System Optimization Design for Wireless Energy Transmission

Tong Zhou

School of Physics and Electronic Electrical Engineering, Huaiyin Normal University, Huai'an, 223300, China
1708230045@stu.hytc.edu.cn

Abstract. This paper provides an in-depth study of the relationship between series compensation network and system power loss, and the efficient transmission efficiency of wireless energy transmission systems.In this paper, the S-S series compensation network is taken as an example, and by studying the characteristics of the S-S system and its constant-current output characteristics, it is concluded that the S-S system has a constant-current output at the resonant frequency, and the output current is independent of the load size, which has a good stability. This characteristic gives the S-S system a distinct advantage in wireless energy transmission. Therefore, this study takes the S-S system as an example to find the maximum efficiency of the system. Through an in-depth study of the S-S series compensation network, the constant-current output characteristics of the system, the law of variation of the system coupling coefficient K and coil quality factor Q with frequency, and the characteristics of the system efficiency with the value of Q are clarified. Based on these findings, a strategy is proposed to optimize the system's efficiency for maximum efficiency.These research results provide a theoretical basis and practical guidance for the design and application of wireless energy transmission systems.

Keywords: Wireless Energy Transmission, Series Compensation Network, Efficiency

1 Introduction

Wireless energy transmission technology is widely used in multiple fields. As a new type of technology that realizes the transmission of electric energy without physical contact, it is mainly used in the fields of electric vehicles, cell phone charging and so on. Its importance lies in its ability to realize close-range high-power transmission.However, WPT systems still face challenges such as low transmission efficiency, limited transmission distance, and poor electromagnetic compatibility in practical applications. The solution of these problems relies on the optimized design of the system.

Optimized design is the key to improving the performance of WPT systems. The core objective is to maximize the transmission efficiency and extend the transmission distance while ensuring security and reliability.Optimized design involves a number of

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aspects, including the design of the coils at the transmitter and receiver ends, the matching of resonant frequencies, the efficiency improvement of power amplifiers, and the application of electromagnetic shielding technology.In addition, factors such as system cost, volume and weight need to be considered to meet the needs of different application scenarios [1].

In recent years, with the development of new materials, new devices and advanced control algorithms, the optimal design of WPT systems has made significant progress.For example, the use of metamaterials enhances the focusing ability of electromagnetic fields, while intelligent algorithms enable dynamic impedance matching to improve the overall performance of the system.

Series compensation network plays an important role in wireless power transmission. It can maintain stable power transmission under different load conditions. In wireless energy transmission system, the transmission efficiency and performance of the system can be optimized by reasonable design of series compensation network.For example, in the MRC-WPT system, a series-type compensation network is used. It can effectively regulate the resonant state of the coil and improve the power transfer capability and transmission efficiency of the system. Meanwhile, in the application of near-field metamaterials, the design of series compensation network is also often involved to realize the precise regulation of electromagnetic field.

Tiago Ressurreic's research focused on underwater autonomous vehicles (AUVs), designing electronic systems for wireless charging of AUVs from docking stations.The working principle of Class D power driver in S-S series - series inductive resonant coupling topology is studied and analyzed. The effectiveness of the system is experimentally verified and certain power transfer is achieved under specific conditions [2].

Aiming at the problems of magnetic resonance coupled wireless power transmission (MRC-WPT) systems, dual-frequency multidirectional transmission systems are involved and introduced into near-field metamaterials.By constructing an equivalent circuit model and optimizing the parameters of the magnetic coupling mechanism, the multi-directional power supply for devices with different frequencies is realized.It is experimentally verified that dual-frequency near-field metamaterials can enhance the system transmission efficiency and reduce the leakage field, which enhances the electromagnetic safety [3].

In order to solve the power supply problem of on-line monitoring equipment for 500 kV transmission lines, Zhijun Wu establishes a WPT system model and analyzes the factors affecting the system performance. The multiple factors are optimized by particle swarm optimization algorithm, and the non-isometric arrangement optimization scheme is proposed.It improves the system transmission efficiency by 20.56% and verifies that there is no significant effect on insulator insulation performance [4].

