Chapter 7
Analysis of Transmission Efficiency of Magnetically Coupled Resonant Radio Energy

Xiaohu Yin and Yue Zhao

Abstract Magnetically coupled with resonant radio energy transmission technology can realize medium-distance power transmission between power supply equipment and electrical equipment. Working principle of resonant coupled radio energy transmission is introduced in this paper, and bilateral compensation method is used to analyze the two factors of large leakage inductance and low coupling coefficient, which affect the transmission efficiency of the system. In practical applications, to achieve maximum efficiency transmission of the system, it is necessary to determine the appropriate circuit operation mode, resonant frequency and coil parameters. According to the four different compensation topologies, the influence of the secondary quality factor and transmission distance of the wireless energy transmission system on the transmission efficiency of the system is analyzed in detail based on MATLAB simulation.

7.1 Introduction

In the recent years, wireless energy transmission technology has always been a hot issue in human research. Inductively coupled power transfer (ICPT) is a new type of power access method that achieves non-contact transmission of electrical energy in a small scale [1, 2], but the transmission distance is still limited to a small within the scale, transmission of 15 cm has been considered a considerable distance [3, 4]. In 2007, Professor Marin Soljacic of the Massachusetts Institute of Technology (MIT) and others made breakthroughs in radio energy transmission. They used the principle of electromagnetic resonance to realize the wireless transmission of medium-distance power, and a 60 W in 2 m distance. The bulb is lit and the transmission efficiency is around 40% [5].

Resonant coupled radio energy transmission utilizes electromagnetic near-field resonance coupling to efficiently transfer energy from one resonator to another in the form of a 'tunnel' without energy exchange with or little with non-resonant

X. Yin · Y. Zhao (✉)
Xi'an University of Science and Technology, Xi'an, Shanxi, China
e-mail: 1950247346@qq.com

objects. In theory, the energy that is not absorbed by the load will return to the transmitting end, so that it will not affect the efficiency [6]. The wireless energy transmission technology based on magnetic coupling resonance has the advantages of high transmission efficiency, large transmission distance, small radiation, non-magnetic objects and little harm to the human body [7], and it will certainly be a kind safe and reliable charging method.

However, at this stage, the resonant coupled power wireless transmission technology is still in its infancy, and many problems need to be solved, transmission efficiency, transmission power, transmission distance, electromagnetic compatibility, electromagnetic radiation pollution and biosafety issues. Especially, in the aspect of transmission efficiency analysis, MIT's analysis is only limited to physical analysis, and related theoretical and experimental research is still lacking [8, 9].

In this paper, the mathematical modeling and simulation analysis of the circuit topology of PSSS, PSSP, PPSS and PPSP are carried out, and the transmission characteristics of the resonant compensation mode are compared.

7.2 Resonant Coupled Power Wireless Transmissions Works

Magnetically coupled resonant radio energy transmission technology is a near-field strongly coupled radio energy transmission technology. The core is to use two inductive coils with the same operating frequency to achieve efficient power transmission when resonance occurs, and still at medium distance. It can carry out higher efficiency and higher power transmission of electric energy [10].

The resonant coupled power wireless transmission technology mainly utilizes two resonant circuits having the same frequency to realize wireless transmission of energy from the stationary power supply system to the power supply device through magnetic field coupling.

7.3 Circuit Design of Electromagnetic Coupling Resonant Radio Energy Transmission System

7.3.1 The Importance of Resonance Compensation

The wireless energy transmission system achieves non-contact transmission of energy through the resonant coupling of the separable transformer. The separable transformer of the wireless energy transmission system is a loosely coupled transformer. The gap between the primary and secondary is relatively large, resulting in a large magnetic leakage, which greatly reduces the transmission performance of the wireless transmission system. In order to reduce the voltage and current stress of

the transformer [11], the unnecessary power in the power transmission network is effectively compensated, so the resonance compensation technique is used.

In order to improve the efficiency of the system, at the beginning of the wireless energy transmission system, the secondary circuit is added with an appropriate equal amount of compensation capacitance and the leakage inductance of the primary and secondary coils to form a resonance compensation circuit [12]. According to the different topological structure of the resonant circuit, there are eight kinds of compensation methods. The primary coil and the secondary coil are denoted by *P* and *S,* respectively; the series and the parallel are, respectively, denoted by *S* and *P*.

