Demand Analysis of Key Parameter Offsets for Operating Frequency Bands in Wireless Power Transmission System

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Abstract. With the mass production and application of wireless charging system for electric vehicles (EV), and in the process of production and use of the device, it is inevitable that there will be offsets between the actual parameter and the theoretical parameter. This will lead to the deviation of the intrinsic frequency from the design value. Finally, the transmission performance decreases and the actual design requirements are not met. Therefore, based on SS resonance compensation topology and the key parameters in SAE standard, this paper analyzes the self-inductance allowable values at different power levels and frequency points. In addition, the range of allowable operating frequency bands under the inductance offset is derived, which plays a certain guiding role in the production of key devices and practical engineering applications.

1. Introduction

Car is an indispensable means of transportation. However, the development of traditional vehicles has brought the shortage of fossil energy and the deterioration of the environment. In order to save energy, reduce emissions and develop low-carbon economy, it is necessary to promote the development of new energy vehicles. Electric vehicle wireless charging system with its unique advantages has become the trend of new energy vehicle market, and increasingly towards industrialization and commercialization [1]-[2].

However, when the WPT is used in the EV charging widely, related devices will be produced and applied on a large scale. It is inevitable that there will be errors between the actual parameter value of device and the theoretical parameter. This means that the intrinsic frequency of the system will deviate from the design value. In addition, due to the increase of working time, the device will have a certain temperature rise in the actual application process. As a result, the electrical parameters of the device drift. The intrinsic frequency of the system is also affected, which affects the normal operation of the wireless charging system to some extent.

Reference [3] and [4] developed an eddy current loss model applied in undersea WPT system. By analyzing the eddy current loss under different conditions, it is found that the optimal operating...
frequency should be larger than the resonant frequency, and the optimal operating frequency is obtained based on the analysis model. Reference [5] analyzed the influence of mutual inductance and coil shape on frequency, and propose a maximum power-efficiency tracking method by estimating the system’s coupling coefficient. Based on the particle swarm optimization (PSO) algorithm, reference [6] proposed an adaptive frequency-tracking method to solve the problem of sharp power drop caused by frequency splitting in WPT. For one or multiple receivers in WPT system, reference [7] proposed a method for ensuring the optimized transfer efficiency and the output power by configuring the operating frequency. It can be seen that the current literature mainly studies the optimal frequency point of submarine WPT system and the frequency regulation method to find the maximum efficiency/power. It is based on the theoretical parameter values, but it does not consider the actual situation of offset resonant frequency caused by device parameter deviation and temperature rise. Therefore, through theoretical and simulation analysis, the range of allowable operating frequency bands is obtained in this paper, which has theoretical guiding significance for device manufacturers and electric vehicle manufacturers.

According to the influence of parameter deviations of inductance and capacitance of resonant compensation topology on frequency band range in WPT system, this paper analyzes the energy efficiency characteristics of system based on SS topology. Taking the deviation of inductance parameter as an example, the energy efficiency characteristics of the system under the condition of frequency detuning were analyzed. Then the allowable deviation range of inductance parameters is obtained. Finally, based on the above analysis, the frequency band requirements at different power levels and different frequency points are obtained.

2. Theoretical analysis

As the most basic compensation topology, SS resonance compensation topology has been widely used. Therefore, this paper mainly analyzes the influence of key parameters (inductance/capacitance) changes on energy efficiency characteristics for SS type resonant compensation topology in WPT system. The analysis above has certain representative significance. The mutual inductance model in SS resonant compensation network is shown in Fig. 1.