In order to solve the problem of energy consumption during data transmission and to optimize the data transmission and energy consumption in Internet of Things (IoT) networks, XIU ZHANG thought of an approach using Wireless Power Transfer (WPT) technology. The problem is represented as an optimization problem of minimizing the network cycle time through modeling, solving and experimental validation. Experiments are conducted with examples of the three-stage approach to demonstrate that the method is effective in reducing network energy consumption [5].

In the face of 5G network development facing energy constraints and a dramatic increase in the number of IoT devices, SWIPT-assisted CoR technology has been used to enhance electrical and spectral efficiency. This in turn improves transmission reliability, increases coverage and system capacity.Nausheen Ashraf et al. comprehensively reviewed that the combination of SWIPT technology with CoR provides efficient solutions to challenges such as underwater IoT applications [6].

In the future, with the continuous breakthrough of technology, WPT system will be widely used in more fields, bringing revolutionary changes to the way of energy transmission.

This paper is based on the S-S series compensation network followed by the derivation of the formula.In the S-S series compensation network, the angular frequency ω directly affects the resonant frequency, quality factor Q and efficiency of the system.The relationship between quality factor Q, angular frequency ω, and efficiency is plotted using tools such as VISIO, MATLAB Simulink, and MATLAB code to investigate the maximum efficiency of the wireless energy transmission system.

2 Related Work

The process of transmitting wireless energy uses certain theoretical foundations to ensure that the system transmits efficiently. The first is the resonant circuit. In the design of the resonant circuit, for the series compensation network, the system applies the resonance principle.In LC resonant circuits, the resonant state of the system is achieved at a specific frequency through the resonant characteristics of the capacitor and inductor, thus improving the system transmission efficiency.In a resonant circuit, the greater the mutual inductance, the lower the output current.The energy loss is minimized by setting the appropriate inductance and capacitance parameters. So that the system is in the best working condition to achieve the highest transmission efficiency [7].

Next is impedance matching. By designing the impedance matching in the power and load side of the compensation network system, the reflection loss is reduced to further improve the energy transmission efficiency and increase the stability and reliability of the system.

Wireless energy transmission technologies have stability and reliability issues. Additional DC/DC conversion stages also reduce power density and increase cost and losses.To improve this phenomenon, a new control strategy was proposed by JIANTING LI et al. to eliminate real-time wireless feedback communication (RTWFC) and optimize the efficiency through a series-compensated dual active bridge-based wireless power transfer (WPT) converter. The strategy is experimentally verified to improve the efficiency and speed up the transient response. The final efficiency is improved by 5% and the peak efficiency can reach 93.6% at 24V output with strong magnetic coupling [8].

In real life, the use of electric vehicles is gradually increasing, but charging problems limit its development. Dynamic wireless charging technology (DWPT) is involved as an effective solution to these problems.JUAN C. QUIRÓS and ALICIA TRIVIÑO proposed guidelines for the design of compensating networks by analyzing the effect of system variables on THD and efficiency through the THA model [9].

The increasing number of asynchronous distributed renewable energy sources, energy storage, and demand response units has created a number of complications in the distribution network. In order to improve the status quo of power import/export constraints and increased network losses, Robert Fenlon and Mark Norton propose Modular Static Synchronous Series Compensators (MSSSCs). This achieves the same compensation function as series reactors or capacitors, effectively optimizing power system planning and operation [10].

3 Methodology

In this study, Microsoft Visio Drawing was used to build the S-S series compensation network model for the S-S system. The output characteristics of the S-S system are analyzed through formula derivation. The derivation results are then simulated using MATLAB Simulink. The correctness of the formulas is corroborated by simulation plots. The value of Q (=*L/r) is derived from the set of experimental data collected for RESISTANCE. Finally, MATLAB code is used to program different sets of Q, values based on different sets of K values and inputting different sets of Q, values based on each set of K values. From the final run out of the system output efficiency curve with Q, the relationship between Q and the system output efficiency is derived to find the maximum efficiency of the system.

4 Implementation

4.1 Experimental Environment

Present the S-S system model in Microsoft Visio Drawing. Simulate in MATLAB with Simulink to see the output characteristics of the S-S system. Programming in MATLAB code produces graphs of Q versus ω, Q versus system efficiency at different values of K.