According to the theoretical analysis, the single-side resonance compensation topologies PSS_, P_SS, PPS_, P_SS can only improve the working efficiency of the primary loop and the secondary loop unilaterally. In order to increase the efficiency of the entire radio energy transmission system, a bilateral compensation topology is required. According to the above analysis, the bilateral compensation topology can be divided into the following four types: PSSS, PSSP, PPSS and PPSP.

7.3.2 Circuit Design of the Resonant Coupling Part

The diagram of the system's structural frame is shown in Fig. 7.1.

Among them, C_1 and C_2 are series or parallel compensation capacitors of primary and secondary inductors L_1 and L_2, respectively, and M is mutual inductance. When using bilateral compensation, there are two quality factors: primary and secondary quality factor. For the convenience of calculation, the internal resistance of the power
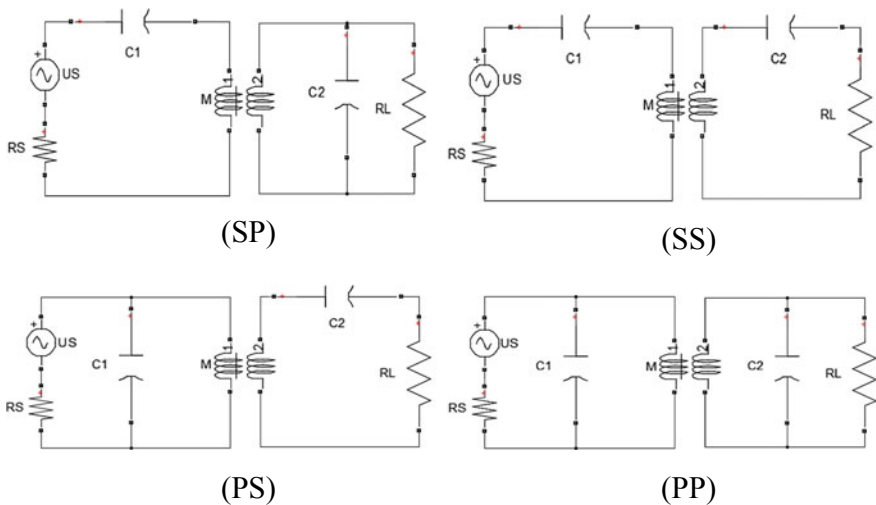

(SP)   (SS)

(PS)   (PP)

Fig. 7.1 Resonant coupling circuit design

supply. Quality factor as Formula (7.1):

$$Q = \frac{wL}{r} = \frac{1}{wCr} = \frac{1}{r}\sqrt{\frac{L}{C}} \tag{7.1}$$

7.3.3 Experimental Analysis

In practical applications, the wireless energy transmission system needs to provide energy to different loads, and the change in load causes a change in the secondary quality factor. Based on the MATLAB under the compensation topology, the influence of the secondary quality factor and the transmission distance of the two coils on the transmission efficiency are analyzed.

For the secondary loop, the secondary loop transmission capability is proportional to its quality factor. However, the improvement of the quality factor will also lead to an increase in the volt-ampere characteristics of the secondary circuit. Therefore, it is a very important parameter in the entire wireless energy transmission system. In practical applications, the value is generally between 2 and 10, and the primary circuit. The geometrical characteristics and primary current determine the value of the primary quality factor. The primary quality factor is affected by different design schemes, and the range of values is generally between 2 and 50.

A. Analysis of the influence of secondary quality factor and transmission distance on voltage gain.

The voltage gain is the ratio of the output to the input voltage. The expression for the voltage gain of the wireless energy transmission system is derived below. Taking the PSSS resonance compensation topology as an example, the voltage gain expression is derived:

The ratio of the operating frequency to the magnitude of the resonant frequency can be expressed as Formula (7.2):

$$\omega_n = \frac{\omega}{\omega_0} \tag{7.2}$$

The coupling coefficient k is expressed as Formula (7.3):

$$k = \frac{M}{\sqrt{L_P L_S}}, \quad M = \frac{\mu_0 \pi N_1 N_2 r_1 r_2}{2D^3} \quad \mu_0 = 4\pi * \left(10^{-7}\right) \text{N/A}^2 \tag{7.3}$$

The magnetic permeability in the vacuum is the radius of the coil, and the distance between the coils is the number of turns of the coil.

