

## High Efficiency with Multi Load Wireless Power Transmission

Borong Hu, Li Ran

**ABSTRACT**—In this paper, we present a model of magnetically coupled resonators in terms of passive circuit elements and derive system optimization parameters. An analysis of system transmission characteristics, with single load and multi load, is elaborated in forms of the impacts of system load and transmission distance on transmission system output load and efficiency in respectively, which is important from a practical standpoint because, in many applications, the range and orientation of the receive device with respect to the transmit device vary with user behavior.

**Index Terms:** Wireless power transmission, high frequency, high efficiency, multi load, smart home

### I. INTRODUCTION

ADVANCES IN wireless communication and semiconductor technology have enabled a wide variety of portable consumer electronic, medical, and industrial devices. However, users are still required to manually plug in these mobile devices, limiting ultimate mobility and disrupting use when charge is depleted. Furthermore, as portable devices shrink, connectors become a larger fraction of system size. Wireless power offers the possibility of connector-free electronic devices, which could improve both size and reliability. Thus, there is a desire to use wireless power technology to eliminate the remaining wired power connection.

Presently, several wireless power techniques are being pursued. It is useful to categorize these efforts in terms of their underlying power-transfer mechanism to understand implications for range, adaptation, and efficiency.

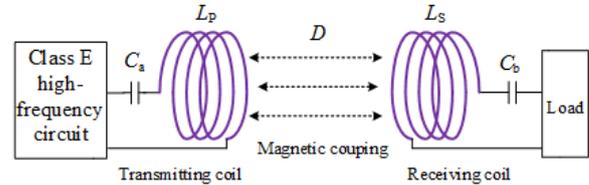


Fig. 1. Magnetically resonant coupling wireless power transmission system diagram

Far-field techniques use propagating electromagnetic waves that transfer energy the same way radios transmit signals. This method has been successfully used to power UHF RFID tags, which have no batteries and an operating range of 1~10 m. One of the drawbacks to far-field approaches is the inherent tradeoff between directionality and transmission efficiency. There are many examples of RF and microwave systems that use high-gain antennas to transfer power over kilometer distances at efficiencies of over 90%. These systems suffer from the need for sophisticated tracking and alignment equipment to maintain a line-of-sight (point-to-point) connection in unstructured and dynamic environments.

Alternatively, RF broadcast methods, which transmit power in an omnidirectional pattern, allow for power transfer anywhere in the coverage area. In this case, mobility is maintained, but end-to-end efficiency is lost since power density decreases with a  $1/r^2$  dependence, resulting in received power levels many orders of magnitude less than what was transmitted.

Inductive coupling (or near-field) techniques do not rely on propagating electromagnetic waves. Instead, they operate at distances less than a wavelength of the signal being transmitted. Applications include rechargeable toothbrushes and the recently proliferating “power” surfaces. These techniques can be very efficient but are limited to transmission distances of about a centimeter. Alternatively, near-field RFID pushes the limit on distance by sacrificing

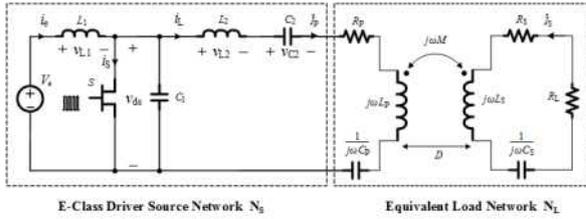


Fig. 2. Wireless power transmission system equivalent circuit

efficiency. Near-field tags have a range of tens of centimeters but only receive power in the microwatt range with 1%–2% transmission efficiency.

Previously demonstrated magnetically coupled resonators used for wireless power transfer have shown the potential to deliver power with more efficiency than far-field approaches, and at longer ranges than traditional inductively coupled schemes. However, this prior work is limited to a fixed distance and orientation, with efficiency falling off rapidly when the receiver is moved away from its optimal operating point.

In this paper, we present a model of magnetically coupled resonators in terms of passive circuit elements and derive system optimization parameters. In addition, an analysis of system transmission characteristics, with single load and multi load, is elaborated in forms of the impacts of system load and transmission distance on transmission system output load and efficiency in respectively. In wireless power transmission experiment, the experiment results are in accordance with the theory we expounded. This is important from a practical standpoint because, in many applications, such as laptop recharging, the range and orientation of the receive device with respect to the transmit device vary with user behavior.

