Transmission characteristics analysis of an MCR-WPT system with SP resonance structure based on harmonic current influence

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**Abstract**

Aiming at harmonic current influence on transmission characteristics in a magnetically coupled resonance wireless power transfer (MCR-WPT) system with a series-parallel (SP) structure, this paper develops a transmission characteristics expression method and a WPT system with a power factor correction (PFC) structure. Using the mutual inductance theory with harmonic current influence, the equivalent circuit model of the system was established and the formula for the transmission characteristics was obtained. An input current harmonic suppression method was developed, and a dual-boost PFC structure was designed on the transmitter side of the system to reduce the influence of the input current harmonic. According to the determined parameters, simulation analysis on transmission characteristics comparison between different systems was conducted. The experiment platform was built. The results of load experiment, frequency experiment and waveform analysis experiment show that the harmonic suppression and transmission characteristics were improved.

**Keywords:** wireless power transfer, transmission characteristics, harmonic analysis, harmonic distortion rate, power factor correction

**Classification:** Energy harvesting devices, circuits and modules

1. **Introduction**

Magnetically coupled resonant wireless power transfer (MCR-WPT) is a kind of transmission mode that transfers electric energy from the power supply to the load through non-electric direct contact. Compared with the wired power transmission mode, it avoids traditional problems such as wire friction and aging [1, 2, 3]. Additionally, WPT is safe and convenient for electric vehicles [4, 5, 6, 7], electronic equipment [8, 9, 10], and biomedicines [11, 12, 13].

The transmission characteristics of WPT systems have been studied extensively in recent years [14, 15, 16, 17]. Huang et al. [18] analyzed that the optimal efficiency of an MCR-WPT system with SP resonance structure coincides with the maximum power when the frequency is changed. However, the power supply used in the experiment was 10 V, and the influence of harmonics on its transmission characteristics was neglected. Gao [19] proposed a mathematical model and its parameter design method of compensation network, which can reduce the instantaneous value of the higher harmonic current through the power tube. However, the paper did not analyze the influence of the input harmonic current on the system transmission characteristics. For an MCR-WPT system with different resonant structures, the transmission characteristics under the fundamental voltage are only discussed in some papers [20, 21, 22, 23]. Because the square wave is changed by the high-frequency inverter as the input voltage wave, harmonic current can not only pollute the public power grid, but also affect the transmission characteristics. Therefore, research on the influence and its suppression method of the harmonic current on transmission characteristics in an MCR-WPT system has important significance.

The remainder of this paper is organized as follows. Using the mutual inductance theory with harmonic current influence, the equivalent circuit model of the system was established in Section 2 and the formula for the transmission characteristics was obtained. The harmonic analysis of system input current is presented in Section 3. Then, according to the determined parameters, the harmonic suppression design was developed and simulation analysis on transmission characteristics comparison between different systems was conducted in Section 4. In Section 5, the experimental platform is set up and related experiments are conducted to analyze the system transmission characteristics. Section 6 presents the conclusions.

2. **The equivalent circuit model**

The MCR-WPT system with SP resonance structure is shown in Fig. 1.

![Fig. 1. Series-parallel wireless power transfer system.](image)

The DC voltage input is \(U_{in}\), and the inductances of the transmitting coil and receiving coil are \(L_p\) and \(L_r\), respectively. The mutual inductance of the two coils is \(M\). The compensation capacitors of the transmitting side and the receiving side are \(C_p\) and \(C_r\), respectively. The filtering capacitor is \(C\). The load is \(R_L\).
In general, the fundamental component of AC output voltage after full-bridge inverter $U$ is only considered [20, 21, 22], and the $U$ is

$$U = \frac{2\sqrt{2}}{\pi} U_{in}$$  \hspace{1cm} (1)

In practical applications, the harmonic component of the system input voltage cannot be ignored, thus, $U$ should be:

$$U = \frac{4U_{in}}{\pi} \left( \sin 60t + \frac{1}{3} \sin 30t + \frac{1}{5} \sin 150t + \ldots \right)$$  \hspace{1cm} (2)

In order to simplify the analysis, this paper only considers the 3rd and 5th harmonics. In addition, the rectifier bridge on the receiving side of the system can be equivalent to resistance $R_{eq}$ [24]. The fundamental wave, 3rd harmonic voltage and 5th harmonic voltages are equal to:

$$R_{eq} = \frac{8}{(\pi f_t^2)} R_L \quad (n = 1, 3, 5)$$  \hspace{1cm} (3)

Fig. 2 shows the equivalent circuit under these conditions is in $R_p$ and $R_s$ are the resistances of transmitting coil and receiving coil, respectively.