The reflected impedance when the secondary series is (4)–(6):

$$Z_r = \text{Re} - j\text{Im} \tag{7.4}$$

$$\text{Re} = \frac{\omega^4 C_s^2 M^2 R_L}{(1 - \omega^2 C_s L_s)^2 + \omega^2 C_s^2 R_L^2} \tag{7.5}$$

$$\text{Im} = \frac{\omega^3 C_s M^2 \left(1 - \omega^2 C_s L_s\right)}{\left(1 - \omega^2 C_s L_s\right)^2 + \omega^2 C_s^2 R_L^2} \tag{7.6}$$

The voltage gain of PSSS is (7):

$$G_v = \frac{nk\omega_n^2}{\sqrt{\omega_n^2(1 - \omega_n^2)^2 + (Q_S(1 - \omega_n^2)^2 - k^2 Q_S \omega_n^4)^2}} \tag{7.7}$$

It can be seen from the above formula that the voltage gain is related to n, w, D, r_1, r_2 and the like. Similarly, Cocoa derives the voltage gain expressions for the other three compensation topologies.

B. Influence of secondary quality factor and transmission distance D on current gain.

The ratio of the output current to the input current is called the current gain. The expression of the current gain of the wireless power transmission system is derived based on the PSSS compensation structure as Formula (7.8):

$$i_2 = \frac{j\omega M i_1}{j\omega L_2 + \frac{1}{j\omega C_2} + R_L} \tag{7.8}$$

Therefore, the current gain in the PSSS compensation circuit is expressed in Formula (7.9):

$$G_i = \frac{n\omega_n^2 Q_s k}{\sqrt{Q_s^2(1 - \omega_n^2)^2 + \omega_n^2}} \tag{7.9}$$

Similarly, the current gain expressions of the other three compensation topologies can be derived.

C. Influence of secondary quality factor and transmission distance D on system efficiency.

The purpose of introducing resonance compensation into the radio energy transmission system is to improve transmission efficiency. Transmission efficiency can be expressed as Formula (7.10):

$$\eta = \frac{P_o}{P_i} = \left| \frac{v_o i_o}{v_i i_i} \right| = G_v G_i \tag{7.10}$$

The transmission efficiency is equal to the ratio of the output power to the input power, that is, the product of the voltage gain and the current gain, as in the above equation.

$$N1 = N2 = 10, \quad r1 = r2 = 0.01,$$

$$\mu = 4\pi \times 10^{-7} L1 = L2 = 3.94 * 10^{-6}, n = 1$$

From this, an expression about the relationship between efficiency and the secondary quality factor and the coupling coefficient can be obtained. Here, it represents the output voltage and current of the system, and represents the input voltage and current of the system. Substituting the above voltage gain and current gain expressions into the above equation yields an expression about the relationship between efficiency and secondary quality factor, and transmission distance. In the simulation below, let, so;

String-string compensation loop:

① Secondary quality factor affects transmission efficiency ($D = 0.05$ m).

The simulation diagram is shown in Fig. 7.2.

Can be seen from Fig. 7.2. When the system operating frequency is equal to the resonant frequency, different quality factors can achieve the highest efficiency. However, when $D = 0.5$ and 1, the curve has only one peak; when it is equal to 4, 8 and 10, the curve shows three peaks, indicating that when it becomes larger, it will cause frequency bifurcation.

② Transmission distance D affects transmission efficiency:

The simulation diagram is shown in Fig. 7.3.

