Electric vehicle wireless charging system transmission model based on two-port network

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Abstract: In recent years, the use of electric vehicles has been promoted all over the world in order to reduce the dependence on non-renewable resources such as oil. However, the problems of slow charging and few charging piles of electric vehicles have always troubled the users. In order to solve this problem, this paper investigates the wireless charging problem of electric vehicles. This paper focuses on the relationship between the transmission efficiency of the wireless charging system and the transmitting frequency and matching impedance of the non-vehicle part. First, this paper converts the equivalent circuit of wireless charging system into a two-port network diagram, establishes the relationship between the output signals, and performs simulation calculations for ten sets of experiments. Then, considering the different chassis heights of different models, the relationship between coil distance and mutual inductance coefficient is focused on. Finally, a single-objective optimization model with the maximization of transmission efficiency as the objective function is established considering the economy, and the model is solved by multiverse optimization algorithm, and the transmission efficiency is successfully improved to 93.10%.

1. Introduction
As the country’s awareness of protecting the environment and saving resources has been strengthened, electric vehicles have been vigorously promoted. Electric vehicles generally have problems such as insufficient range, mismatch between the actual range and the nominal range and fast battery decay. If electric vehicle owners find that the power is insufficient and there are no charging piles around, it will definitely reduce the experience of the owners. According to the China Association of Automobile Manufacturers 2021 data, as shown in Figure 1, the production and sales volume are around 1 million units in recent years, and both are steadily increasing. The era of pure electric vehicles has come, and if the charging problem of pure electric vehicles can be solved, their production and sales will surely be further increased. Therefore, it is necessary to develop wireless charging for electric vehicles.
At present, the research on wireless charging of electric vehicles mainly focuses on localization, foreign object detection and charging efficiency. Ying Sun [1] proposed a method to determine the area of foreign objects based on temperature rise, and also established the loss model and temperature rise model of foreign objects to exclude the area of foreign objects with safety hazards. Zeqian Cheng [2] proposed a localization and foreign object detection method based on feature learning of magnetic field data, which achieves accurate localization and foreign object detection while also reducing the cost and manufacturing difficulty of the system. Shihui Xu [3] proposed an optimized proximity precise positioning method, which improves the positioning accuracy of the charging system and can still maintain high positioning accuracy when the body has a certain angle of deflection. Mingyang Deng [4] proposed an electric vehicle charging method based on interpolation coupling technology, which enables the charging coil to charge within the effective charging distance. Xiaoshuai Dong [5] proposed a novel phase-locking method to realize secondary active rectifier control and zero-voltage switching operation of primary and secondary converters. Yong Tian [6] proposed a parameter optimization design method of LCC-S topology based on weighted average efficiency, which enables the topology parameters to better adapt to the operating characteristics of dynamic wireless charging systems and improves the overall efficiency of the charging system. Wenjie Zhang [7] established an analytical model of mutual inductance in the case of polarization coupler misalignment and studied the mutual inductance characteristics of polarization coupler in the case of misalignment. Songcen Wang [8] proposed an optimal design method for the number of coil layers and analyzed the positive effect of increasing the number of coil layers on improving the coupling coefficient. Throughout the existing studies, there is a lack of research on the effects of distance and offset on transmission efficiency.

2. Parameter setting
The parameters of the wireless charging system set up in this paper are shown in Table 1.

| Table 1. Launcher parameters. | Value |
|-------------------------------|-------|
| Transmitter resistance(Ω)    | 1.55  |
| Receiver resistance(Ω)       | 432.24|
| Emission frequency(kHz)      | 30    |
| Coil radius(cm)              | 35    |
3. Two-port network modeling and simulation calculation

3.1 Establishment of two-port network model

The two-port network model uses the port parameters to represent the whole or part of the circuit without considering the specific structure inside the network, which can simplify the research work of wireless charging system. In this paper, the equivalent circuit diagram of the wireless charging system for electric vehicles is equated to a two-port network diagram, as shown in Figure 2:

![Figure2. T-shaped two-port network](image)

where $L_m$ denotes the equivalent excitation reactance, i.e:

$$L_m = k_{12}L_4$$

In this paper, it is assumed that the coupling coefficient of energy transmission loss between the power supply and the transmitting coil, the receiving coil and the load, and the two RLC circuits is 1. To study the wireless charging transmission between the transmitting and receiving coils, the two LRC circuits can be considered as a linear passive two-port network. The reference direction of their currents is determined to flow into the two-port network, and the relationship between the output signals is established through the S-parameters, whose transmission equation can be expressed as

$$
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\begin{bmatrix}
V_2 \\
-I_2
\end{bmatrix},
$$

where $S$ denotes the scattering matrix and each parameter in the matrix denotes the scattering parameter.

