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The Consistent Output of LCC-LCC Circuit under Distance Variation

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Abstract. With the advancement of wireless charging technology and the increasingly widespread use of wireless chargers in everyday life, wireless charging technology is gradually coming into the focus of public scientific research. However, the currently available wireless charging technologies mostly have significant shortcomings, both in terms of anti-offset and anti-interference capabilities, as well as in output stability. This paper focuses on the output consistency control of LCC-LCC wireless charging. By changing the coefficients of the circuit components (inductance's mutual inductance — coupling coefficient), the functional relationship between the component coefficients and the final output voltage was derived. Under the premise that there may be minor detuning issues throughout the circuit, this study accomplished the control of the output voltage function, ensuring that the output voltage remains basically unchanged despite slightly fluctuations. This study provides a theoretical basis and practical guidance for improving the robustness and reliability of wireless charging systems under real-world operating conditions, thereby contributing to the development of more stable, user-friendly, and efficient wireless power transfer technologies for applications such as electric vehicles and consumer electronics.

Keywords: Electric engineering, wireless charging, LCC network

1. Introduction

Wireless charging technology has attracted widespread attention in the field of power supply for smart devices due to its advantages of convenience and flexibility. However, in practical applications, the dynamic changes in charging distance can lead to changes in the system's coupling coefficient, which in turn affects output stability. How to achieve constant voltage output and constant current output at different distances has become a key point in the practical application process of current wireless charging technology, and this research is dedicated to addressing this issue.

Existing research has fairly well addressed the design of compensation networks and the parameter decoupling of magnetic coupling mechanisms, but the current wireless charging technologies still have significant shortcomings, both in terms of offset and interference resistance or output stability. To solve these issues, some research was done but only a tiny part of the problem was solved. For example, some scholars tried to address the problem of transmission efficiency declining exponentially with distance by equipping relay resonators. However, this method fails to

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consider the impact of the self-inductance of the relay coil on the overall magnetic field, resulting in large parameter fluctuations [1]. Some other scholars attempted a different approach by using genetic algorithms to optimize parameters to improve transmission performance. However, this method has a delay, making it difficult to promptly adjust to demand of the power output caused by changes in the load side position, which may finally cause voltage oscillations and consequently lead to safety risks in the system [2].

To address these issues, this paper focuses on the structure of the LCC-LCC compensation topology. By taking the given receiving device as the research's object (that has a constant voltage output demand), this paper explores how to suppress the impact of coupling coefficient variations on transmission performance by changing the inductance parameters of the primary and secondary sides, thereby achieving long-lasting and stable power transmission. That is, based on the LCC-LCC network's application function, how to make the output voltage consistently stable.

2. Theory of achieving consistent output based on the traditional LCC-S circuit

2.1. Traditional LCC-S circuit

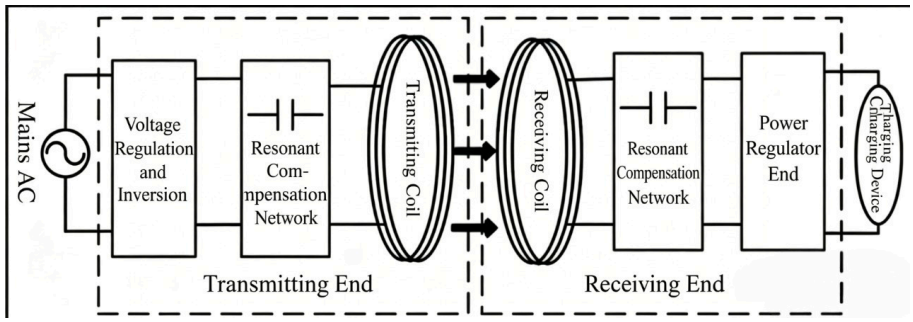

Figure 1. General wireless charging circuit model(picture credit : original)