Fig. 7.2 String-string compensation and relationship curve
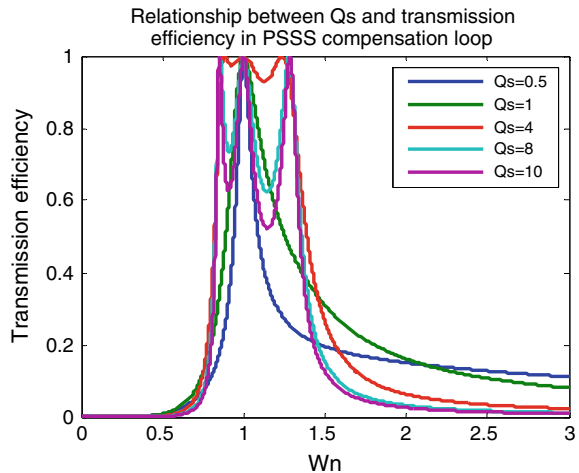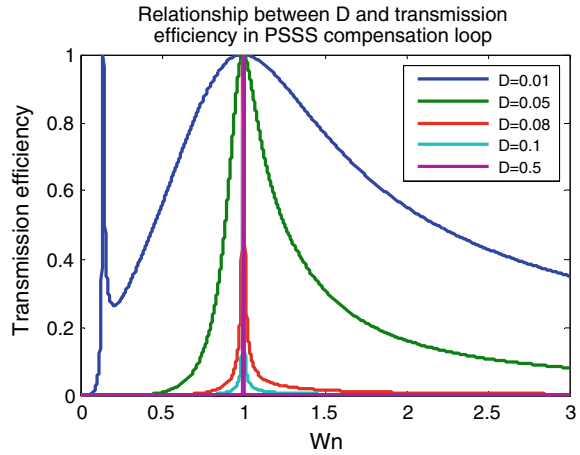
**Fig. 7.3** String-string compensation D and the relationship curve

When the serial string compensation topology is used, when the secondary quality factor is determined, the curve around the apex is steepest when the distance is transmitted. As D decreases, the curve gradually becomes gentle, indicating that when D is small, the wireless energy transmission system can achieve higher efficiency and a wider range.

String and compensation loop

① Secondary quality factor affects transmission efficiency:

The simulation diagram is shown in Fig. 7.4.

Fig. 7.4 String and compensation curve
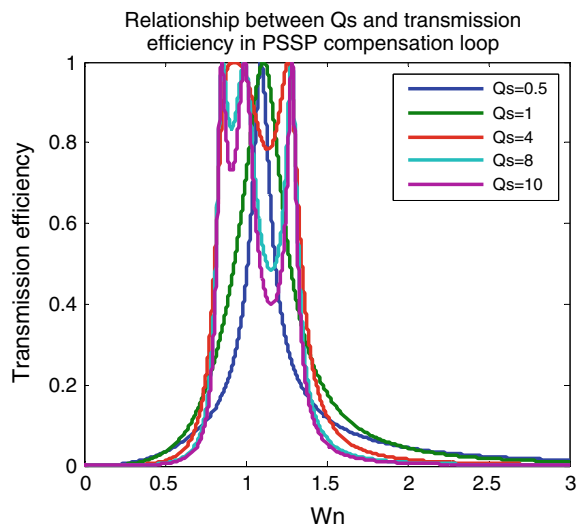
As the number continues to increase, the frequency bifurcation phenomenon becomes more apparent.

② Transmission distance D affects transmission efficiency:

The simulation diagram is shown in Fig. 7.5.

As the transmission distance D becomes smaller, frequency bifurcation is prone to occur.

Parallel compensation loop

① Secondary quality factor affects transmission efficiency:

The simulation diagram is shown in Fig. 7.6.

Fig. 7.5 Series and compensation for the relationship between D and
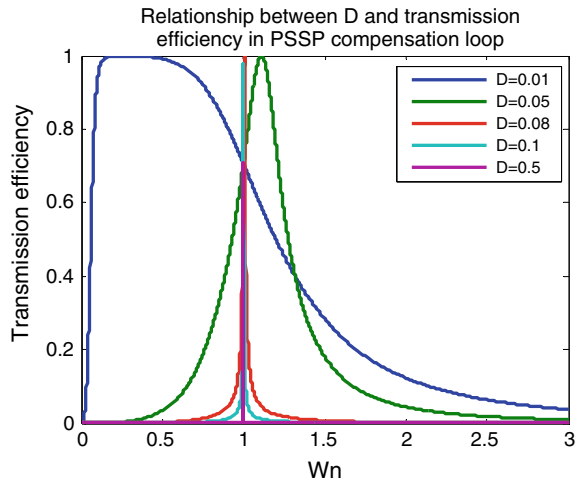

