Influence and Optimization of Magnetic Coupling Resonant Radio Energy Transmission Efficiency Based on SS Model

Yafei Jiang[1], Afei Li[1], Yi Zhang[2], Gaofei Liang[3]

[1]College of Physical Science and Technology, Bohai University, Jinzhou, Liaoning, 121000, China
[2]College of Pharmacy, Shenyang Pharmaceutical University, Benxi, Liaoning, 117000, China
[3]College of Computer and Information Engineering, Chuzhou University, Chuzhou, Anhui, 239000, China

Abstract: Firstly, through the knowledge of circuit, this paper determines the equivalent circuit diagram of wireless charging system, studies and analyzes the relationship between the physical quantities in the primary side loop (off-board circuit) and the secondary side loop (on-board circuit). The functional expression between AC is too complex, so the sinusoidal scale is used to show the above relationship and list the KVL equations. By solving the KVL equations, the functional expression of current in off board circuit and on-board circuit is obtained, the relationship between current, power supply voltage and load impedance is analyzed, and the variation model of transmission efficiency with respect to matching impedance and transmission frequency under the condition of complete resonance is established. Taking the emission frequency of 30 kHz as the constraint condition, it is obtained that the transmission efficiency corresponding to 10 experimental data under the condition of complete resonance is about 20%-2%.

Keywords: Wireless charging, Circuit Science, least square method

1. Introduction

With the development of electric vehicle wireless charging technology, more and more people choose to buy electric vehicles[1]. However, due to the large number of electric vehicle manufacturers, wireless charging must meet the principle of "special vehicle for special use", that is, special wireless charging equipment must be used for special models, resulting in a great waste of power resources. In order to realize the interconnection between wireless charging equipment and electric vehicles of different manufacturers, we hope to study the influence of various parameters on transmission efficiency through the optimization of wireless charging system and circuit knowledge, so as to provide theoretical guidance for the experiment.

Under the given limiting conditions and 10 experimental data, the mathematical models of transmission frequency, matching impedance and radio energy transmission efficiency are established, and the electric energy transmission efficiency corresponding to 10 experimental data is calculated[2]. For this problem, according to the relevant knowledge of circuit, the wireless charging model diagram is equivalent to the circuit model diagram, and the SS circuit equivalent model of wireless transmission system is obtained when the influence of secondary side loop rectifier circuit is ignored. The KVL equations are established and the parameters of each electric appliance are expressed by sinusoidal quantity. The functional expressions of electric energy transmission efficiency, matching impedance and emission frequency are obtained, and then the electric energy transmission efficiency corresponding to 10 experimental data is obtained[3].

2. Establishment of power transmission efficiency model

Step 1: Establish the equivalent model of automobile wireless charging system.
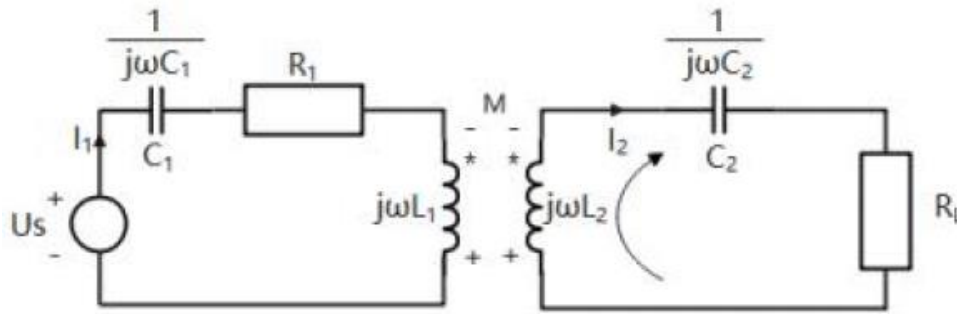
Figure 1: Relationship between radial displacement of main cable node and h.

The vehicle wireless charging system is equivalent to the SS model shown in Figure 1.

As shown in Figure 1, the off board part of the circuit is called the primary side loop, and the on-board part of the circuit is called the secondary side loop.