The structure of a traditional LCC circuit usually consists of a transmitting end and a receiving end [3]. As shown in Fig. 1, on the primary side, the compensation network consists of a series inductor, a parallel capacitor, and a series capacitor, which together forms a multi-resonant topology with the transmitting coil. This design can effectively compensate for the coil's leakage inductance and make the system input impedance exhibit purely resistive characteristics, therefore reducing meaningless power loss [4]. On the secondary side, the capacitor connected in series resonates with the receiving coil, which further improves power transfer efficiency. The main advantage of the LCC-S network is that it possesses constant current output characteristics, which can simplify system control strategies while also having good offset resistance performance and ensure stable power output even when the transmitting coil and the receiving coil are not perfectly aligned. Through precise parameter design, this network can also effectively suppress higher-order harmonics, reduce electromagnetic interference, and meet the requirements of traditional wireless charging systems for high efficiency and high reliability [5]. By adjusting the LCC-S circuit, a complete compensation structure can also be added to the secondary side of the circuit to replace the secondary part of the original structure. This modification can not only improve the whole network's offset resistance but also minimize the impact of changes in the coupling coefficient on the circuit's resonant frequency, making the research more practical.

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2.2. LCC-LCC circuit

Due to considerations of using wireless charging devices in real life, the receiving end of a wireless charging device may not be able to accommodate too many components because of factors such as limited space occupied by too many components may affect the operation of the device being charged [6]. Considering this situation, the LCC-S network circuit can be simplified by removing the compensation network at the receiving end and instead using power supply voltage adjustment to control consistent output.

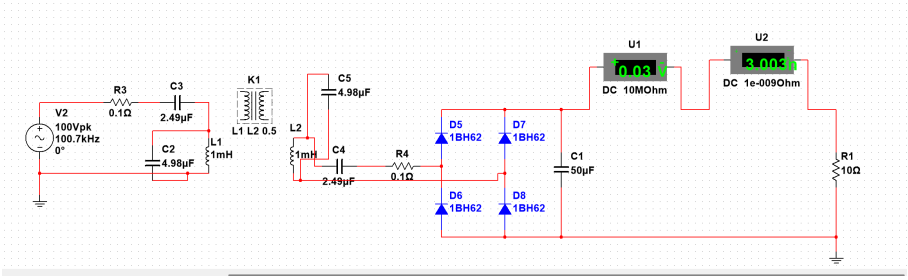

Figure 2. Simulation test circuit(picture credit : original)

Fig. 2 shows the circuit used in the experiment, where all coupling inductors are 1 mH.

The transmitter of this circuit is composed of an LCC structure, and the receiver uses series capacitor compensation, which is another version of the LCC-S network. In this circuit:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = 2256Hz \tag{1}$$

Using the data in Fig 2 for calculation, it is found that when the coupling coefficient k = 0.5, the resonant frequency is approximately 2256 Hz, meeting the system's resonance requirements. In the resonant state, the circuit satisfies:

$$\omega = 2\pi f = \frac{1}{\sqrt{LC}} \tag{2}$$

The entire circuit is in a purely resistive state, and there is no phase difference between the voltage and current in the circuit. Additionally, the impedance of the parallel branch L1C3 is large, which increases the current flowing into the transmit coil and thus improves the energy transfer efficiency of the entire coil. Moreover, the problem of oscillating energy back and forth in the coil is resolved, further increasing the efficiency.

3. Circuit simulation

To achieve the goal of a constant output voltage, it is necessary to adjust the voltage of the AC power supply when the coupling coefficient k changes, so that the final output voltage Vout remains unchanged.

First, the concept of coupling coefficient is introduced. The coupling coefficient is a dimensionless parameter describing the degree of magnetic field coupling between two coils, and its formula is:

$$k = \frac{M}{\sqrt{L1 \times L2}} \tag{3}$$

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Since the research topic explores the consistent output under varying distances between coils, k is combined with the distance d between the coils to establish a relationship between the two variables.

$$M = \frac{\mu_0 \pi N_1 N_2 (r_1 r_2)^2}{2\left(d^2 + r_1^2\right)^{\frac{3}{2}}} \tag{4}$$

From equation (4), it can be concluded that d and M exhibit a positive correlation. Since equation (1) already shows that k is directly proportional to M, it can be inferred that k and d also exhibit a positive correlation. When applied to the scenario, M should be maximized while d is as large as possible. Therefore, given that the number of turns, N_2 is limited by space, the number of turns of the transmitting coil L_1 should be as large as possible to achieve a higher coupling coefficient k.

