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Renewable Energy Based Wireless EV Charging System

SHUBHAM SINGH, VINISHA GURJAR, VISHAL SHARMA, YOGESH CHANDEL

MR. YUSUF SHARIF DEPARTMENT OF ELECTRICAL ENGINEERING, SWAMI KESHVANAND INSTITUTE OF TECHNOLOGY MANAGEMENT & GRAMOTHAN

Abstract:

The industry of electric vehicles is developing rapidly. But because of the limited driving distance, the electric vehicle has not been effectively promoted. Therefore, the analysis of the wireless inductive charging system of EVs is particularly important. In this paper, the wireless charging system based on Wind/PV system is studied, including the coil topology, the circuit structure, and the control mode. Ansoft and MATLAB/Simulink Ares was used to simulate and analyse the system. The research provides a theoretical basis for the development and application of wireless charging systems.

Keywords: Wireless inductive charging; Wind/ PV system; Coil topology; Simulation; Winding construction

1. Introduction

Fossil fuels are increasingly being used today, which will cause air pollution and some other problems. At the same time, automobile is the main travel tools in our daily lives. It also uses fossil fuels, but the efficiency is very low. So now, a high efficiency and environmentally friendly trip mode need to be consummated.

Solar energy is inexhaustible and renewable. The radiation power on the earth surface annual year is about 8 1013 kW, which in per second, the exposure to the Earth is equal to the energy released in burning 5 million tons of coil. Similarly, the wind resources are also very considerable. The total amount of available resources is about 72 trillion, even if only about 20%, the resources is about 7 times of the sum of world energy consumption or electricity demand. But at the same time, wind power resources and solar energy resources still have many problems, such as big fluctuation, low utilization rate, low efficiency, poor reliability, low stability and so on. Target at the above problems, the Wind/Solar hybrid system is proposed. The Wind/Solar hybrid system makes the use of complementary of wind and solar energy in time, along with the energy storage system, making an organic combination of them three. So that the renewable energy can be stable and efficient.

Different from traditional cars using gasoline, electric vehicles use electricity as the power source. Electric vehicles can effectively solve environmental pollution and energy transformation [5]. Conventional charging method for charging piles can be divided into wired charging and wireless charging. Wired charging piles use cables to transfer power. The advantage is that the efficiency of it is very high. But the disadvantage is that it may produce electric sparks, charging is limited by location and so on. Wireless charging solves the above problems properly. Nowadays, it is mainly used on phones, computers and some other low power equipment [6,7]. The technology of wireless power transfer on electric vehicles is now a hot spot. The common ways of wireless charging are divided into 3 aspects: electromagnetic inductive coupling, magnetic coupling resonance and microwave irradiation. The disadvantage of magnetic coupling resonance and microwave irradiation is that the efficiency and power of them is low. The method of electromagnetic inductive coupling has the advantage of high efficiency and so on [8]. With the high development of information technology, wireless charging has become an inevitable requirement for the future development of electric vehicles. At the same time, the use of wireless charging technology also makes the development of electric vehicles more broad. The technology of wireless charging for electric vehicles is shown in Fig. 1. The schematic diagram of the circuit structure is in Fig. 2.

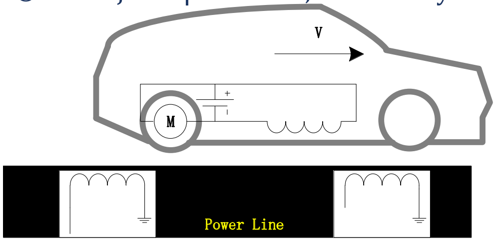

Fig. 1. The schematic of dynamic charge.

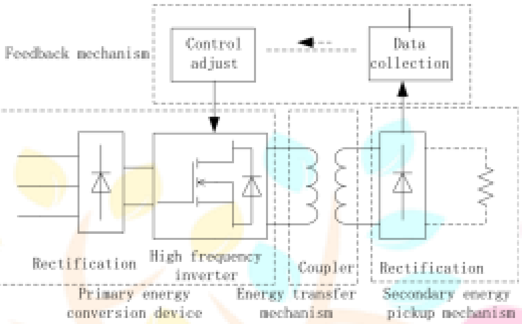

Fig. 2. The schematic diagram of the circuit structure.

