Design and Application of Early Warning Model for Electric Vehicle Charging Safety

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Abstract: In order to improve the charging safety of electric vehicles, it is necessary to design the early warning model of charging safety, so as to overcome the overload defects in the charging process of electric vehicles. An electric vehicle charging safety warning model was proposed based on contactless charging design. The electromagnetic induction coil and electromagnetic coupler installed on the charging pile are used to design the electromagnetic coupling induction with the driving electric vehicle tire wire, and the electromagnetic coupling control and charging stability adjustment of the electric vehicle are carried out by using the inductive power transmission technology. According to the overload regulation of electric vehicle during charging, the overload interruption control of electric vehicle charging is carried out by mutual inductance coupling method, and the parameters such as resonance frequency, mutual inductance coefficient and coil internal resistance during charging are analyzed. The parameter steady-state regulation method is used for non-contact charging, and the electric vehicle charging safety early warning control is realized, and the parameter optimization design of electric power transmission system in the process of electric vehicle charging is carried out. According to the parameter optimization result, the electric vehicle charging safety early warning test is realized. The test results show that the proposed method has good control performance and can effectively realize the wireless energy transmission of 100W in 100cm, the charging efficiency and the charging safety are improved.

1. Introduction
With the society pay more and more attention to the use of new energy, new energy has the characteristics of safe and environmental protection, high utilization rate, which can effectively reduce the pollution of energy consumption to the environment. Nowadays, there are more and more cars in the transportation system of our country, and the pollution to the environment is more serious[1]. In order to reduce the pollution of automobile to the environment effectively, the electric vehicle has become the key research subject of our country through the innovation and research of the new energy. In the process of electric vehicle charging, insulation factor is one of the important factors that affect
the safety hidden trouble. Good insulation can play a good role in protecting people and electrical equipment. First of all, the insulation of the shell in the charging equipment, the insulation of the shell directly affects the charging safety, and the connectors must also be connected to take appropriate protection measures\cite{2}. The second is to consider the electrical gap and creeping distance during the charging process to ensure that the voltage is not too large and breakdown insulation. The dielectric strength of the insulator should also be considered to ensure that the dielectric strength meets the requirements. Thirdly, the resistance value of insulation resistance, because of the difference of environment, the larger the resistance value of insulation resistance, the more safe the charge can be guaranteed. The size of contact current will cause different harm to human body directly, so the corresponding protective measures must be taken to prevent the contact current from happening\cite{3}.

In actual use, the charging facilities will be used in spring, summer, autumn, winter, wind, frost, rain and snow. However, the charging insulation materials will be affected by temperature, vibration, harmful gases, chemicals, humidity, dust, radiation and other factors. However, temperature plays a key role in insulation material and insulation structure aging. The car stops at the right place at the end of the journey, trying to avoid direct sunlight and cold weather. In winter and summer, the climate is more harmful to the battery, and the damage to the battery seriously affects the safety of charging. Therefore, we must take appropriate measures to cure the safety of charging. Through the analysis of the safety grade mentioned above, we can see that the solution to the charging safety problem of electric vehicle needs to start from the protection of these three safety levels, which can be divided into three levels according to the safety level\cite{4}. Three security lines are needed to protect them. The first is to protect people, to take measures to strengthen the safety protection of charging piles, to ensure the safety of electric vehicles belongs to human protection. Secondly, the establishment of protective measures for the surrounding facilities. Finally, the establishment of the safety protection measures for the charging facilities themselves, according to the priority and importance of these three security lines of defense, to take the corresponding safety protection measures. 2007, The MIT team in the United States has proposed electromagnetic resonance radio energy transmission technology. The team used two coils with the same inherent resonance frequency to light the 60W light bulb at a distance of 2m under resonant excitation\cite{5}. The efficiency of the whole system reached 40%. Electromagnetic resonance has irreplaceable advantages over electromagnetically induced electric power transmission: for example, the location of the coil is not strictly required, so it can be charged for the moving device; moreover, because the resonance frequency is relatively strict, Therefore, the power supply frequency can be controlled to charge different electrical appliances. However, the current research in this direction is either too theoretical or experimental, lacking of quantitative guidance for engineering design. In order to improve the safety of electric vehicle charging, it is necessary to design an early warning model of electric vehicle charging safety\cite{6}.