For the transmitting coil radius r_1 , in order to make k as large as possible, the derivative of the entire expression of M is taken. Let $\mu_0 \pi N_1 N_2 (r_2)^2$ be a constant a, and d^2 to be a constant b, then:

$$M' = \frac{4ar_1\left(b + r_1^2\right)^{\frac{3}{2}} - 6ar_1^3\left(b + r_1^2\right)^{\frac{1}{2}}}{4\left(b + r_1^2\right)^3} \tag{5}$$

To find the extreme points of this expression, set the numerator equal to 0, then r_1=√2b

Due to the effect of varying magnetic fields on electromagnetic coupling in the simulated circuit, and the lack of a compensation network on the receiving end of this LCL circuit to regulate the voltage, the relationship between the coupling coefficient and the input voltage is very likely not linear. Instead, it is a complex functional relationship caused by the current output of the transmitting coil being affected by the reflected impedance. Therefore, in the following, a fitting function method is used to derive the relationship between k and the input voltage [5].

To find the functional relationship between the coupling coefficient k and the power supply voltage, set Vout as a fixed value, and measure the relationship between the array Vin and the coupling coefficient k, as shown in Table 1.

Table 1. Voltage coupling coefficient relationship table

Power supply voltage V/V	Coupling coefficient k	Vout
26.7	0.2	100
51.1	0.3	100
70.8	0.4	100
66.8	0.5	100
114.1	0.6	100
139.7	0.7	100
164.5	0.8	100

Through analyzing and observing this column of discrete data obtained from the test, an initial relationship between the entire power supply voltage and the coupling coefficient is found. And it appears to be a piecewise function. According to the least squares method, perform curve fitting to obtain the equation of the final curve (relating Vin as the function value to the variable coupling coefficient k) [6-8].

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$$Vin(k) = \begin{cases} -370k^2 + 478k - 43.70.2 \leq k \leq 0.4 \\ -40k + 86.80.4 \leq k \leq 0.5 \\ 326.8k - 96.60.5 \leq k \leq 0.9 \end{cases} \quad (6)$$

According to the formula in (6), a control algorithm can be set at the input power source to update the value of the coupling coefficient k between the coupled inductors, thereby deriving the required magnitude of the input voltage in real time through the function [9].

In the above simulation process, the simulation system considered the effects of reflection impedance, slight detuning, losses, and other interfering factors. As a result, the final function outcome does not follow the theoretical inverse relationship between the coupling coefficient and input voltage but instead yields a quadratic relationship.

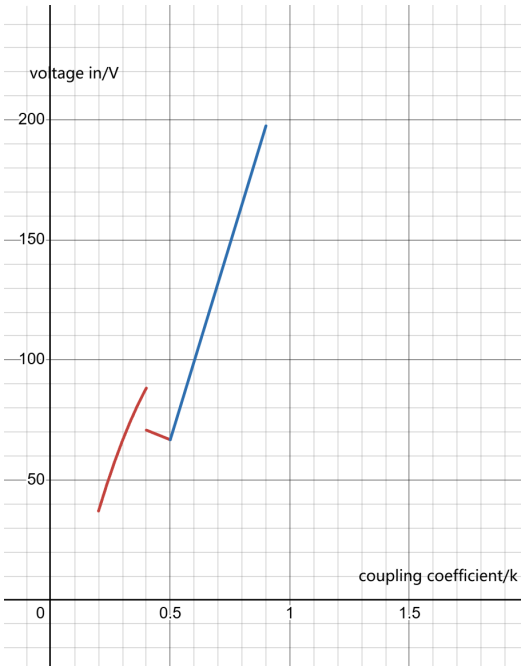

Figure 3. Output voltage-coupling coefficient relationship(picture credit : original)

Based on the analysis in Fig 3, the following conclusions can be drawn. 0.2≤k≤0.4,For under-coupled rising section. In this range, the coupling coefficient is small, the mutual inductance is weak, and the overall circuit is in an under-coupled state. Vin rises rapidly with increasing k, showing a significant nonlinear increasing trend, making it impossible to use the same linear or low-order model as the subsequent high-coupling section, and therefore requires separate segmentation. The mutual inductance energy transfer is insufficient, and the mutual inductance value is directly determined by the coupling coefficient k. At low k, magnetic coupling is weak, and the energy transfer efficiency from the primary to the secondary side is low, so the input voltage Vin must be increased to maintain constant output power.