![Fig. 2. The equivalent circuit.](image)

With the angular frequency $\omega$ of the system, the impedance $Z_p$ of the transmitting side and the impedance $Z_s$ of the receiving side are determined by:

$$Z_p = R_p(1 + jQ_p)$$  \hspace{1cm} (4)

$$Z_s = R_s \left( 1 + jQ_s \frac{\omega}{\omega_0} + \frac{1}{\omega Q_s \omega_0} + \frac{1}{\omega Q_s \omega_0} \right)$$  \hspace{1cm} (5)

where $Q_p$ and $Q_s$ are the quality factors of the transmitting coil and the receiving coil, respectively. $Q_p = \omega_0 L_p / R_p$, $Q_s = \omega_0 L_s / R_s - \omega_0 C_p R_p$, $\omega_0 C_p R_p$, $\omega_0 C_p R_s$; $\omega_0$ is the generalized detuning factor $\xi = Q \left( \omega_0 / \omega_0 - \frac{1}{\omega_0} \right)$.

Since the coil internal resistance $R_s \ll$ equivalent resistance $R_{eq}$, Eq. (6) can be rewritten as:

$$Z_s \approx R_s \left[ 1 + jQ_s \left( \frac{\alpha_0}{\omega_0} - \frac{\alpha_0}{\omega_0} \right) \right] = R_s(1 + j\xi)$$  \hspace{1cm} (6)

The reflected impedance from the receiving side to the transmitting side can be defined as $Z_r$, which is equal to:

$$Z_r = \frac{\alpha_0^2 M^2}{Z_s}$$  \hspace{1cm} (7)

Then, the fundamental wave component $I_{p1}$, the 3rd harmonic component, and the 5th harmonic component of the system input current of the system input current are equal to, respectively:

$$I_{p1} = \frac{U_n}{Z_n + Z_s} = \frac{U_n}{R_p(1 + j\xi_p) + \frac{\alpha_0^2 M^2}{R_s(1 + j\xi_s)}} \quad (n = 1, 3, 5)$$  \hspace{1cm} (8)

$$I_p = \sqrt{I_{p1}^2 + I_{p3}^2 + I_{p5}^2}$$  \hspace{1cm} (9)

where $U_1$, $U_3$, and $U_5$ are the input AC voltage effective values of the fundamental component, the 3rd harmonic component, and the 5th harmonic component; $\xi_1$, $\xi_3$, and $\xi_5$ are the generalized detuning factors of the fundamental wave, 3rd harmonic, and 5th harmonic, respectively.

Therefore, with the 3rd and the 5th harmonic components, the total harmonic distortion (THD) of the system input current is

$$THD = \frac{\sqrt{I_{p1}^2 + I_{p3}^2 + I_{p5}^2}}{I_{p1}}$$  \hspace{1cm} (10)

Similarly, the output currents of the system with fundamental wave, 3rd harmonic, and 5th harmonic are, respectively:

$$I_{Ln} = \frac{j\alpha_0 M I_n}{(\alpha_0 C_s R_{eq} + 1)Z_{in}} \quad (n = 1, 3, 5)$$  \hspace{1cm} (11)

$$I_L = \sqrt{I_{L1}^2 + I_{L3}^2 + I_{L5}^2}$$  \hspace{1cm} (12)

Refer to Eqs. (9) and (13), output power and transmission efficiency only with fundamental wave are equal to, respectively,

$$P_{out} = \frac{I_{L1}^2 R_{eq}}{\eta_1}$$  \hspace{1cm} (13)