In order to solve the above problems, an electric vehicle charging safety warning model based on contactless charging design is proposed. The electromagnetic induction coil and electromagnetic coupler installed on the charging pile are used to design the electromagnetic coupling induction with the driving electric vehicle tire wire, and the electromagnetic coupling control and charging stability adjustment of the electric vehicle are carried out by using the inductive power transmission technology. According to the overload regulation of electric vehicle during charging, the overload interruption control of electric vehicle charging is carried out by mutual inductance coupling method, and the non-contact charging is carried out by parameter steady-state regulation method. The electric vehicle charging safety warning control is realized, and the parameter optimization design of the electric power transmission system during the electric vehicle charging process is carried out. According to the parameter optimization result, the electric vehicle charging safety early warning test is realized. Finally, the simulation results show that the proposed method can improve the early warning capability of electric vehicle charging.

2. Working principle of electric vehicle charging system

Firstly, the input power is converted into a high frequency power supply, and then the primary
emission induction coil and the electromagnetic coupler installed on the charging pile side are converted into the electromagnetic power source after the energy shunt. The primary resonance is then radio-transmitted to the secondary resonance in the automobile tire[7]. The receiving coil induces the energy of the secondary resonance link and performs magnetoelectric transformation. The received electric energy is then adjusted to charge the car battery.

The magnetic resonance power transmission mode is different from the inductive power transmission mode, which described as:

1) The inverter frequency of electromagnetic induction power transmission is generally less than 100K Hz, which is determined by the performance of magnetic core and the switching frequency of inverter power supply. The magnetic resonance mode generally uses signal generator and power amplifier to provide power supply, so the inverter frequency of the energy conversion link can be greatly increased to 10MHz.

2) Compared with the electromagnetic induction mode, there are only two coils for electromagnetic induction, and two resonance links are added to the magnetic resonance power transmission mode. The resonance coil uses its own distributed capacitance to realize resonance in an open circuit. In this case, the topology of the system is relatively fixed[8]. The magnetic resonance mode system topology of the electric vehicle charging safety warning system designed in this paper is shown in figure 1.

![Figure 1. Schematic diagram of magnetic resonance mode radio energy transmission system for electromagnetic induction coils and electromagnetic couplers](image)

3. Electromagnetic coupling induction design and stability control of electric vehicle charging safety

3.1. Electromagnetic coupling induction design

During the use of the battery, assuming the existence of overdischarge will increase the probability of the difference of the battery. During the over-discharge of the lead-acid battery, the terminal voltage drops faster, which easily leads to the appearance of coarse grain lead sulfate in the electrode plate. It can be found that the battery can reduce the battery capacity and service life even if the battery is switched off. Because of the timeliness and reliability of the interrupt voltage monitoring, the battery energy management system cannot complete the discharge control better, so the problem of overdischarge of the battery with lower capacity cannot be avoided. Because of the increasing gap in the battery capacity, the battery with lower capacity will overdischarge more and more seriously[9].

In this paper, a new method of electromagnetic resonance radio energy transmission using automobile tire wire is presented. In this method, the transmitting coil is fixed on the charging pile to
form an electromagnetic induction coil and an electromagnetic coupler, and the energy is transmitted by electromagnetic resonance with the automobile tire\[10\]. The topological structure used in the system is shown in figure 2.

![Figure 2. Topological structure of magnetic resonance power transmission system](image)