4.2 Experimental Step

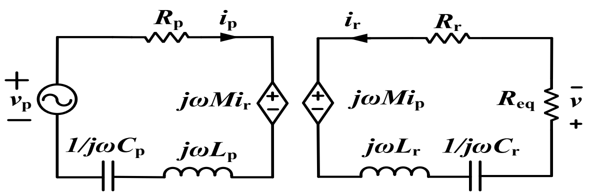

Fig. 1. Kirchhoff's current and voltage laws (KVL, KCL)(Picture credit : Original)

As shown in Figure 1, according to Kirchhoff's current and voltage laws (KVL, KCL):

$$j\omega M i_{\mathrm{p}} = -i_{\mathrm{r}}[R_{\mathrm{r}} + R_{eq} + j(\omega L_{\mathrm{r}} - \frac{1}{\omega Cr})] \quad (1)$$

At the resonant frequency, $j(\omega L_{\mathrm{r}} - \frac{1}{\omega C_{\mathrm{r}}}) \approx 0$

in that way, $i_{\mathrm{p}} = -\frac{i_{\mathrm{r}}(R_{\mathrm{r}}+R_{\mathrm{eq}})}{j\omega M}$ (2)

$V_{\mathrm{p}} = i_{\mathrm{p}}[R_{\mathrm{p}} + j(\omega L_{\mathrm{p}} - \frac{1}{\omega C_{\mathrm{p}}})] + j\omega M i_{\mathrm{r}}$ (3)

At the resonant frequency, $j(\omega L_{\mathrm{p}} - \frac{1}{\omega C_{\mathrm{p}}}) \approx 0$

in that way, $V_{\mathrm{p}} = i_{\mathrm{p}} R_{\mathrm{p}} + j\omega M i_{\mathrm{r}}$ (4)

Neglecting Rp in (4),then, $i_{\mathrm{r}} = \frac{V_{\mathrm{p}}}{j\omega M}$

Bringing in (2), and ignoring Rr, then, $i_{\mathrm{p}} = -\frac{V_{\mathrm{p}} R_{\mathrm{eq}}}{\omega_2 M_2}$

The output characteristic of the S-S system is a constant current output. However, in practice, the transmitter and receiver coils are particularly close together. This means that the higher the mutual inductance, the lower the output current and the lower the output power. So: the S-S system is not suitable for transmitting high power in strongly coupled situations. In this case, the LCC-S system can be used. However, if the mutual inductance is very small (e.g. LC circuits), the output current will be infinite, which will burn out the inverter, etc. So: the offset capability of S-S system is poor.

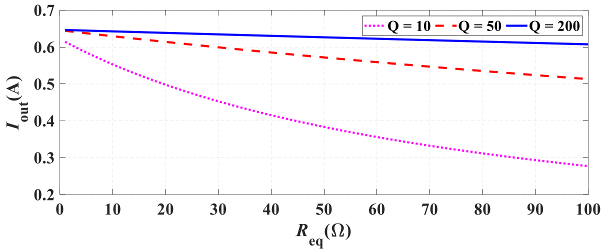

Fig. 2. Current output characteristics of S-S series compensation network system(Picture credit : Original)

As shown in Figure 2, the constant current output characteristics of the S-S system (when ESR=0) are demonstrated for different Q values. The resulting curves of output current (Is) versus load resistance (Req) for different values of Q are obtained.

It can be seen that the constant current characteristic of the output current (Is) becomes more obvious as the loss decreases with the increase of Q value. Especially at high Q values (for instance, Q=200), the output current (Is) remains almost constant over a wide range of loads, exhibiting good constant current characteristics.

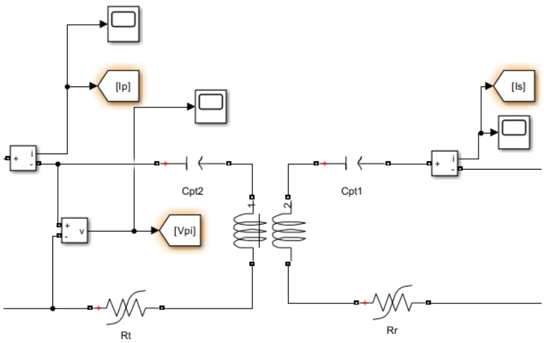

Fig. 3. Simulink model diagram of S-S series compensation network(Picture credit : Original)