2. The analysis of wireless charging

For the dynamic wireless charging of electric vehicles, the transmitting coil is buried under the highway. When the electric vehicle, which carries receiving coils that passing through transmitting coils, the power is transferred through magnetic coupling. Combining the Wind/Solar hybrid system with the wireless charging system of electric vehicles and building up a wireless charging system of electric vehicles based on Wind/Solar hybrid system. The system schematic of it is as in Fig. 3.

2.1. Structure analysis

For a good performance of the charging system, there are two aspects which should pay attention to. Firstly, efficiency, and secondly, power. The way to improve efficiency is to change the structure of coil, change the structure of circuit and the choice of system control. The structure of coil is mainly about the shape of the coil and winding method of coil.

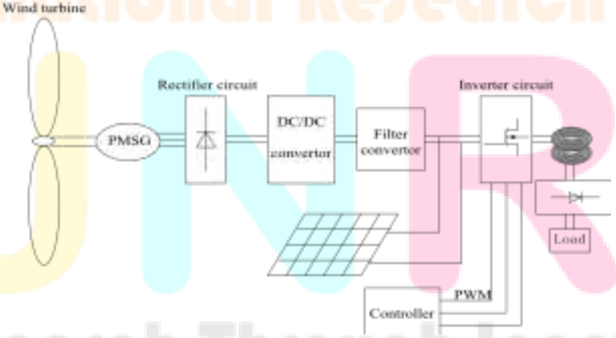

Fig. 3. The structure of EV's wireless inductive charging system.

For the coil of flat type, the common shape is mainly about circular or rectangular coil. As is shown in Figs. 4 and 5.

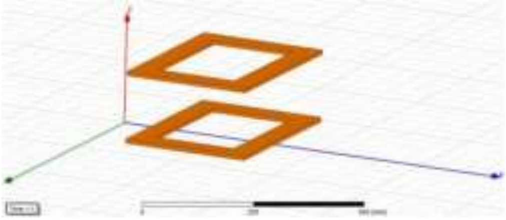

Fig. 4. Rectangle coil.

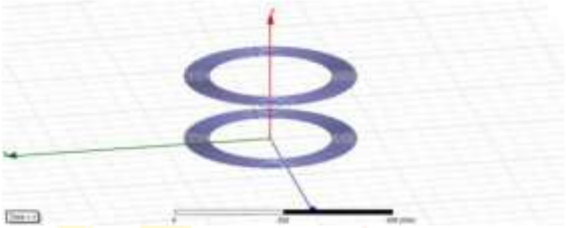

Fig. 5. Circular coil.

2.2. Calculation and analysis

For loosely coupled coils based on electromagnetic induction coupling, it is usually called loosely coupled transformer. For concentric single-turn circular coil, the mutual inductance between them is as follows:

$$M = \mu_0 \cdot \sqrt{r_1 \cdot r_2} \frac{2}{f} \left[\left(1 - \frac{f^2}{2} \right) \cdot K(f) - E(f) \right] \tag{1}$$

f can be obtained by the following formula:

$$f = \sqrt{\frac{4 \cdot r_1 \cdot r_2}{z^2 + (r_1 + r_2)^2}} \tag{2}$$

μ_0 is the permeability of vacuum ($\mu_0 = 4 \cdot \pi \cdot 10^{-7} H/m$), r_1,r_2 is the effective radius of the circular coil, and z is the distance between two concentric circular coils, $K(f)$, $E(f)$ are the first type of incomplete elliptic integrals and the second type of incomplete elliptic integrals. When two concentric single-turn circular coils have the same effective radius, the mutual inductance between the two coils can be rewritten as follows:

$$M = \mu_0 \cdot \frac{r}{f} \cdot \left[\left(2 - f^2\right) \cdot K(f) - 2 \cdot E(f) \right] \tag{3}$$