Where US is the input voltage of the primary circuit, I_1 is the current of the primary circuit, C_1 is the primary capacitance, R_1 is the internal resistance of the primary circuit, L_1 is the primary inductance, I_2 is the current of the secondary circuit, C_2 is the secondary inductance, R_2 is the secondary capacitance, and L_2 is the load resistance.

Step 2: list the relationship between physical parameters

According to the knowledge of circuit Science:

$$u_{R1} = R_1 I_1, u_{L1} = L_1 \frac{d\dot{i}_1}{dt}, u_{c1} = \frac{1}{C_1} \int I_1 dt \tag{1}$$

Therefore, the input voltage of the primary circuit is:

$$u = R_1 I_1 \frac{d\dot{i}_1}{dt} + \frac{1}{C_1} \int I_1 dt \tag{2}$$

Expressed as sinusoidal quantity, i.e.:

$$U_s = R_1 \dot{I}1 + j\omega L_1 \dot{I}_1 + \frac{\dot{I}_1}{j\omega C_1} \tag{3}$$

Because the secondary side circuit is closed, the mutual inductance of the secondary side circuit to the primary side circuit is considered on this basis.

$$u_{12} = M_{12} \cdot \frac{d\dot{I}_2}{dt} \tag{4}$$

U_{12} represents the induced voltage generated by the secondary side loop of the 2 loop to the primary side loop of the 1 loop. Because the induction coefficient M_{21} of the primary side circuit to the secondary side circuit and the induction coefficient M12 of the secondary side circuit to the primary side circuit are equal, there is no need to distinguish by subscript. Expressed as sinusoidal quantity:

$$U_{12} = j\omega M \dot{I}_2 \tag{5}$$

According to the hypothesis, the upper part of the two loop coils is the same name end, and the secondary loop current I2 flows out from the upper part of the coil, so the potential is "-" lower "+", and the potential of the same name end of the primary loop coil should be consistent with the potential of the same name end of the secondary loop, so the potential of the primary loop coil is upper "-" lower "+", which is opposite to the "+" lower "-" of the power potential in the primary loop, Therefore, U_{12} hinders the input voltage of the primary circuit, and the "negative sign" should be taken.

Step 3: simultaneous establishment of various relations and establishment of KVL equations

The expression of the input voltage of the primary loop is obtained by combining the equations:

$$U_s = \dot{I}_1\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right) - j\omega M\dot{I}_2 \tag{6}$$

Similarly, for the secondary side circuit:

$$U_s = \dot{I}_1\left(R_1 + j\omega L_1 + \frac{1}{j\omega C_1}\right) - j\omega M\dot{I}_2 \tag{7}$$

Note that the impedance Z_{11} and Z_{22} of the primary side loop and the secondary side loop are respectively:

$$Z_{11} = R_1 + j\omega L_1 + \frac{1}{j\omega C_1}$$
$$Z_{22} = R_L + j\omega L_2 + \frac{1}{j\omega C_2} \tag{8}$$

In the case of full resonance:

$$0 = j\omega L + \frac{1}{j\omega C} \tag{9}$$

Write as:

$$Z_{11} = R_1$$
$$Z_{22} = R_L \tag{10}$$

KVL equation:

$$\begin{cases} Z_{11}\dot{I}_1 - j\omega M\dot{I}_2 = \dot{U}_s \\ -j\omega M\dot{I}_1 + Z_{22}\dot{I}_2 = 0 \end{cases} \tag{11}$$

Step 4: establish the equation of transmission efficiency with various parameters

It can be solved simultaneously:

$$\dot{I}_1 = \frac{\dot{U}_s}{Z_{11} + \frac{(\omega M)^2}{Z_{22}}} \tag{12}$$

$$\dot{I}_2 = \frac{j\omega M\dot{U}_s}{Z_{11}Z_{22} + (\omega M)^2} \tag{13}$$

The input power of the primary loop is:

$$\dot{P}_{in} = \dot{U}_s\dot{I}_1 \tag{14}$$

The power consumed on the load is:

$$\dot{P}_{out} = \dot{I}_1 \cdot R_l \tag{15}$$

$$P_{out} = \frac{\omega^2 M^2 U'}{R_1 R_L + \omega^2} \frac{R_L}{M^-} \tag{16}$$

The circuit transmission efficiency can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\omega^2 M^2}{R_1 R_L + \omega^2 M} \tag{17}$$

Known:

$$\omega = 2\pi f \tag{18}$$

Where f is the transmission frequency, the result is:

$$\eta = \frac{4\pi^2 f^2 M^2}{R_1 R_L + 4\pi^2 f^2 M^2} \tag{19}$$

The coupling coefficient is defined to indicate the tightness of the coupling between the two circuits:

$$k^{\text{def}} = \frac{M}{\sqrt{L_1 L}} \tag{20}$$

The functional expressions of transmission efficiency with respect to transmission frequency and matching impedance are obtained.