## II. SYSTEM ANALYSIS AND CIRCUIT MODEL

Magnetically resonant coupling wireless power transmission technology (MCR-WPT) is the use of two coils for the same resonance frequency, electromagnetic coupling produces an alternating magnetic field of the same frequency, and the receiving device

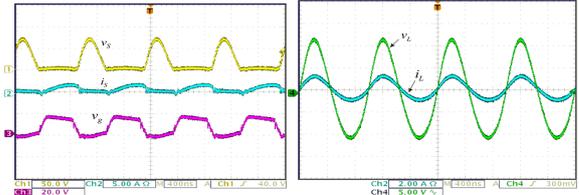


Fig. 3. High frequency power source and receiving end load waveform

Table 1: System circuit and transmission coil parameters

Parameters	Value	Parameters	Value	Parameters(Coil)	Value
$V_{cc}/V$	20	$r/cm$	10	$N$	10
$f/MHz$	1	$a/mm$	1.9	$R_{coil}/\Omega$	3.15
$R_l/\Omega$	20	$R_{OPT}/\Omega$	20	$L_{coil}/\mu H$	34.65
$L_1/\mu H$	35	$L_2/\mu H$	16	$C_{comp}/pF$	740
$C_1/nF$	3.6	$C_2/nF$	1.7		

continues to gather energy to the load, thus achieving a high efficiency of wireless power transmission.

Magnetically coupled resonant wireless power transmission system structure shown in Figure 1, the Class E high-frequency inverter circuit is used for a system frequency driver source, the power transmitting coil  $L_P$  will come out power in the form of electromagnetic radiation in the near field received by receiving coil  $L_S$ , the magnetic coupling distance between the two transmission coils for  $D$ .

At high frequencies, the transmission coil  $L_P$  and  $L_S$  have parasitic capacitance, the small capacitance value cannot compensate the two transmission coils to achieve a resonant state, therefore one need to compensate a capacitor  $C_a$  and  $C_b$  in series to transmit and receive circuits respectively, so that both ends of the transmitter and receiver circuits are in resonant state, working in the strong coupling resonance condition, to ensure the system to achieve optimal transfer efficiency and load maximum transmit power.

According to Figure 2, using circuit theory, we deduct the wireless power transmission system equivalent circuit model to calculating transmission formula. According to KVL formula, the coil circuit current  $i_P$  and  $i_S$  in  $L_P$  and  $L_S$  respectively are:

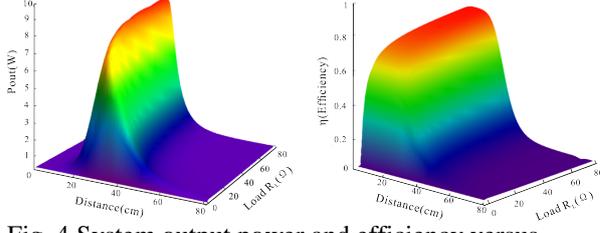


Fig. 4 System output power and efficiency versus transmission distance and load.

$$I_P = \frac{Z_S U_S}{Z_P Z_S + (\omega M)^2}$$

$$I_S = \frac{-j\omega M U_S}{Z_S Z_P + (\omega M)^2}$$
(1)

According to formula(1), the desired optimum transmission distance  $D$  as follows can be obtained when the receiving side of the load is constant, in order to ensure that the output impedance of the class E inverter circuit is also a constant value:

$$D = \sqrt[3]{\frac{\pi^2 f \mu_0 N^2 r^4}{(Z_{in} - R)(R + R_L)}}$$
(2)

When the receiving end is connected with a given load at a certain distance, E class high frequency inverter output terminal impedance  $Z_{in}$  is:

$$Z_{in} = R + \frac{\pi^4 f^2 \mu_0^2 N^4 r^8}{(R + R_L) D^6}$$
(3)

At higher  $Q_L$ , sinusoidal harmonic components of load are lower, but the efficiency of the converter will be reduced. At lower  $Q_L$ , the converter can work in the higher efficiency state, but the harmonic components of the output sine wave are higher.  $Q_L$  when we choose, we must take into account these two factors. In general we choose  $Q_L$  from 5 to 10. The other parameters can be measured by quality factor  $Q_L$ .