$$f = 2 \cdot a \cdot \sqrt{\frac{1}{z^2 + 4a^2}} \tag{4}$$

Similarly, for the concentric single-turn rectangular coil, the mutual inductance formula can be written as follows:

$$M = \frac{2\mu_0}{\pi} \left[\begin{array}{l} \sqrt{2(a+c)^2 + z^2} + \sqrt{2(a-c)^2 + z^2} - 2\sqrt{2a^2 + 2c^2 + z^2} - \\ (a+c) \cdot \operatorname{arctan} h \dfrac{a+c}{\sqrt{2(a+c)^2 + z^2}} - (a-c) \cdot \operatorname{arctan} h \dfrac{a-c}{\sqrt{2(a-c)^2 + z^2}} + \\ (a+c) \cdot \operatorname{arctan} h \dfrac{a+c}{\sqrt{2a^2 + 2c^2 + z^2}} + (a-c) \cdot \operatorname{arctan} h \dfrac{a-c}{\sqrt{2a^2 + 2c^2 + z^2}} \end{array} \right] \tag{5}$$

When the coils on both sides are of the same length, the mutual inductance between them can be rewritten as follows:

$$M = \frac{2\mu_0}{\pi}\left(\begin{array}{l}\sqrt{8b^2+z^2}+|z|-2\sqrt{4b^2+z^2}- \\ 2a\cdot\operatorname{arctan}h\frac{2b}{\sqrt{8b^2+z^2}}+2b\cdot\operatorname{arctan}h\frac{2b}{\sqrt{4b^2+z^2}}\end{array}\right) \tag{6}$$

By calculating the mutual inductance, the coupling coefficient can be calculated.

$$K = \frac{M}{\sqrt{L_1 \times L_2}} \tag{7}$$

Where M is the mutual inductance between the two coils, L_1 and L_2 are the self-inductance of primary coil and secondary coil. For conventional transformers, the coupling coefficient is essentially one, but for a loosely coupled transformer in an electric vehicle, the coupling coefficient is usually around 0.2. The improvement of the coupling coefficient represents the improvement of the system efficiency. Therefore, by comparing the mutual inductance of two cases, also represents the relationship about the coupling coefficient, also on behalf of the efficiency of the two cases. So take the same effective radius, putting the data into the Matlab to calculate the efficiency of them (see Fig. 6).

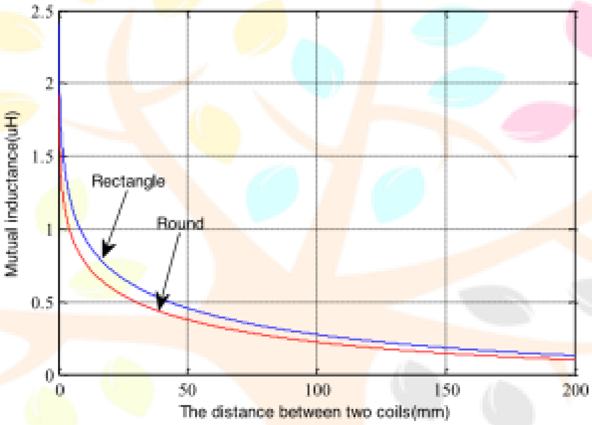

Fig. 6. The analysis of Mutual inductance.

It can be found that when the distance is between 0 mm and 200 mm, the mutual inductance of the rectangular coils is bigger than the circular coil's. That is to say, when using the structure of rectangular coil, the secondary coil receives more energy, and the efficiency will be higher. So in this article, the analysis and calculation will use the structure of rectangular coil.

For the conventional wireless charging structure, the primary single coil and secondary single coil are analysed and simulated by Ansoft Maxwell. The output power is 1.5 kW (see Table 1).

Table 1. Simulation data.