The electromagnetic induction coil and electromagnetic coupler installed on the charging pile are used to design the electromagnetic coupling induction with the driving electric vehicle tire wire, and the electromagnetic coupling control and charging stability adjustment of the electric vehicle are carried out by using the inductive power transmission technology\[11\]. According to the overvoltage regulation of the load during the electric vehicle charging, the overload interruption control of the electric vehicle charging is carried out by using the mutual inductance coupling method, and the ohmic loss and radiation loss of the electrified coil will be produced at high frequency. In this system, the ohmic loss is much larger than the radiation loss, so the radiation loss is ignored and only ohmic loss is considered. In this paper, parallel capacitors are used to carry out resonance at the energy pickup end\[12\]. When the coil is in resonant state, the resonant angular frequency is \(\omega_0\). Assuming that the effective value of the transmitting coil current is \(I_p\), the effective value of the coil 1 current \(I_s\), the current RMS value on the resonance coil 2 is \(I_{r2}\), and the current effective value on the load \(R_o\) is \(I_o\), they are calculated respectively as:

\[
I_s = \frac{\omega_0 M_{ps} I_p}{R_s + Z_{r1}} \quad (1)
\]

\[
I_r = \frac{\omega_0 M_{ps} I_p}{R_r + Z_{r2}} \quad (2)
\]

\[
I_o = \frac{M_{pl} I_p}{L_o} \quad (3)
\]

The reflection impedance of the electromagnetic induction coil on the charging pile is \(Z_{r1}\):

\[
Z_{r1} = \frac{M_p R_s}{L_i} - j \frac{\omega_0 M_{p1}^2}{L_i} \quad (4)
\]

In parallel, the reflective impedances between the electromagnetic coupler and the moving electric vehicle tire are \(Z_{r1}\), \(Z_{r2}\), \(Z_{ps}\), calculated as follows:

\[
Z_{r1} = \frac{M_{ps} R_s}{L_i^2} \quad (5)
\]

\[
Z_{r2} = \frac{\omega_0 M_{ps}^2}{M_p^2 R_s / L_i^2 + R_s} \quad (6)
\]

\[
Z_{ps} = \frac{\omega_0 M_{ps}^2}{Z_{ps}} \quad (7)
\]

The output power of electric vehicle charging pile mutual inductance coupling is expressed as follows:

\[
P_o = \frac{\omega_0^2 M_{ps}^2 M_{p2}^2 L_i^2 I_p^2 R_s}{(\omega_0^2 M_{ps}^2 L_i^2 + R_s L_i^2 + R_s M_{ps}^2)^2} \quad (8)
\]
The transmission efficiency of electric vehicle during charging is expressed as follows:

\[
\eta = \frac{P_o}{I_p^2(Z_{ps} + R_p)} \cdot \frac{\omega_0^4 M^2_{ps} M^2_{sr} M^2_{r} I^2_p R_o}{h_1(\omega_0^2 M^2_{ps} I^2_p R_r + \omega_0^2 M^2_{sr} M^2_{r} R_o + h_1 R_p)}
\]

Where, \(h_1 = \omega_0^2 M^2_{sr} I^2_p + R_p R_r I^2_p + R_o R_M M^2_{sr} \).

3.2. Stability control of electric vehicle charging safety

According to the overload regulation of electric vehicle during charging, the overload interruption control of electric vehicle charging is carried out by using mutual inductance coupling method, and the resonant frequency and mutual inductance coefficient during charging are analyzed. The coils internal resistance and other parameters are controlled by parameter steady-state adjustment method\[13\]. The main charging circuit uses the step-down chopper circuit. The working principle is to output PWM wave from MSP430F2274 single chip microcomputer and complete the FET control by using the MOSFET drive circuit. The charge and discharge operation of the battery is effectively completed, the main circuit in the actual operation of the circuit can use the appropriate capacitance and inductance and PWM wave frequency, at the same time, it can effectively shorten the charging time and enhance the voltage leveling. The potential difference information of the motor system at \(t_0\) time is calculated by PID control. The formula is expressed as follows:

\[
q^+_{n}(t) = (q^+_{n}(t))_0 + \left(\frac{\partial q^+_{n}(t)}{\partial a_n}\right)_0 \partial a_n + \left(\frac{\partial q^+_{n}(t)}{\partial b_n}\right)_0 \partial b_n + \left(\frac{\partial q^+_{n}(t)}{\partial c_n}\right)_0 \partial c_n
\]

\[
\left(\frac{\partial q^+_{n}(t)}{\partial a_n}\right)_0 = -\left(\frac{1}{q^+_{n}(t)_0}\right) (a^+-a^+_n) = f^+_{an}(t)
\]

\[
\left(\frac{\partial q^+_{n}(t)}{\partial b_n}\right)_0 = -\left(\frac{1}{q^+_{n}(t)_0}\right) (b^+-b^+_n) = g^+_{bn}(t)
\]

\[
\left(\frac{\partial q^+_{n}(t)}{\partial c_n}\right)_0 = -\left(\frac{1}{q^+_{n}(t)_0}\right) (c^+-c^+_n) = h^+_{cn}(t)
\]