$\eta=\frac{I_s{}^2R_L}{I_s{}^2R_L+I_s{}^2R_r+I_t{}^2R_t}$ （Efficiency formula）

${I_s}^2R_L$ is the system output power， ${I_s}^2R_r+{I_t}^2R_t$ is the system power loss

$\eta_{\max}=\frac{R_L}{R_t(R_L+R_r+{X_r}^2)+\frac{R_L+R_r}{\omega^2+M^2}}\approx\frac{1}{(1+KQ)^2}$ （Maximum efficiency formula） （5）

In equation (5), $K=\frac{M}{\sqrt{L_tL_r}}$（K：Coupling coefficient of the system）

In equation (5), $Q=\frac{\omega L}{R}$（Q：Coil quality factor）

Simplification process: at the resonant frequency, ${X_r}^2=0$.Within a specific parameter range, ${X_r}^2$ in $R_t(R_L+R_r+{X_r}^2)$ and some higher-order minima in $\frac{R_L+R_r}{\omega^2+M^2}$ can be ignored (the reasonableness of the specific approximation needs to be judged according to the actual parameters and operating conditions of the system).

To approximate the denominator, assume that $R_t(R_L+R_r+{X_r}^2)\approx R_t(R_L+R_r)$， $\frac{R_L+R_r}{\omega^2+M^2}$ also performs a reasonable approximation. $R_t=\frac{1}{K^2Q^2R_r}$ can be obtained under some specific conditions (the derivation process depends on the S-S equivalent circuit model of the system and the relevant physical quantity relations).

Substituting the above relations into the original equation and organizing it, a series of algebraic operations and approximations (including combining and simplifying the terms R_L,R_r and so on) leads to $\eta_{\max}\approx\frac{1}{(1+KQ)^2}$.

If $[R_t(R_L+R_r+{X_r}^2)+\frac{R_L+R_r}{\omega^2+M^2}]$ is smaller， $\eta_{\max}$ will be bigger. Because of $\omega=2\pi f$, the bigger ω is, the bigger f will be as well.And R varies exponentially, as shown in Figure 3, and finally there is a peak in Q with frequency.

From (1) the formula for the maximum efficiency of the system, it can be seen that the maximum efficiency of the system is affected by K and Q. Since R varies exponentially, Q does not vary infinitely high with frequency . The efficiency point of the highest Q can be obtained by analyzing, K, Q becomes larger η becomes larger and reaches η_max.

Relationship between K, Q and efficiency (effect of K and Q on efficiency):

From Q=ωL/R, a graph of Q versus ω can be seen in figure 4:

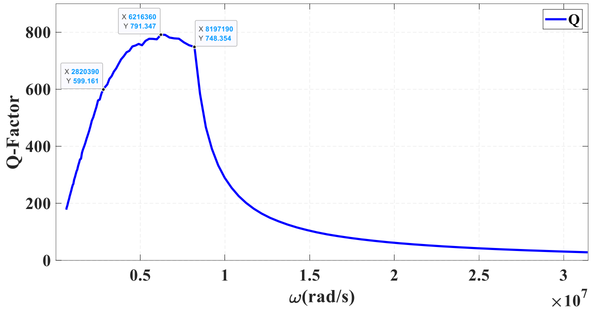

Fig. 4. Plot of Q versus ω(Picture credit : Original)

From ω=2πf, a graph of Q versus frequency can be seen in figure 5

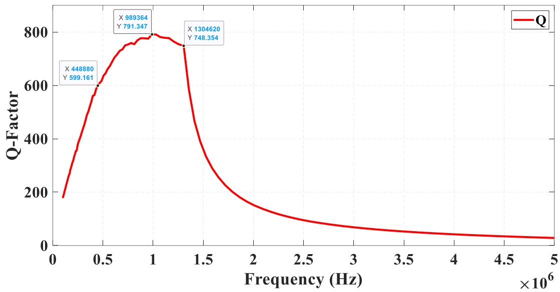

Fig. 5. Plot of Q versus frequency(Picture credit : Original)

From Figure 5, it can be seen that Q does not vary infinitely high with frequency . In Figure 5, the maximum value of Q is 791.347, which is about 790. taking the corresponding Q values for lower and higher frequencies, they are 599.161, which is about 600, and 748.354, which is about 750, respectively.