Self-inductance (primary winding)/μH	238
Self-inductance (secondary winding)/μH	77.5
Source of direct current/V	150
Resonant capacitor (primary winding)/F	$1.47*10^{-8}$
Resonant capacitor (primary winding)/F	$4.52*10^{-8}$
Load resistance/⍰	10
Frequency/KHz	85 KHz

Use MATLAB/Simulink to calculate the overall efficiency of the system and the voltage and current of primary and secondary side. The above data is added into the following Simulink model. In order to maintain the stability and efficiency of the system, the PLL is added to keep the system operating in constant frequency (see Fig. 7).

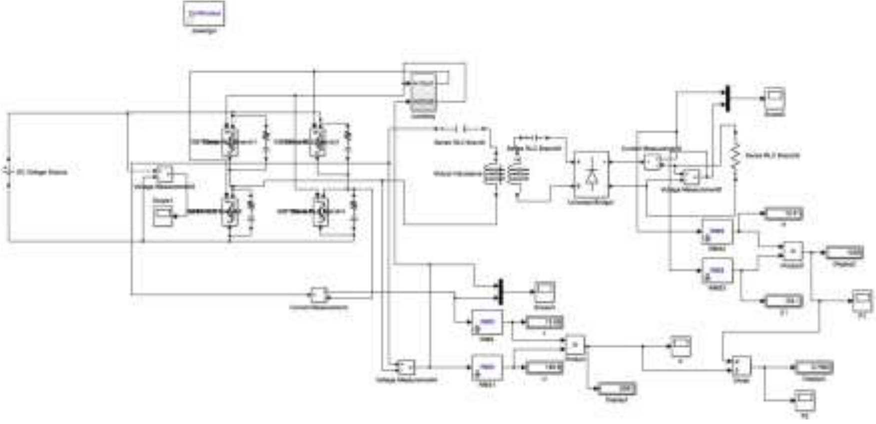

Fig. 7. Simulation diagram.

After running the model, the following curves can be gotten (see Figs. 8–10):

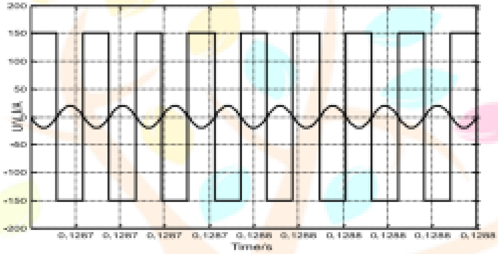

Fig. 8. The current and voltage of the primary winding.

From the curve, it can be seen that the efficiency can reach about 73%.

From the above analysis, considering from the structure, using rectangular coil for simulation, the system efficiency is at around 73%. As described above, after changing the coil structure, the circuit configuration of the coil will also be changed. For the conventional case of the circuit structure, that is, single-side primary coil and secondary coil. Expand the number of primary coil into two or more, as shown in the following Fig. 11.

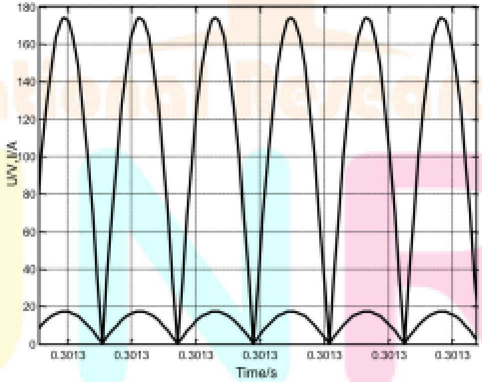

Fig. 9. The current and voltage of the secondary winding.

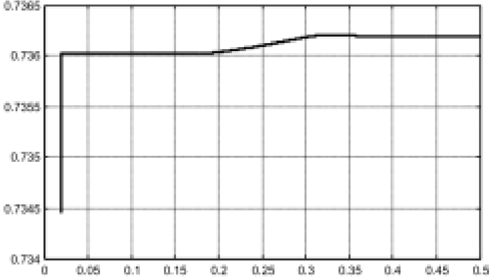

Fig. 10. The efficiency of the system.

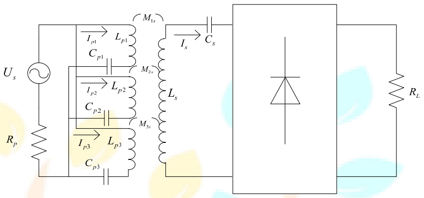

Fig. 11. Circuit diagram of three transmitting coils.