The rechargeable magnetic resonance mode of electric vehicle is constructed by planar coil and coupled by two coils. The 3D distribution of electromagnetic field of electric vehicle is shown in figure 3.

Figure 3. 3D structure of magnetic field distribution in charging coil of electric vehicle

If the system topology is composed of four coils in series, the charging main circuit is in parallel with the transmitting coil during the actual operation of the circuit, and the other coils are in series\[14\]. The output power and efficiency of the charging system of the electric vehicle are expressed as follows:

\[
P_o = I_o^2 R_o = \frac{\alpha_0^2 M^2_{ps} M^2_{sr} M^2_{r} I^2_p R_o}{(M^2_{sr} R_o + M^2_{r} R_o + R_p R_o)^2}
\]
Where, \( h_i = M_{\alpha}^2 R_s + M_{\alpha}^2 R_0 + \frac{R R_0}{\omega_0^2} \). The system model adopts mutual inductance model, considering resonance frequency and mutual inductance synthetically. Each parameter of internal resistance can be controlled by high voltage and overload protection according to the load during charging process of electric vehicle. It can describe the transmission characteristic of radio energy transmission system of magnetic resonance mode more accurately, and has different distance and deviation. The system performance under the angle is tested\(^{[15]}\).

### 4. System analysis and optimization of early warning model for charging safety

Under the condition of mid-range resonance, if parallel resonance is adopted, the input current, load and resonant frequency remain the same, then it will decrease with the increase of the distance. According to the overload regulation of electric vehicle during charging, the overload interruption control of electric vehicle charging is carried out by using mutual inductance coupling method, and the resonant frequency and mutual inductance coefficient during charging are analyzed. The coils internal resistance and other parameters are controlled by the parameter steady-state regulation method, and the output power can be expressed as follows:

\[
P_o = \frac{M_{\alpha}^2 M_{\beta}^2 L_{\beta}^2 R_0}{M_{\alpha}^2 L_{\beta}^2} \tag{14}
\]

When the distance continues to increase, \( R R_0 L_{\beta}^2 + R R_0 M_{\beta}^2 \gg \omega_0^2 M_{\alpha}^2 L_{\beta}^2 \), the output power can be expressed as:

\[
P_o = \frac{\omega_0^2 M_{\alpha}^2 M_{\beta}^2 M_{\alpha}^2 M_{\beta}^2 R_0}{(R R_0 L_{\beta}^2 + R R_0 M_{\beta}^2)^2} \tag{15}
\]

When the coil distance exceeds the middle distance range, the output power decreases with the increase of the distance. The system output efficiency is similar to this. Therefore, reducing the internal resistance of the resonance coil and increasing mutual inductance can effectively increase the transmission distance. The main way to increase the transmission power is to increase the resonant frequency. Therefore, there is an optimal mutual inductance \( M_{\alpha}^2 \) value to maximize the output power. Make:

\[
\frac{dP_o}{dM_{\alpha}^2} = 0 \tag{16}
\]

The parameter optimization design of electric power transmission system in electric vehicle charging process is carried out. According to the result of parameter optimization, the electric vehicle charging safety early warning test is realized, and the maximum power of transmitting electromagnetic induction coil and electromagnetic coupler is obtained. The mutual inductance value under the transmission target is:

\[
M = \frac{h_i (\omega_0^2 M_{\alpha}^2 M_{\beta}^2 R_0 + \omega_0^2 M_{\alpha}^2 M_{\beta}^2 R_0 + R R_0)}{\omega_0^2 L_{\beta}^2 R_0} \tag{17}
\]

The electromagnetic induction coil and electromagnetic coupler mounted on the charging pile are used to transmit the electric magnetic resonance radio energy with the automobile tire wire to realize the charging of the electric vehicle in motion, and the early warning protection of the charging safety is realized.