Using these three values of Q, a graph of the variation of efficiency with Q is created as a way to find the maximum efficiency of the system. The following figure 6 shows the system efficiency variation with Q for different values of k:

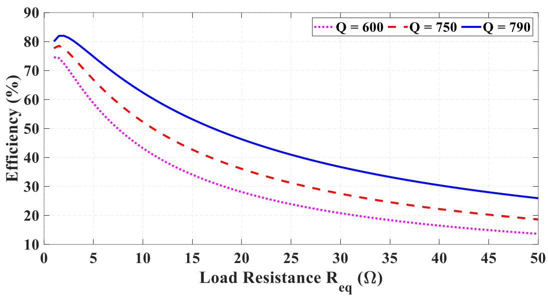

Fig. 6. Graph of variation of system efficiency at K=0.1(Picture credit : Original)

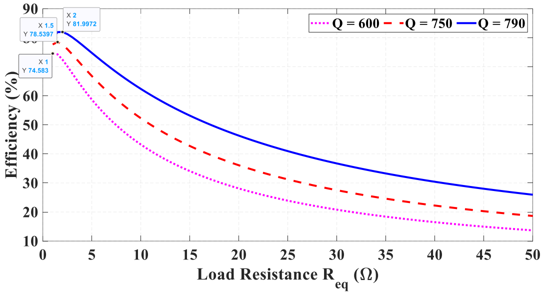

Fig. 7. Maximum and logarithmic values of system efficiency for K=0.1 (Picture credit : Original)

From Figure. 7, it can be seen that the efficiency is higher when K=0.1 and Q=790. The system efficiency is maximized at 81.9972% when Req=2.

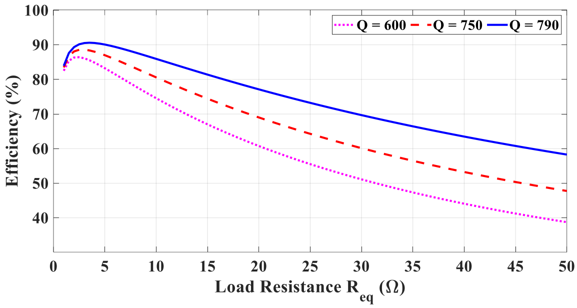

Fig. 8. Graph of variation of system efficiency at K=0.2(Picture credit : Original)

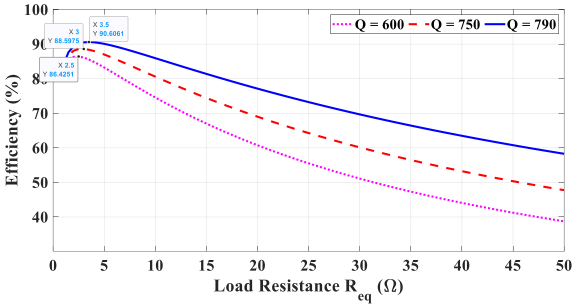

Fig. 9. Maximum and logarithmic values of system efficiency for K=0.2(Picture credit : Original)

From Figure 8and figure 9, it can be seen that the efficiency is higher at K=0.2 and Q=790. The system efficiency is maximized at 90.6061% when Req=3.5.