Based on mutual inductance coupling theory, taking the three-coil structure as an example, the equivalent expression of the circuit structures as follows:

$$\begin{bmatrix} U_s \\ U_s \\ U_s \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{p1} & jwM_{12} & jwM_{13} & -jwM_{1s} \\ jwM_{12} & Z_{p2} & jwM_{23} & -jwM_{2s} \\ jwM_{13} & jwM_{23} & Z_{p3} & -jwM_{3s} \\ -jwM_{1s} & -jwM_{2s} & -jwM_{3s} & Z_s \end{bmatrix} \cdot \begin{bmatrix} I_{p1} \\ I_{p2} \\ I_{p3} \\ I_s \end{bmatrix} \tag{8}$$

Among them, U_S is the voltage of the primary side, Z_{P1}, Z_{P2}, Z_{P3} are the impedance of three branches of primary side. Z_S is the impedance of the secondary circuit. M_{12}, M_{13}, M_{23} are the mutual inductance between the three primary coils, M_{1S}, M_{2S}, M_{3S} are the mutual inductance between the primary coil and secondary coil respectively. I_{P1}, I_{P2}, $I_{P3}$are the current of the primary sides respectfully. I_S the current of the secondary side.

In the calculation, in order to simplify the calculation process, the mutual inductance between the primary coils is ignored, so the relation is $M_{12} = M_{13} = M_{23} = 0$. Also, it is assumed that the magnitude of the impedance about the primary coils is the same. Then the above equivalent expression can be written as follows:

$$\begin{bmatrix} U_s \\ U_s \\ U_s \\ 0 \end{bmatrix} = \begin{bmatrix} Z_p & 0 & 0 & -jwM_{1s} \\ 0 & Z_p & 0 & -jwM_{2s} \\ 0 & 0 & Z_p & -jwM_{3s} \\ -jwM_{1s} & -jwM_{2s} & -jwM_{3s} & Z_s \end{bmatrix} \cdot \begin{bmatrix} I_{p1} \\ I_{p2} \\ I_{p3} \\ I_s \end{bmatrix} \tag{9}$$

The expression is expanded to calculate the current value of the secondary side and the primary side. The following expression can be obtained:

The current value of the secondary side:

$$\mathrm{Is} = \frac{1-k^2}{k^4 R_L^2 L_1/L_2^2 + w^2 L_1 (1-k^2)^2} \tag{10}$$

The current value of the first primary coil:

$$I_{p1} = \frac{U_s\left(Z_p Z_s + w^2 M_{2s}^2 + w^2 M_{3s}^2 - w^2 M_{1s} M_{2s} - w^2 M_{1s} M_{3s}\right)}{Z_p (Z_p Z_s + w^2 M_{1s}^2 + w^2 M_{2s}^2 + w^2 M_{3s}^2)} \tag{11}$$

The current value of the second primary coil:

$$I_{p2} = \frac{U_s\left(Z_p Z_s + w^2 M_{1s}^2 + w^2 M_{3s}^2 - w^2 M_{1s} M_{2s} - w^2 M_{2s} M_{3s}\right)}{Z_p (Z_p Z_s + w^2 M_{1s}^2 + w^2 M_{2s}^2 + w^2 M_{3s}^2)} \tag{12}$$

The current value of the third primary coil:

$$I_{p3} = \frac{U_s\left(Z_p Z_s + w^2 M_{1s}^2 + w^2 M_{2s}^2 - w^2 M_{1s} M_{2s} - w^2 M_{2s} M_{3s}\right)}{Z_p (Z_p Z_s + w^2 M_{1s}^2 + w^2 M_{2s}^2 + w^2 M_{3s}^2)} \tag{13}$$