### 5. System experiment and performance analysis

The magnetic resonance power transmission mode experiment is designed by Matlab 7, in which the transmitting electromagnetic induction coil and the electromagnetic coupler are composed of two coils.
The distance between the two launch coils is about 2500m for the front and rear wheelbase of the ordinary sedan, and the diameter of the launching coil and the receiving coil simulates the diameter of the automobile tire, about 700mm. The distance between the receiving coil and the transmitting coil varies from 500mm to 1000mm. At the same time, in order to simulate the charging performance of the vehicle, the receiving coil and the transmitting coil have a certain angle. At the same time, the system performance is measured under two different excitation modes, one is phase excitation and the other is different excitation mode. In order to enhance the contrast, the transmission performance of a single coil was also tested. In this paper, the power shunt device is used to supply the two coils, and the inverse device is used to realize the two excitation modes. The mutual inductance values corresponding to the coil distance from 50 cm to 100 cm are shown in Table 1.

Table 1. Parameters of magnetic resonance power transmission system

| Transmitter terminal 1 | Transmitter terminal 2 | Resonance coil 1 | Resonance coil 2 | Receiving terminal |
|------------------------|------------------------|------------------|------------------|-------------------|
| $L_{r1} = 2.1 \mu H$ | $L_{r2} = 2.3 \mu H$ | $L_r = 40.5 \mu H$ | $L_r = 55.6 \mu H$ | $L_i = 2.1 \mu H$ |
| $C_{r1} = 405 pF$ | $C_{r2} = 403 pF$ | $C_r = 12.6 pF$ | $C_r = 14.6 pF$ | $C_i = 356 pF$ |
| $R_{r1} = 45 \Omega$ | $R_{r2} = 44 \Omega$ | $R_r = 2.5 \Omega$ | $R_r = 3.2 \Omega$ | $R_i = 30 \Omega$ |
| $f = 27 MHz$ | $f = 27.06 MHz$ | $f = 27.05 MHz$ | $f = 27.08 MHz$ | $f = 27.8 MHz$ |

For Figures 4 and 5. It is shown from the experimental results that the relationship between the transmission efficiency and the power and distance of the magnetic resonance energy transmission system is not linear, and there is an optimization value. As can be seen from table 2 and figure 5 and 6, the relationship between the transmission efficiency and the power and distance of the magnetic resonance energy transmission system is not linear. The mutual inductance of the output power and efficiency is similar with the reality. Because the theoretical calculation neglects the high frequency radiation loss, and there are certain errors in the winding and measurement of the coil, the experimental result is different from the theoretical value. It can be seen that the mutual inductance between the resonance coils is increased by increasing the resonance frequency of the resonance coil, and the common mutual inductance between the resonant coils is increased. The internal resistance of the vibration coil can improve the efficiency of the radio energy transmission system in magnetic resonance mode. The simulation results show that the proposed method can effectively realize the electric vehicle charging safety warning.
6. Conclusions
In this paper, an electric vehicle charging safety warning model is proposed based on contactless charging design. The electromagnetic induction coil and electromagnetic coupler installed on the charging pile are used to design the electromagnetic coupling induction with the driving electric vehicle tire wire, and the electromagnetic coupling control and charging stability adjustment of the electric vehicle are carried out by using the inductive power transmission technology. According to the overload regulation of electric vehicle during charging, the overload interruption control of electric vehicle charging is carried out by mutual inductance coupling method, and the parameters such as resonance frequency, mutual inductance coefficient and coil internal resistance during charging are analyzed. The parameter steady-state regulation method is used for non-contact charging, and the electric vehicle charging safety early warning control is realized, and the parameter optimization design of electric power transmission system in the process of electric vehicle charging is carried out. According to the parameter optimization result, the electric vehicle charging safety early warning test is realized. The process of parameters changing process of electric vehicle charging safety warning is simulated. The experimental analysis shows that the method in this paper can effectively realize the electric vehicle charging safety warning, and the charging safety is guaranteed.

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