When Port 1 is the power input and Port 2 is the power output, the input power consists of two parts: $|S_{11}|^2$ indicates the power reflected by the system, and $|S_{21}|^2$ indicates the power transmitted by the system to Port 2 and absorbed by the load. When Port 1 is the power output and Port 2 is the power input, the input power also consists of two parts: $|S_{22}|^2$ indicates the power reflected by the system and $|S_{12}|^2$ indicates the power transmitted by the system to Port 1 and absorbed by the load.

By analyzing the equivalent circuit diagram, the two-port network can be considered to have a symmetric structure. Define the normalized angular frequency coefficients as:

$$w_n = \frac{w}{w_0},$$

the ratio of the actual operating angular frequency to the natural harmonic angular frequency, and take the natural resonant angular frequency $w_0 = 1/\sqrt{L_4C_1}$, where the S parameter can be expressed as:
where $Q_1$ denotes the quality factor. When the system resonates, the two-port network shows purely resistive characteristics, so the resonant frequency can be deduced from the transfer conductance parameter $S_{12}$ satisfying:

$$k_{12}^2 - \left(1 - \frac{1}{w_n^2} - \frac{j}{Q_1}\right)^2 = 0$$

The gain characteristics of the output response to the input excitation signal can be reflected by the voltage transfer function $K_V$ and the current transfer function $K_I$, i.e.

$$K_V = \frac{V_2}{V_1} = \frac{V_2}{S_{11}V_2 + S_{12}(-I_2)} = \frac{1}{S_{11} + S_{12}/R_L},$$

$$K_I = \frac{I_2}{I_1} = \frac{I_2}{S_{21}V_2 + S_{22}(-I_2)} = \frac{1}{S_{21}R_L + S_{22}}.$$
where $R_1$ is the transmitter resistance and its value is a constant. At this point, the two-port network model based on the transmitting frequency $f$, matching impedance $L_1$ and radio energy transmission efficiency $\eta$ is established.

4. **Distance and mutual relationship model**

In this paper, considering that the arbitrary distance between the on-board part of the wireless charging and the ground will lead to the change of the mutual inductance coefficient between the two coils. Therefore, the relationship between the mutual inductance coefficient and the distance between the two coils is found on the basis of model I.

4.1 **Model established**

4.1.1 **Neumann model**

The two coils are in a coaxial and parallel state, the coils are of equal radius $r$. Its structure is shown in Figure 3.

As shown in figure 4, two coils are in a co-axial parallel position, and the centers of the two coils are $(0,0,Z_1)$ and $(0,0,Z_2)$ respectively. The axial distance between the coils is $h$. The currents flowing through the two coils are $I_1$ and $I_2$, and the coordinates of the two points $P$ and $Q$ are $P(r_1, \theta_1, Z_1)$ and $Q(r_2, \phi_2, Z_2)$, respectively:

$$d = \left( r^2 (\cos \theta - \cos \phi)^2 + r^2 (\sin \theta - \sin \phi)^2 + h^2 \right)^{\frac{1}{2}}$$

From the Neumann’s Formula, we have

$$M = \frac{u_0}{4\pi} \iint \frac{dl_1 dl_2}{d}$$

and

$$\begin{cases} dl_1 = r (\cos \theta - \sin \theta) d\theta \\ dl_2 = r (\cos \phi - \sin \phi) d\phi \end{cases}$$

Combining the above three equations, we get

$$M = \frac{u_0}{4\pi} \int_0^{2\pi} d\theta \int_0^{2\pi} \frac{r^2 \cos(\theta - \phi) d\phi}{\sqrt{\left( r^2 (\cos \theta - \cos \phi)^2 + r^2 (\sin \theta - \sin \phi)^2 + h^2 \right)}}$$
5. Maximize charging efficiency model

In this paper, considering the economy of wireless charging, we focus on improving the transmission efficiency by adjusting the transmitting frequency and matching impedance in order to avoid the energy loss.