According to the parameter optimization theory, load  $R_L$  is  $20\Omega$ , MOSFET drive voltage frequency is 1MHz, pulsation amplitude is 6V, pulse period is 1000ns, and pulse width is 50ns. Make class E inverter in the best condition, namely to achieve zero-voltage switch opening. Final adjusted parameters  $L_2$ ,  $C_1$ ,  $C_2$  shown in Table 1. According to the formula for calculating the coil inductance, resistance, and inductance of

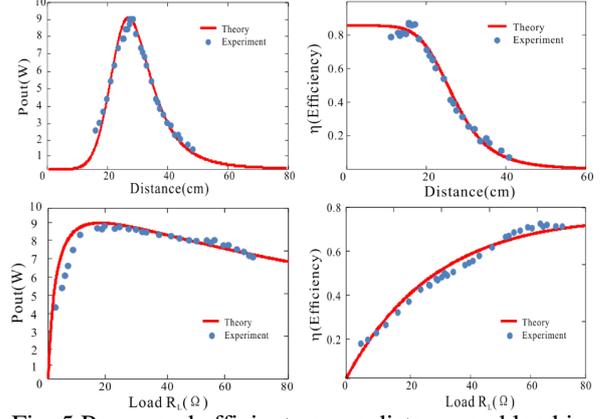


Fig. 5 Power and efficient versus distance and load in theory and experiment.

the coil itself specifications can be obtained parameters are given in Table 1.

When the wireless transmission network receiving end connected to  $20\Omega$  purely resistive load, according to the formula (2, 3) the best load state can be obtained that the transmission distance is set to 23cm, and the output terminal of the inverter circuit E class is load of  $20\Omega$ .

### III. THE EFFECT OF TRANSMISSION DISTANCE AND LOAD ON OUTPUT POWER AND EFFICIENCY

According to above section, we set up the experimental platform, using parameters in table 1. The experimental results as shown in figure 3, (a) is high frequency switcher driver voltage, MOSFET voltage and current waveforms, (b) is receiving end load waveform. The Waveform  $v_s$  is switcher voltage,  $i_s$  is switcher current,  $v_g$  is driving voltage. It can be observed that the power under the working frequency of 1 MHz can achieve soft switch.  $v_L$  and  $i_L$  are voltage and current of the load at receiving end. Wireless power transmission system can stably work under 23cm distance at 1MHz. We can use this WPT system to smart home environment with multiple loads. Under this application condition, the system should be optimized for complex load change, with matching high-frequency power source output impedance to multiple loads network. The influence of coupling magnetic field block by

building and furniture also needs to be taken into account.

With the success of wireless power transmission in our experimental platform, the next step is that analysis the impact of parameters in wireless power transmission on system output power and efficiency, in respectively, such as transmission distance, load, etc. As the above analysis, the system output power can be calculated as formula (4).

$$P_o = \frac{R_L U_s^2 (\omega M)^2}{\left[ R_p (R_s + R_L) + (\omega M)^2 \right]^2} \quad (4)$$

In this experimental condition, emission coil circuit and receiving coil circuit are in resonance condition in 1MHz transmission frequency, so the circuit impedance can be simplified to emission circuit resistance and receiving resistance, and in this paper, we only analysis the resonance working condition in which the wireless power transmission system works as the maximum output power and efficiency, so it is the most useful and the most practical condition we use the transmission system.

The high frequency power loss resistance in emission and receiving circuit has two forms: ohmic loss resistance  $R_0$  and radiation loss resistance  $R_f$ . In magnetically resonant coupling wireless power transmission system, the radiation loss resistance  $R_f$  is far less than ohmic loss resistance  $R_0$ , so that the radiation loss resistance can be neglected, and high frequency power loss can only be simplified to ohmic loss resistance  $R_0$ . As the above analysis, the system output efficiency can be calculated as formula (5).

$$\eta = \frac{R_L (\omega M)^2}{(R_0 + R_L) \left[ R_0 (R_0 + R_L) + (\omega M)^2 \right]^2} \times 100\% \quad (5)$$

As the formula (4, 5), the impact of transmission distance  $D$  and load  $R_L$  on transmission output power and efficiency is illustrated in figure 4.

As the figure 4 shown, first figure describe the output power versus transmission distance and load. At any distance, output power increase as load increase. Under optimization

load resistance  $20\Omega$ , output power is very low, in the other hand, when the load resistance beyond optimization load, output power can keep in a maintain state 9W. As the transmission increase from 0 to  $80\Omega$ , output power increase to a maximum point and then decrease to zero with a maximum output power point appearance at about the optimization distance 23cm. In the second figure, as load increase from zero, transmission system efficiency increase in a high speed, and then keep in a maintain state about 80%. Like to the impact of distance on output power, the system efficiency increase in a high speed to a maximum point and then decrease slow down as distance increasing from zero.

As the above analysis, optimization load resistance is  $20\Omega$  and optimization transmission distance is 23cm. The experiments were carried out in two cases: in the first condition, system load is fixed in optimization load resistance  $20\Omega$ , the system output power and transmission efficiency are tested in varied coil distance; in the second condition, transmission distance is fixed in optimization coil distance 23cm, the system output power and transmission efficiency are tested in varied system load resistance.