![Figure 1. Inductance model in SS resonant compensation network.](image)

The meanings of the symbols in Fig. 1 are tabulated in Table 1.

| Symbol | Meaning                                      |
|--------|---------------------------------------------|
| $U_1$ (V) | Input voltage of transmitter coil          |
| $C_1$ ($\mu$F) | Resonant capacitance of transmitting coil |
| $L_1$ ($\mu$H) | Inductance of transmitting coil            |
| $C_2$ ($\mu$F) | Resonant capacitance of the receiving coil |
| $L_2$ ($\mu$H) | Inductance of the receiving coil            |
| $R_L$ ($\Omega$) | Load equivalent resistance                 |
| $R_1$ ($\Omega$) | Equivalent resistance transmitting coil     |
| $R_2$ ($\Omega$) | Equivalent resistance receiving coil        |
By writing the KVL equation in the equivalent model in Fig. 1, it can be obtained as

\[
\begin{align*}
U_1 &= Z_{11}I_1 - j\omega M I_2 \\
J\omega M I_1 &= Z_{22}I_2
\end{align*}
\]  

(1)

Where

\[
\begin{align*}
Z_{11} &= \frac{1}{J\omega C_1} + j\omega L_1 + R_1 \\
Z_{22} &= \frac{1}{J\omega C_2} + j\omega L_2 + R_2 + R_L
\end{align*}
\]  

(2)

\[
\omega = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}
\]  

(3)

According to (1) - (3), the current can be expressed by

\[
\begin{align*}
I_1 &= \frac{U_1}{Z_{11} + (J\omega M)^2} \\
I_2 &= \frac{J\omega M U_1}{Z_{11}Z_{22} + (J\omega M)^2}
\end{align*}
\]  

(4)

According to (4) and \(P_2 = I_2^2 \times R_L\), the output power of the system can be calculated

\[
P_2 = \frac{J\omega M U_1}{Z_{11}Z_{22} + (J\omega M)^2} I_2^2 \times R_L
\]  

(5)

When the system operates in a frequency detuned state, some of the energy transferred from the power supply is converted into reactive power. Reactive power does not lose energy, but it degrades the transmission performance of the whole system. Therefore, reactive power should also be considered when evaluating the transmission performance of the system. The parameter \(\beta\) can be used to represent the transmission performance of the system. It is shown in (6), where the input energy is calculated in terms of apparent power \(S_1\), defined by \(S_1 = U_1 \times I_1\).

\[
\beta = \frac{P_2}{S_1} = \frac{(J\omega M)^2 R_L}{Z_{11}Z_{22} + (J\omega M)^2 Z_{22}}
\]  

(6)

From formula (6), it can be seen that when the inductance value of resonance compensation topology is offset, the imaginary part of \(Z_{11}\) and \(Z_{22}\) will increase. It will lead to an increase in the denominator of the formula and a decrease in the energy transfer performance \(\beta\). Therefore, in the next section, the effect of inductance changes on energy efficiency characteristics will be analyzed. Under the conditions of allowable deviation range of inductance, the upper and lower limits of frequency band can be obtained.

3. Demand analysis of frequency band

According to SAE standard [8], the power level of electric vehicles can be divided into 3.7kW, 7.7kW and 11.1kW. Similarly, coil types are mainly divided into circular coil and DD coil. Considering that
circular coil has a weaker external radiation magnetic field than DD coil and has less influence on the coexistence between systems [9]. Therefore, the self-induction parameters of circular coil in SAE standard were selected for analysis.

Considering that the rated operating frequency of wireless charging system for EV is 85 kHz in the SAE standard. In addition, a small number of enterprises or research institutions recommend the use of 20 kHz or 40-60 kHz frequency due to balance the performance and cost of WPT system. Therefore, this paper takes the power level of 11.1kw and the working frequency of 85kHz as an example to analyze the allowable deviation range of inductance and obtain the upper and lower limits of frequency bands under different power levels (3.7kw, 7.7kw and 11.1kw) and frequency (85kHz, 50kHz and 20kHz). According to the circular coil parameters, power level, operating frequency and transmission performance in SAE, the system parameters with the output power about 11.1kw and transmission performance about 85% at rated operating frequency of 85kHz are determined. The parameter values are shown in Table 2.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $L_1$    | 38μH  | $L_2$    | 38μH  |
| $C_1$    | 0.0923μF | $C_2$ | 0.0923μF |
| $R_1$    | 0.41Ω | $R_2$ | 0.41Ω |
| $R_L$    | 5.1Ω  | $M$    | 9.5μH |
| $f$      | 85kHz | $U_1$ | 258V |

As is shown in Fig. 2, Output power and transmission performance of the WPT system changes with inductance parameters $L_2, L_2$ has been verified with a power level of 11.1kW and a transmission performance of 85%. The test case are performed by using MATLAB.