By the above equations, the output power of the system can be calculated:

$$P_{out} = |I_s|^2 \cdot R_L = \left| \frac{jwU_s\,(M_{1s} + M_{2s} + M_{3s})}{Z_p Z_s + w^2 M_{1s}^2 + w^2 M_{2s}^2 + w^2 M_{3s}^2} \right|^2 \cdot R_L \tag{14}$$

And then the efficiency of the system can be calculated as follows:

$$\eta = \frac{P_{out}}{U_s \left| I_{p1} + I_{p2} + I_{p3} \right|} \tag{15}$$

The current value of the primary side and the output power are added into the above formula.

$$= \frac{\left| \frac{jwU_s(M_{1s}+M_{2s}+M_{3s})}{Z_pZ_s+w^2M_{1s}^2+w^2M_{2s}^2+w^2M_{3s}^2} \right|^2 \cdot R_L}{U_s \left| \frac{U_s(Z_pZ_s+w^2M_{2s}^2+w^2M_{3s}^2-w^2M_{1s}M_{2s}-w^2M_{1s}M_{3s})}{Z_p(Z_pZ_s+w^2M_{1s}^2+w^2M_{2s}^2+w^2M_{3s}^2)} + \frac{U_s(Z_pZ_s+w^2M_{1s}^2+w^2M_{3s}^2-w^2M_{1s}M_{2s}-w^2M_{2s}M_{3s})}{Z_p(Z_pZ_s+w^2M_{1s}^2+w^2M_{2s}^2+w^2M_{3s}^2)} + \frac{U_s(Z_pZ_s+w^2M_{1s}^2+w^2M_{2s}^2-w^2M_{1s}M_{2s}-w^2M_{2s}M_{3s})}{Z_p(Z_pZ_s+w^2M_{1s}^2+w^2M_{2s}^2+w^2M_{3s}^2)} \right|} \tag{16}$$

The value of them are added into the above formula, for example $U_s = 500$ V, $R_L = 30$. According to the standard of American Automobile Association, the frequency of the system is 85 KHz. Based on the simulation data through Ansoft, the curve is calculated by MATLAB. The following curve can be gotten. This Curve includes the primary single coil, double coil and three coils (see Fig. 12).

From the curve, it can be seen that when the primary side is a structure of single coil, the obtained efficiency value is almost the same as the efficiency value obtained by the model built by Simulink, which is about 73%. When the number of primary coils increased to 2, the blue curve in the figure is the efficiency curve in the case of double coils. It can be seen that when the number of primary coils increases, the efficiency will be improved, but at the original resonant point, efficiency will be reduced, and next to the original point of resonance, there will be two peak points. This phenomenon is called frequency splitting. This is because the complexity of the system increases as the number of primary windings increases. Further analysis shows that as the number of primary windings continues to increase, the efficiency increases even more, the but the frequency splitting becomes more serious. In the original point, on both sides, there will be two peak points. So in ideal conditions, the structure of two primary coils is better. And in real conditions, the structure of single primary coil is better.

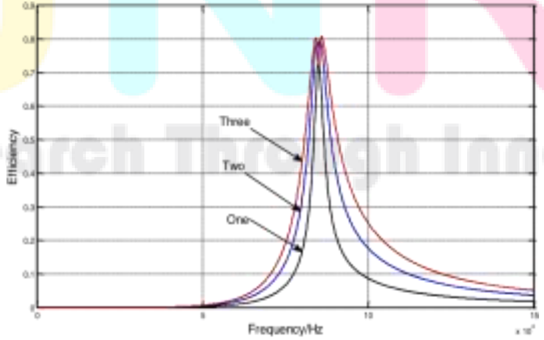

Fig. 12. The efficiency of three conditions.

Then the frequency splitting phenomenon is analysed, when the load size changes, the frequency splitting phenomenon will also change, as shown Fig. 13:

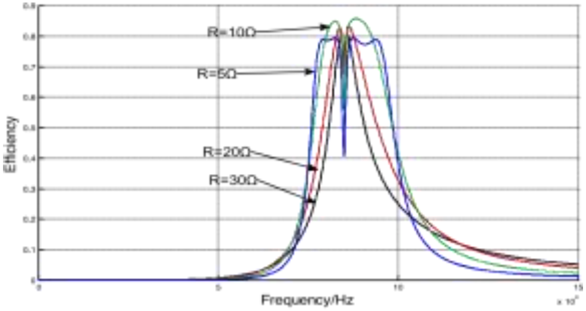

Fig. 13. The efficiency of different RL(RL=5, 10, 20, 30).