In constant system optimization load, transmission output power has a maximum point in optimization distance 23cm, and the maximum output power is 9W; system efficient decrease with transmission distance increasing. When the distance is under 20cm, the system efficiency is maintained in about 85%. The efficiency decreasing rapidly from 80% to 10% with distance increasing from 20cm to 40cm, and then efficiency is gradually approaching to zero. At optimization distance 23cm, system efficiency is only about 70%. When system load is optimization load, the maximum output power and system transmission efficiency don't appearance at the same transmission distance, so that the practical transmission distance one used is cooperating with utilization requirement and condition.

In constant optimization transmission distance, transmission output power has a

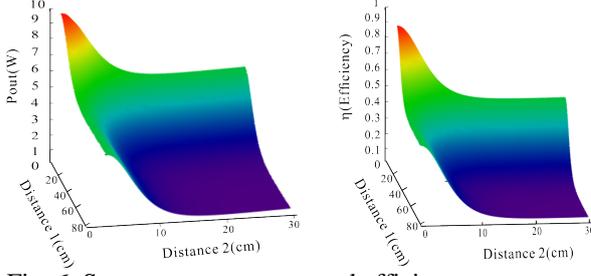


Fig. 6. System output power and efficiency versus two load transmission distance.

maximum point in optimization system load  $20\Omega$ , and the maximum output power is  $9W$ . When the system load is under  $20\Omega$ , the output power increasing rapidly from  $0$  to  $9W$  with distance increasing from  $0$  to  $20\Omega$ , and then the output power is maintained in about  $8W$ . System efficient increases from  $0$  to  $0.7$  with system load increasing from  $0$  to  $80\Omega$ . At optimization load  $20\Omega$ , system efficiency is only about  $40\%$ . When transmission distance is optimization load, the maximum output power and system transmission efficiency don't appearance at the same system load, so that the practical system load one used should be cooperating with utilization requirement and condition.

According to equivalent circuit model with single load, emission coil circuit current and receiving coil circuit current can be derived in multi load transmission system.

$$I_s = \frac{U_s}{\left( Z_s + \frac{\omega^2 M_1^2 Z_2 + j\omega^3 M_1 M_2 M_{12}}{Z_1 Z_2 + \omega^2 M_{12}^2} + \frac{\omega^2 M_2^2 Z_1 + j\omega^3 M_1 M_2 M_{12}}{Z_1 Z_2 + \omega^2 M_{12}^2} \right)} \quad (6)$$

$$I_1 = \frac{-\omega^2 M_2 M_{12} + j\omega M_1 Z_2}{Z_1 Z_2 + \omega^2 M_{12}^2} I_s \quad (7)$$

$$I_2 = \frac{-\omega^2 M_1 M_{12} + j\omega M_2 Z_1}{Z_1 Z_2 + \omega^2 M_{12}^2} I_s \quad (8)$$

As formula 6, 7, 8, the system transmission efficiency and output power can be derived.

$$P = I_1^2 R_{L1} + I_2^2 R_{L2} \quad (9)$$

$$\eta = \frac{P}{U_s I_s \cos\theta} \times 100\% \quad (10)$$

As the formula 8, 9, the impact of two loads transmission distance  $D_1$  and  $D_2$  on transmission output power and efficiency is illustrated in figure 6.

As the figure 6 shown, output power increase as two load transmission distance increase. Under optimization load resistance  $20\Omega$ , in the transmission distance  $10$  to  $20cm$  range, output power is around  $5W$  to  $6W$ , and system efficient is about  $50\%$ . It is a practical output power and efficiency and can be used is actual application. When the two load transmission distance increase, the output power and efficiency decrease rapidly, so it is better to use in the optimal transmission range from  $10cm$  to  $20cm$  for the actual application.

## IV. CONCLUSION

In this paper, we present a model of magnetically coupled resonators in terms of passive circuit elements and derive system optimization parameters. In addition, an analysis of system transmission characteristics, with single load and multi load, is elaborated in forms of the impacts of system load and transmission distance on transmission system output load and efficiency in respectively. In wireless power transmission experiment, the experiment results are in accordance with the theory we expounded. This is important from a practical standpoint because, in many applications, such as laptop recharging, the range and orientation of the receive device with respect to the transmit device vary with user behavior.

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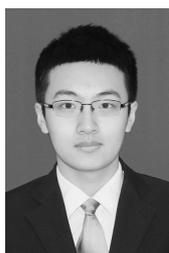
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