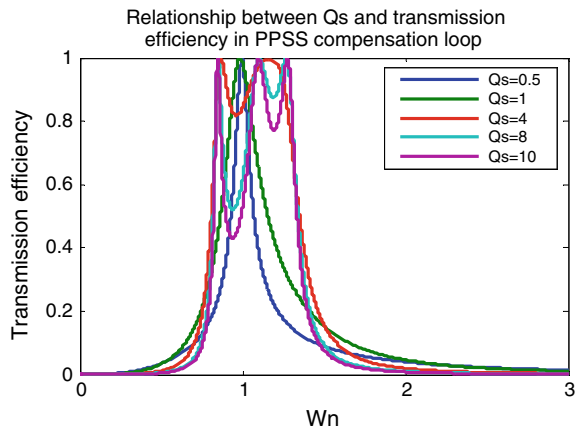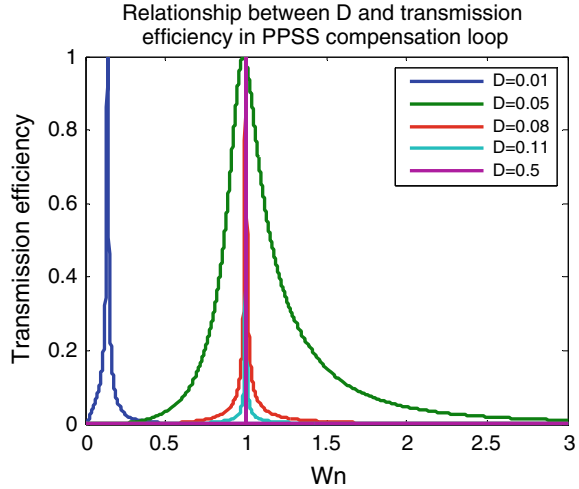**Fig. 7.6** Parallel compensation and relationship curve

Fig. 7.7 Parallel string compensation *D* and the relationship curve

As the number continues to increase, the frequency bifurcation phenomenon becomes more apparent.

② Transmission distance *D* affects transmission efficiency:

The simulation diagram is shown in Fig. 7.7.

When the parallel-compensated topology is used, the frequency bifurcation phenomenon is not easy to occur.

And compensated in the loop

① Secondary quality factor affects transmission efficiency:

The simulation diagram is shown in Fig. 7.8.

When the structure is compensated, as the frequency increases, the frequency bifurcation phenomenon becomes more and more obvious.

② Transmission distance *D* affects transmission efficiency:

The simulation diagram is shown in Fig. 7.9.

When the sum is used and the structure is compensated, the distance is above 0.05 m, and the transmission efficiency reaches a maximum value under resonance. Regardless of the compensation topology used, an increase in the secondary quality factor leads to the occurrence of frequency bifurcation. When the secondary quality factor is determined to be 1, when the transmission distance $D = 0.5$, its curve around the apex is the steepest. As the transmission distance becomes smaller, the curve at the apex becomes more gradual, indicating that the transmission distance D is longer. When small, the radio energy transmission system can achieve a higher efficiency frequency range.

Fig. 7.8 and the relationship
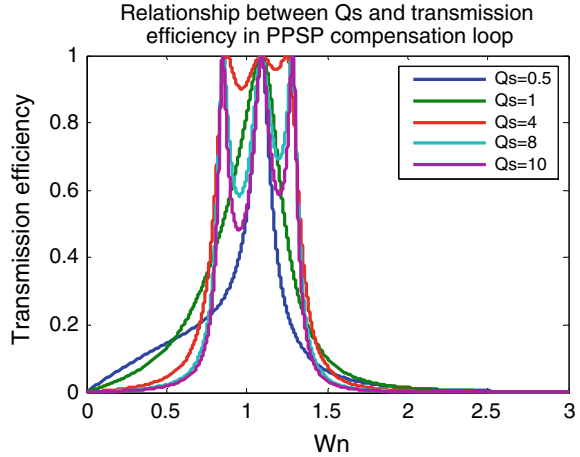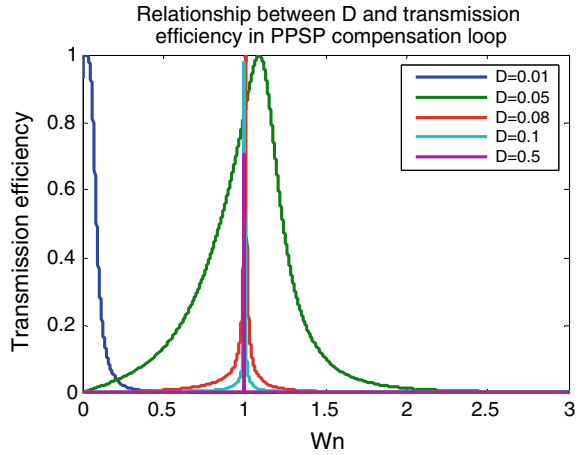between compensation and