In summary:

Function expression of transmission efficiency varying with matching impedance:

$$\eta = \frac{4\pi^2 f^2 k^2 L_1 L_2}{R_1 R_L + 4\pi^2 f^2 k^2 L_1 L_2} \tag{21}$$

3. Model solving and analysis

Step 1: solve the electric energy transmission efficiency corresponding to 10 times of experimental data

According to the data, the power transmission efficiency corresponding to 10 experiments is solved by MATLAB. The corresponding results are shown in Table 1:

Table 1: Inductance and mutual inductance data at different distances.

Num	Distance between two coils	Transmitting coil inductance	Receiving coil inductance	Coil mutual inductance	transmission efficiency
	$h(mm)$	$L1(\mu H)$	$L2(\mu H)$	$M12(\mu H)$	%
1	100	162.21	163.6	63.83	17.77
2	125	161.46	163.04	51.49	12.33
3	150	161.36	163.15	40.17	7.88
4	175	161.75	162.87	33.24	5.54
5	200	161.79	162.96	28.24	4.06
6	225	161.59	163.15	26.17	3.5
7	250	161.53	163.25	24.78	3.15
8	275	161.35	162.72	22.12	2.53
9	300	162.61	163.74	21.25	2.34
10	325	161.39	163.26	20.53	2.19

Step 2: analyze the impact of decision variables on the objective function

Through MATLAB drawing, the variation of transmission efficiency with transmission frequency (see Figure 2) and with matching impedance (see Figure 3) under 10 different coupling coefficients are obtained.
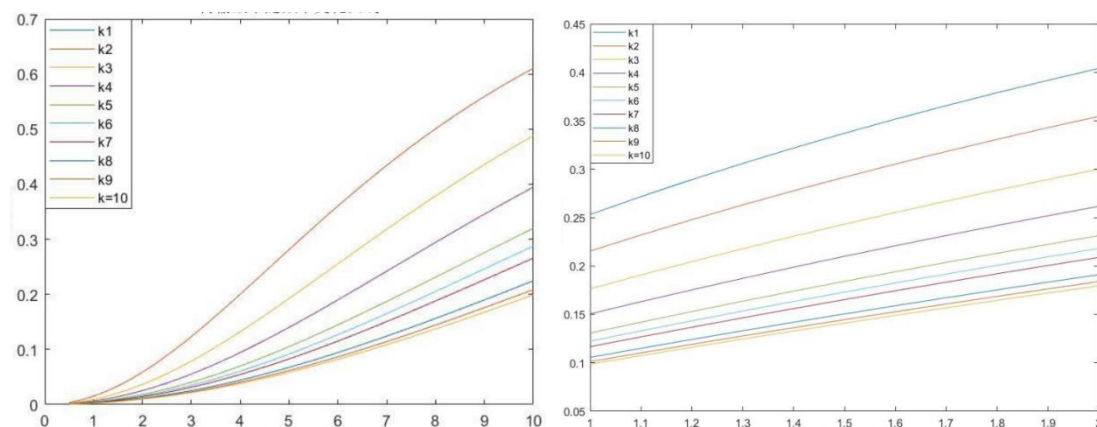

Figure 2: Variation with transmission frequency.   *Figure 3: Variation with matching impedance.*

As can be seen from the figure, when the matching impedance is fixed and the transmission frequency is increased or the transmission frequency is fixed and the matching impedance is increased, the transmission efficiency is in an upward state, but the upward trend is not easy to see.