![Figure 2. System power and transmission performance changes with inductance.](image)

Now, the allowable offset range of output power is set to be ±5%, and the transmission performance of the system is set to be at least 80%. According to the requirements of power and transmission performance, the self-induced allowable deviation region of the primary and secondary coil is made respectively. Meanwhile, the allowable deviation region that meets both requirements is determined. All of the above task cases are shown in Fig. 3. In Fig. 3(c), the black rectangular region is the optimal deviation range that meets the both requirements of power and transmission performance. Outside the rectangular box, it doesn’t.
According to Fig. 3, when the power level is 11.1kw and the operating frequency is 85kHz, the self-induction allowable deviation range of the primary and secondary coil is 0.935~1.065 and 0.925~1.035. When the system parameters are offset, the actual resonant frequency point is

$$\omega = \frac{1}{\sqrt{(L + \Delta L)C}}$$  \hspace{1cm} (7)

Where, $\Delta L$ is the self-induced drift due to production, temperature rise and etc. According to (7), the allowable frequency range is 83.735kHz ~86.064kHz.

Using a similar method, the frequency band limits and the allowable deviation range of self-inductance can be obtained at different power levels, different frequency points. All results are tabulated in Table 3.

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**Figure 3.** Self-induced allowable deviation region.
As can be seen from Table 3, at the same power level, the allowable deviation range of self-inductive L1 decreases gradually with the increase of frequency, while the allowable deviation range of self-inductive L2 increases gradually with the increase of frequency. In addition, the allowable frequency band of normal operation also increases with the increase of frequency. When the operating frequency is 85 kHz, the allowable frequency band of the system is basically kept at 2500Hz. When the frequency is 50 kHz, the frequency band basically remains at 1250Hz. When the frequency is 20 kHz, the frequency band remains at 400Hz. This means that the allowable frequency band of the system does not change with the change of the system power level. However, considering that the higher the power level is, the larger the current flowing through the coil will be, and the range of self-induced drift with temperature rise will also increase accordingly. Therefore, at the same operating frequency, the lower the power level, the smaller the influence on the system operation, and vice versa.

Furthermore, in order to meet the application requirements at different power levels and to guide the manufacturer's production, the intersection of the self-inductive allowable ranges mentioned above can be taken. Finally, the allowable deviation range of primary and secondary self-induction is $0.975L_1~1.02L_1$ and $0.975L_2~1.02L_2$. For the range of working frequency band, the intersection of the above frequency band range can be taken, and the upper and lower limits of the allowable frequency band are 84.091–86.064 kHz, 49.372–50.622 kHz and 19.805–20.202 kHz, respectively, when the rated frequency is 85 kHz, 50 kHz and 20 kHz.

### 4. Conclusion
Based on SS resonance compensation topology in WPT system, this paper takes the self-inductive parameter offset in the topology as an example to analyze the self-inductive allowable range(The allowable range of the primary and secondary coil of self-inductance is $0.975L_1~1.02L_1$ and $0.975L_2~1.02L_2$, respectively) and frequency band allowable range(The frequency bands of 85kHz, 50kHz and 20kHz were 84.091–86.064kHz, 49.372–50.622kHz and 19.805–20.202kHz, respectively) at different power levels and frequency points. It is found that the allowable frequency band of the system does not change with the change of the system power level. However, when considering external factors such as temperature rise, the lower the power level, the smaller the influence on the system.

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