The primary and secondary LC series networks have inherent resonant characteristics at the operating frequency. As k increases, the equivalent impedance of the secondary load reflects to the primary approaches the resonant impedance, reducing the loop equivalent impedance, and increasing the current and transmission capability, which manifests as a rapid rise in Vin.

When the circuit's rectified load is in a weak conduction state, the secondary voltage amplitude is low under low coupling, the conduction angle of the rectifier diode is small, and the filter capacitor

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charges slowly. To maintain Vout = 100V, the input voltage must be significantly increased to compensate for transmission losses, causing Vin – k to exhibit a strongly nonlinear rise.0.4<k≤0.5,For the critical over-coupled micro-decrement section. After reaching a peak, the curve in this interval slightly falls back, and its monotonicity changes, showing discontinuity with both the previous rising segment and the subsequent rapid rising trend. If a single global function is used, significant fitting deviations will occur; it is necessary to segment individually to reflect local extrema and frequency splitting effects.

Achieving critical coupling and optimal resonance matching: k≈0.4 is the circuit's critical coupling point, at which the reflection impedance and the primary LC network achieve approximate impedance matching, resulting in the highest energy transfer efficiency. The Vin required to maintain the same output reaches a minimum point (corresponding to the measured peak).

In the initial stage of over-coupling, the frequency splitting phenomenon causes the resonant system to exhibit frequency splitting when the coupling coefficient slightly exceeds the critical value. The original single resonance peak splits into two resonant points, and the system's gain at the operating frequency slightly decreases, reflected by a slight reduction in Vin.

The rectifier conduction angle tends to stabilize, resulting in a sufficiently high secondary voltage amplitude. The conduction angle of the rectifier diode enters a relatively stable region, and the load equivalent impedance changes smoothly. Therefore, Vin only gently decreases without experiencing drastic fluctuations.0.5<k≤0.8, For the deeply over-coupled linear rising section. After the coupling coefficient further increases, the curve moves away from the resonance-sensitive region, and Vin rises approximately linearly and rapidly with k. The trend is smooth and the slope is stable, showing a clear boundary from the nonlinear behavior of the previous two segments, making it suitable to be described independently by a linear model. At high k, the mutual inductance is too strong, the secondary side reflection impedance deviates significantly from the resonant impedance, the LC network is severely detuned, and the loop impedance increases significantly, causing the energy transfer efficiency to continue to decline. To maintain a constant output power, Vin must increase approximately linearly with k. Due to the saturation of nonlinear effects, the diode conduction angle and the charge-discharge pattern of the filter capacitor enter a stable operating mode, which weakens the influence of nonlinear factors in the circuit. The overall pattern shows an approximately linear trend, making the Vin–k relationship exhibit a good linear characteristic. Detuning causes the charging current to decrease and the dynamic response of the filter capacitor to slow down. It also significantly extends the time for the output voltage to reach steady state. On a global level, in the high coupling region, the input voltage must be further increased to stably maintain Vout = 100V.

4. Conclusion

In the case of an LCC-LCC network, when considering several interference factors such as impedance, the method of improving the circuit through traditional analog techniques requires consideration of many factors and is also very difficult to calculate. In contrast, using a mathematical fitting approach not only allows individual analysis of each output voltage requirement but also results in more concise conclusions, making it more suitable for practical applications [10]. This paper applies the mathematical fitting function method to analyze the trend of the relationship that leads to a constant output voltage. However, the mathematical fitting method also has relatively strict requirements for device positioning. If the coupling coefficient k continuously varies, the mathematical fitting method will lose accuracy due to a lack of inferable data. Overall, the mathematical fitting method is expected to have considerable impact on the development of wireless charging in the future, but further optimization is still needed to find better

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strategies. In the future, by further optimizing algorithms and employing more precise mathematical fitting methods, it may be possible to eliminate the application of analog circuits in wireless charging, greatly reducing the cost required for this technology and popularizing wireless charging technology in a broader range of research fields.

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