Relationship between Qs and transmission
efficiency in PPSP compensation loop

Fig. 7.9 and the relationship
between compensation and

Relationship between D and transmission
efficiency in PPSP compensation loop

The optimum input frequency depends on the relative distance between the
two coils. When the input frequency is equal to the natural frequency (resonant
frequency), the transmission efficiency is maximized when the transmission distance
is 0.05. The simulation analysis is basically consistent with the variation of the
theoretical part.

7.4 Conclusion

Bilateral resonance compensation can effectively compensate for the shortcomings
of low transmission efficiency of the system. In this paper, the bilateral resonant

compensation wireless power supply system is taken as the research object, and the influence of transmission distance and secondary quality factor on transmission efficiency under resonance is derived. The simulation proves that when the secondary quality factor is greater than 1, the frequency bifurcation phenomenon will occur. The larger the secondary quality factor, the more obvious the frequency bifurcation phenomenon; when the transmission distance is too small (near-distance transmission—the distance that the radio energy can transmit is smaller than the device) (No more than two times the size), no resonance compensation circuit is needed at this time. When the transmission distance is increasing, the frequency range in which the wireless power transmission system can achieve less efficiency is relatively narrow.

References

1. Yue, S., Chenyang, X., Xin, D., et al.: Analysis and optimization of mutual inductance coupling parameters of inductively coupled power transmission system. Proc. CSEE **30**(33), 44–50 (2010)
2. Xin, D., Yue, S.: A new power supply mode and related technology analysis of monorail driving. J. Chongqing Univ. **26**(1), 50–53 (2003)
3. Wang, G., Liu, W., Sivaprakasam, M., et al.: A dual band wireless power and data telemetry for retinal prosthesis. In: Proceedings of the 28th IEEE EMBS Annual International Conference (2006)
4. Sallan, J., Villa, J.L., Llombart, A., et al.: Optimal design of ICPT system applied to electric vehicle battery charge. IEEE Trans. Ind. Electron. **56**(6):2140–2149 (2009)
5. Andre, K., Aristeidis, K., Robert, M., et al.: Wireless power transfer via strongly coupled magnetic resonances. Science **317**(6), 83–84 (2007)
6. Kurs, A., Karalis, A., Moffatt, R., et al.: Wireless power transfer via strongly coupled magnetic resonances. Science **317**(5834), 83–86 (2007)
7. Hamam, R. E., Karalis, A., Joannoponlos, J.D., et al.: Coupled-mode theory for general free-space resonant scattering of waves. Phys. Rev. A **75**(5):1–5 (2007)
8. Karalis, A, Joannoponlos, J.D., Soljacic, M.: Efficient wireless non-radiative mid-range energy transfer. Ann. Phys. **323**(1), 34–48 (2008)
9. Fu, W., Zhang, B., Qiu, D., et al.: Maximum efficiency analysis and design of self-resonant coil coupled power wireless transmission. In: Proceedings of the Chinese Society of Electrical Engineering, vol. 29(18), pp. 21–26 (2009)
10. Xia, C.: Analysis and optimization of energy efficiency characteristics of inductively coupled power transmission system. Chongqing: Chongqing University 11 (2010)
11. Zhao, K., Chen, X.: New concept physics course. Electromagnetics, pp. 100–200. Higher Education Press, Beijing (2003)
12. Stielau, O.H., Covic, G.A.: Design of loosely coupled inductive power transfer system. In: International Conference on Power System Technology, 2000. Proceeding. PowerCon2000, pp. 85–90 (2000)