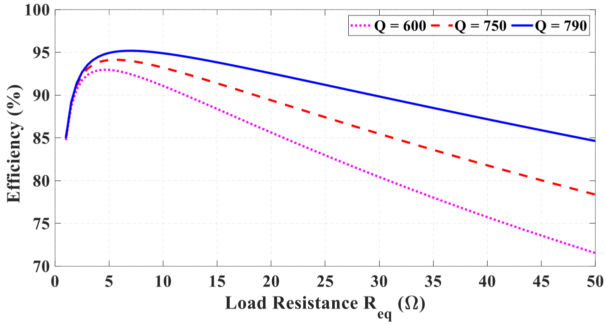

Fig. 10. Graph of variation of system efficiency at K=0.4

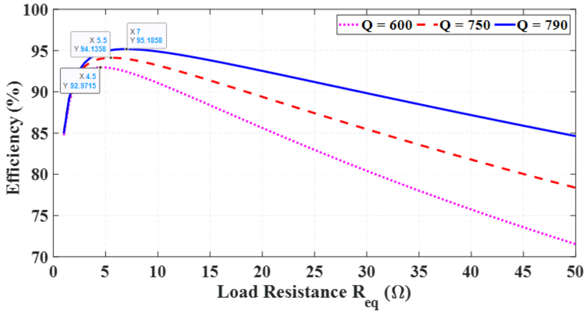

Fig. 11. Maximum and logarithmic values of system efficiency for K=0.4

From Figure 10and figure 11, it can be seen that the efficiency is higher when K=0.4 and Q=790 . When Req=7, the system efficiency is maximized at 95.1858%.

5 Results and Analysis

As shown in Figure 5, the maximum value of Q is about 790. From Figures 7, 9, and 11, it can be seen that among the three sets of k values (0.1, 0.2, and 0.4), the maximum efficiency of the system corresponding to the maximum value of Q is 95.1858% when k = 0.4.

Output characteristics of S-S system: constant current output only when ESR=0 . The maximum efficiency of the system is affected by K and Q, but Q does not vary infinitely with frequency, and the maximum value of Q is about 790; the larger K and Q are at different k values, the larger A is, and the maximum value of A is reached. Among the three groups of k values (0.1, 0.2, 0.4), the K=0.4 group is more efficient than the other two groups corresponding to the same Q value. In the K=0.4 group, the efficiency is higher at Q=790 and the system efficiency reaches its maximum at Req=7, which is 95.1858%. That is, the maximum efficiency of the system corresponding to the maximum value of Q is 95.1858%.

In this study, based on the constant current output characteristics of the S-S system, by adjusting the Q value, it is found that the constant current characteristics of the output current will be more obvious as the Q value increases (which implies that the loss decreases). And the Q value does not increase infinitely, especially at high Q values (e.g., Q=200), the output current (Is) remains almost constant over a wide load range, showing good constant current characteristics. Further, the maximum efficiency of the system is derived from the formulae as influenced by K and Q. In the MATLAB code programming simulation by taking different values of K, Q and observing the efficiency values in the graph, find the value of K, Q when the system efficiency is maximum. It is determined that the greater the K and Q, the greater the efficiency of the system.

In this study, the factors affecting the efficiency of the wireless energy transmission system are found and the relationship is derived, based on which the K and Q parameters can be better adjusted to improve the efficiency of wireless energy transmission, reduce losses and optimize the system design.

In the future, for the wireless energy transmission system of different application scenarios, the main influencing factors K and Q will be used as a starting point in the optimization design. Appropriate values will be set according to different environments in order to achieve the highest efficiency of wireless energy transmission and improve economic benefits.

6 Conclusion

In this paper, starting from the S-S series compensation network, by studying the output characteristics of the S-S system and carrying out the axiomatic derivation and simulation verification, it is concluded that the S-S system has a constant current output at the resonant frequency . The output current is independent of the load size and has good stability. Then this paper explores the characteristics of K and Q with ω related to the system efficiency, and the characteristics of the working efficiency with Q of the wireless energy transmission system with series compensation network. It is concluded that the coupling coefficient K increases with the increase of frequency ω, and tends to stabilize in a certain frequency range.The quality factor Q reaches its maximum value near the resonant frequency and decreases rapidly as the frequency moves away from the resonance point. Therefore optimizing the values of K and Q near the resonant frequency is essential to improve the system efficiency. The system efficiency increases with the increase in the value of Q, but after a certain level of Q, the efficiency improvement levels off.Near the resonant frequency, the system efficiency reaches its maximum value . As the value of Q increases, the efficiency curve becomes steeper. By optimizing the values of K and Q, the system is able to achieve maximum efficiency near the resonant frequency. The efficiency of the wireless energy transmission system can be significantly improved by adjusting the appropriate operating frequency and system parameters during the wireless energy transmission process.

Through an in-depth study of the S-S series compensation network, the constant-current output characteristics of the system, the law of variation of K and Q values with frequency, and the characteristics of the system efficiency with Q value are clarified. Based on these findings, more strategies can be proposed to optimize the system efficiency for maximum efficiency.

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