2.3. Frequency splitting

Based on the references there are two main reasons for frequency splitting, the quality factor *Qs* of the secondary side and the coupling coefficient of loosely coupled transformer K.

$$Qs = \frac{wL}{R} \tag{17}$$

As can be seen from the above figure when the resistance of the load changes, the frequency splitting phenomenon will happen. When the coupling coefficient of the system is fixed, the smaller the *R* is, the more likely the system will generate frequency splitting. In the above, when the number of primary coils increased, the frequency splitting phenomenon occurs, so in this case, the occurrence of the frequency splitting should be due to the change of the coupling coefficient. Taking the series–series (S–S) as an example (see Fig. 14): Based on the model of mutual inductance:

$$U_P = Z_P I_P - jwMI_S \tag{18}$$

$$0 = -\mathrm{jwMI_p} + \mathrm{Z_S I_S} \tag{19}$$

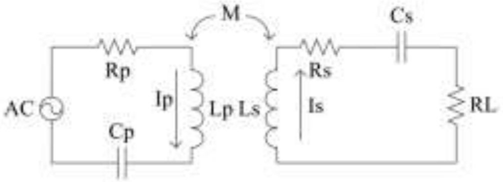

Fig. 14. The S-S structure.

Based on the analysis above, the efficiency of the system is:

$$\eta = \frac{P_{out}}{U_S \cdot |I_p|} = \frac{\left|\frac{jwMU_s}{Z_p Z_s + w^2 M^2}\right|^2 \cdot R_L}{U_S \cdot \left|\frac{U_s \cdot Z_S}{Z_p Z_s + w^2 M^2}\right|} \tag{20}$$

In order to calculate relationship between the coupling coefficient and the efficiency of the system, the mutual inductance is replaced by the K.

The efficiency curves of the system are obtained when the frequency and the coupling coefficient are changed (see Fig. 15):

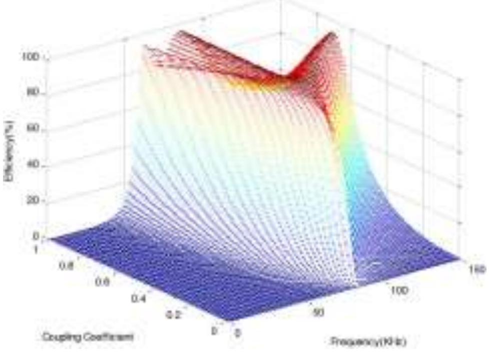

Fig. 15. The efficiency.

Similarly, the running frequency of the system at 85 KHz. It can be seen that when the system works in 85 KHz, the efficiency of the system will reach its maximum. If the coupling coefficient increases, the peak efficiency of the system will be divided into three points, and the under original resonant frequency, the efficiency of the system is reduced. Frequency splitting occurs.

3. Conclusion

Through the analysis and comparison of the wireless charging system, it can be found that when the effective radius is equal, the square coil can produce more mutual inductance than circular coil. The output characteristics of the secondary side can be improved when the number of the primary coil is increased in a certain range. The structure of the original coils can also improve the safety of the inductive charging system. When the coil is aging, we should just replace one parallel branch of them. But when the number of primary winding is increasing, the frequency splitting will happen. Through the analysis, it can be found that the reason of frequency splitting includes the change of quality and coupling coefficient. When the structure of the primary winding is changed, the coupling coefficient of the whole system is also changed so that the frequency splitting will happen. The structure of multiple primary winding is used in many fields. When the structure of multiple primary winding is used, the load resistance and the number of the primary winding should be carefully thought about. The results of this paper on electromagnetic inductive coupling are important for promoting the development of wireless charging technology for electric vehicles.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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