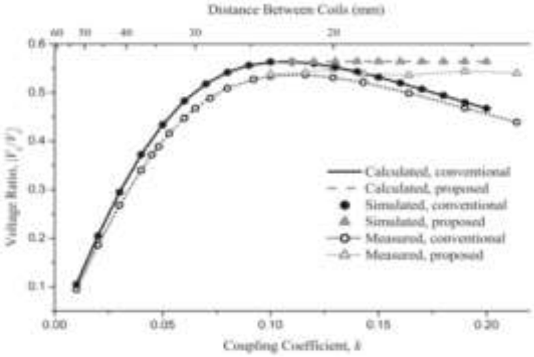
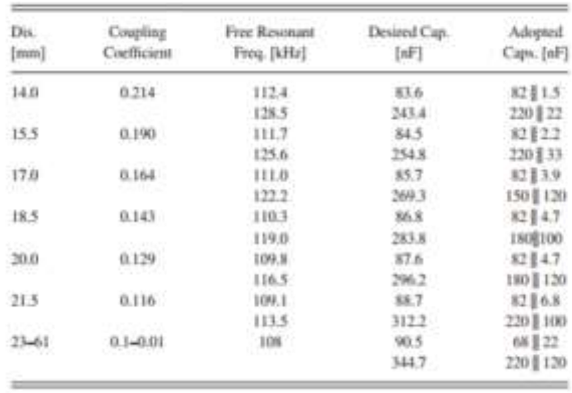


Fig.5 voltage gain with respect to k and coil distance

SYMBOL	NOTES	VALUE
Vs	input voltage ac rms	4.5 V
ω0	Operating angular frequency	2π × 108 × 103 rad/s
L1	Primary inductance	24 µH
L2	Secondary inductance	6.3 µH
R1 p	Primary ESR	0.072 Ω
R2 p	Secondary ESR	0.019 Ω
Rs	Source resistance	0.7 Ω
RL	Load resistance	1.0 Ω

Table. 1 circuit parameters



Dis. [mm]	Coupling Coefficient	Free Resonant Freq. [kHz]	Desired Cap. [nF]	Adopted Caps. [nF]
14.0	0.214	112.4	83.6	82 ‖ 1.5
		128.5	243.4	220 ‖ 22
15.5	0.190	111.7	84.5	82 ‖ 2.2
		125.6	254.8	220 ‖ 33
17.0	0.164	111.0	85.7	82 ‖ 3.9
		122.2	269.3	150 ‖ 120
18.5	0.143	110.3	86.8	82 ‖ 4.7
		119.0	283.8	180‖100
20.0	0.129	109.8	87.6	82 ‖ 4.7
		116.5	296.2	180 ‖ 120
21.5	0.116	109.1	88.7	82 ‖ 6.8
		113.5	312.2	220 ‖ 100
23–61	0.1–0.01	108	90.5	68 ‖ 22
			344.7	220 ‖ 120

Table. 2 series capacitance with respect to k

First we should measure coupling coefficient with respect to coil distance using E5061B analyser providing real time calculation. The offline tuning capacitance are detailed in Table.2.The calculated, experimental and simulated Pout, Pin, system efficiency and gain voltage with respect to k are shown in Fig. 4 and Fig. 5.

The proposed method is only applied in over coupled state and not in under coupled state. The simulation results and calculation results are appear to overlap, but results of experimentation are good with calculations. For the proposed system energy efficiency reaches to almost 50%.Free resonant frequencies are not equal to resonant frequencies.

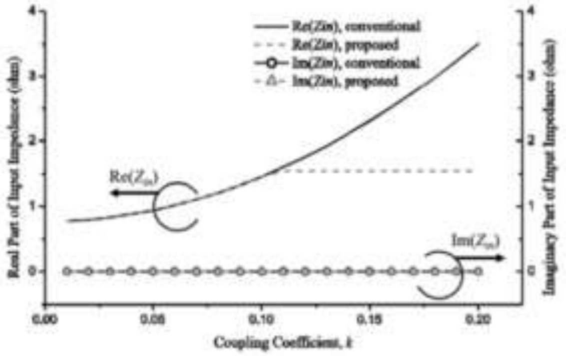


Fig. 6 simulated input impedance with respect to k

5. CONCLUSION

We implemented optimal coupling using frequency splitting to obtain higher power output, efficiency, gain and voltage. We know that splitting of frequencies results decrease in power output. The main parameters affecting output power and transmission efficiency are the distance between the coils, coupling coefficient, resonance frequency and the resistance of the load.

Apart from the theoretical studies, the detailed implementation of wireless power transmission prototype including the design of coil, digital frequency generation, and large frequency power electronics is also introduced. Experiments are implemented to verify the effectiveness of circuit analysis by good tuning the circuit parameters. Because of large factors of the coils, the wireless power transmission is very sensitive to the jigging and frequency drifting. From the circuit theory, the relationship between coupling coefficients power transfer, the circuit parameters and efficiency are analysed. The optimised work area balancing the distance and efficiency is introduced based on the analysis. In order to verify the WPT proposed circuit theories, a practical wireless power transmission prototype is formed and implemented in this paper.

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