It is advisable to take the data of the first test to expand the variation range of transmission frequency
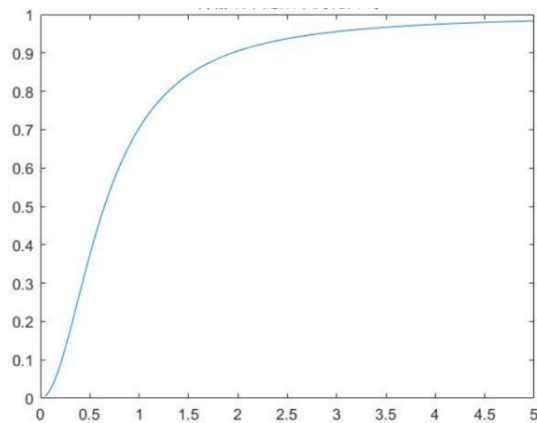
and matching impedance:

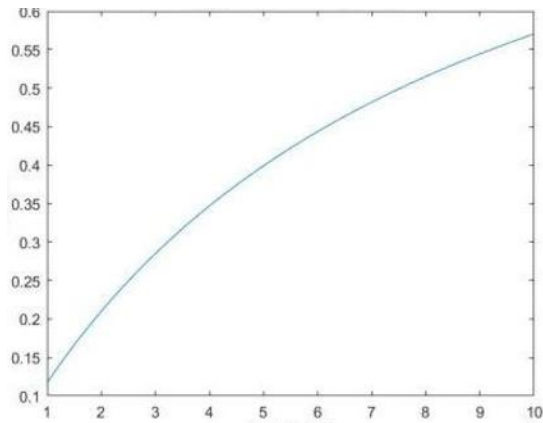*Figure 4: Variation of transmission frequency.*   *Figure 5: Variation of matching impedance.*

The following conclusions can be drawn: When the transmission frequency is increased with the fixed matching impedance, the transmission efficiency increases sharply at first and then slows down with the increase of transmission frequency; When the fixed transmission frequency increases the matching impedance, the transmission efficiency increases with the increase of the matching impedance. Although the transmission efficiency also slows down with the increase of the matching impedance, on the whole, the transmission efficiency is more sensitive to the change of the transmission frequency.

4. Evaluation and generalization of the model

4.1. Evaluation of the model

Using the knowledge of circuit, the formula proves that the process logic is rigorous, which provides a theoretical basis for the wireless charging system.

The text ignores the influence of rectifier circuit on secondary side circuit. Due to the excessive load resistance, the transmission efficiency calculated by this model is low.

4.2. Generalization of model

In this paper, the influence of rectifier circuit on off board part is ignored, and the wireless charging system is simplified to SS model, so as to establish the functional expression of power transmission efficiency with various parameters. However, combined with the actual situation, the rectifier circuit will also have a certain impact on the off-board part. Therefore, on the basis of the model established in this paper, we introduce the influence of the rectifier circuit on the secondary side circuit, that is, we establish the SP model, regard the rectifier circuit as a capacitor, use the same idea, change the KVL equations, and establish a more complete and more practical model of the variation of power transmission efficiency with various parameters. Finally, we can obtain more practical results. The influence of rectifier circuit on secondary side circuit is introduced, and the model of transmission efficiency varying with various parameters is constructed, which is more perfect and more in line with the actual situation than SS model.

4.3. Application of model

This paper focuses on the variation of power transmission efficiency with transmission frequency, matching impedance, coil distance between on-board part and off-board part, and the influence of coil offset on power transmission efficiency in spatial plane. At the same time, the specific values of each parameter are simulated with MATLAB, which provides a theoretical basis for the research and design of wireless charging technology.

References

[1] Meng Xianghan, Guo Feng, Tong Ziyang, Guo Zeyan, Wang Rundong. Design of power adjustable wireless charging system based on bilateral LCC resonant network [J]. Sensors and Microsystems,

39(12): 96-98 + 102, 2020.

[2] Wang Wei. Research on resonator design and optimization of magnetically coupled radio energy transmission system [D]. Jiangsu: Southeast University, DOI: 10.7666/d.y25113292013.

[3] Tan Juhua, Li Xiaofang, Guo Xiaochun. Design and optimization analysis of wireless charging coil of magnetic coupling resonant electric vehicle [J]. Journal of Shenyang University of technology, 42 (01): 84 - 892020.