5.1 Target function

It is known that changing the transmitting frequency and matching impedance can improve the transmission efficiency. In this paper, the first experiment in Table 3 is used as the basis to adjust the appropriate transmit frequency (F) and matching impedance (L₁) to make the transmission efficiency reach the maximum. Therefore, the objective function can be established from model 1.

\[
\text{max } \eta = \frac{4L_1\pi^2 f^2 M_{12}^2}{(\sqrt{4L_1\pi^2 f^2 + R_i^2})^2}
\]

5.2 Restrictions

Considering that the matching impedance and the regulation of the emission frequency must be within a certain range, by reviewing the information there are.

The transmitting coil inductance L₁ is adjusted in the range of 100-200 (uH), i.e.

\[100 \leq L_1 \leq 200\]

The transmitting frequency F is adjusted in the range of 5-100 (kHz), i.e.

\[5 \leq f \leq 100\]

5.3 Model solve

5.3.1 Multi-Verse Optimizer algorithm

In order to reduce the time complexity of the solution, the Multi-Verse Optimizer algorithm is chosen for solving this paper.

Multi-Verse Optimizer (MVO) is a new intelligent optimization algorithm proposed by Seyedali Mirjalili et al. in 2016. It is based on the simulation of the transfer of matter in the universe from a white hole to a black hole through a wormhole. In the MVO algorithm, the main performance parameters are wormhole existence probability and wormhole travel distance rate, which are relatively few parameters and show relatively superior performance in low-dimensional numerical experiments. Combining with the question, this problem only has two values of emission frequency (F) and matching impedance (L₁), which belong to low-latitude numerical experiments, so the multiverse optimization algorithm is chosen.

5.3.2 Model solving result and analysis

Ompiled by matlab software, the results are shown with Table 2.

| Table2. Transmission efficiency table. | Value |
|---------------------------------------|-------|
| Emission frequency F                  | 98.93 |
| Matching impedance L₁                 | 200   |
| Transmission efficiency               | 93.10%|

| Table3. Experimental parameters - efficiency table | Value |
|-----------------------------------------------|-------|
| Emission frequency F                          | 30    |
| Matching impedance L₁                         | 162.21|
| Transmission efficiency                       | 77.26%|
Table 2 has that the transmission efficiency reaches the maximum of 93.10% when the transmitting frequency is 98.93 KHz and the matching impedance L₁ is 200uH. Compared with the 77.26% transmission efficiency of the experiments in Table 3 (emission efficiency of 30 KHz and matching impedance L₁ of 162.21), the transmission efficiency is improved by 15.84%, indicating that the effect of optimizing the emission frequency (F) and matching impedance (L₁) is significant, which proves the validity and robustness of the model.

In order to verify the accuracy of the results, the results are analyzed by making graphs below. Compiled using matlab, the images of the transmission efficiency as a function of transmit frequency (F) and matching impedance (L₁) were obtained in three dimensions, as shown in Figure 4.

![Figure 4. Output efficiency function graph](image)

As can be seen from figure 4, the optimal solution also appears roughly at the limit values of the transmitting frequency (F) and the matching impedance (L₁), which is in high agreement with the results of the multiverse optimization algorithm, proving the effectiveness of the algorithm.

6. Conclusions
By building a two-port network model, a Neumann model and a single-objective model that maximizes transmission efficiency, the following conclusions can be drawn.

(1) The maximum transmission efficiency of the electric vehicle wireless charging system is only related to the transmitting frequency f and matching impedance L₁ by the two-port network model analysis. Meanwhile, as the distance increases, the mutual inductance coefficient decreases, leading to a decrease in transmission efficiency.

(2) The relationship between the mutual inductance coefficient and its corresponding distance between the two coils for wireless charging of electric vehicles is obtained through the analysis of the Neumann model.

(3) By modeling the maximized output efficiency, the experimental transmission efficiency can be increased from 77.26% to 93.10% under the constraints of this paper.

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