Then the output power and transmission efficiency of the system with harmonics are, respectively,

$$P_{out} = \frac{I_{L1}^2 R_{eq}}{\eta_1}$$  \hspace{1cm} (14)

$$P_{out} = \frac{I_{L1}^2 R_{eq}}{\eta_1} \quad \frac{I_{L1}^2 R_{eq}}{\eta_1} - \frac{I_{L1}^2 R_{eq}}{\eta_1}$$  \hspace{1cm} (15)

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_{L1}^2 R_{eq}}{U_{in} I_{p1}}$$  \hspace{1cm} (16)

3. Harmonic analysis of system input current

By Eqs. (8), the input harmonic current of the system is related to quality factor $Q$ and mutual inductance $M$ of the coil. According to the distance between two coils in an electrical motor, the coupling coefficient $k$ between 0.1 and 0.3 is introduced [25]. In practice and according to the standard SAE J2954, the system output power is required as 3.2 kw with 85 kHz, and the system parameters are shown in Table I.

The harmonic distortion rate THD of the system input current with different $Q$ and $k$ is shown in Fig. 3. THD increases with the increase of $Q_p$ and $Q_s$ when the $k$ is

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $Q_p$ | 5–160 | $f$ | 85 kHz |
| $Q_s$ | 5–160 | $k$ | 0.1–0.3 |
constant. When $k = 0.3$, THD reaches the minimum values of 3.74% as $Q_p$ is equal to 0 and $Q_s$ is equal to 8.42. THD reaches the maximum values of 4.56% as $Q_p$ and $Q_s$ are both equal to 160. Similarly, the range of THD at $k = 0.1$ and $k = 0.2$ can also be obtained. In addition, THD decreases with the increase of $k$. When $Q_p$ and $Q_s$ of the coils are both equal to 5, THD reaches the minimum values of 3.79%, 3.76%, and 3.74% as $k$ is equal to 0.1, 0.2, and 0.3, respectively; when $Q_p$ and $Q_s$ of the coils are both equal to 160, THD reaches the maximum value of 34.86%, 5.88%, and 4.56% when $k$ is equal to 0.1, 0.2, and 0.3, respectively. So, the smaller $Q_p$ and $Q_s$ are, the less influence the coupling coefficient $k$ has on the THD of the system input current.

4. Suppression method and design for harmonic current

Aiming at reducing the THD and increasing the transmission characteristics, in this paper, the traditional converter with diode and full-bridge rectifier is replaced by a dual-boost power factor correction (PFC) structure designed on the transmitter side according to the output power. The dual-boost PFC structure consists of two basic boost single circuits in parallel, and a staggered conduction method is adopted [26]. The inductance ripple current of each branch is interleaved to reduce the harmonic influence of input current on transmission characteristics. With a higher output power of 3.2 kw, the control strategy is designed as continuous conduction mode (CCM) with double closed loop control type [27].

The main circuit of PFC and its control circuit are shown in Fig. 4. The signals of the outer voltage loop are input voltage and output voltage, and the signal of the inner current loop is switch current. The circuit can realize the tracking function of peak current and voltage and keep the input voltage and the input current in the same phase to make the MCR-WPT system in the resonant state. UCC28070 is adopted in the control circuit, which can provide two interleaved pulse signals to drive the two switches to reduce the ripple of input current and output current [28]. The system simulation parameters are shown in Table II.

The system simulation analysis with traditional AC-AC converter and AC-AC converter with PFC is shown in Fig. 5(a) and Fig. 5(b), respectively.

The waveform analysis of input voltage (the red curve) and input current (the black curve) at the power supply side of the system are shown in Fig. 6. In a traditional system, the system input current has a peak at 110 A and its starting current reaches 913 A. In addition, different phases in the voltage and current on the power supply side result in a lower power factor. With the designed high-frequency converter with PFC, the input current of the system is a sinusoidal wave and maintains the same phase as that of the input voltage to obtain a high power factor and better transmission characteristics.

The input currents of the system with a traditional AC-AC converter and the PFC high-frequency converter were analyzed using the fast fourier transform (FFT) method in Powergui [29], as shown in Fig. 7. The fundamental input currents and THD of the system are 12.1 A, 11.14 A and 297.82%, 6.33%, respectively. The system input current and THD in the designed system are reduced by 0.96 A and

![Fig. 3. The relationship between THD, $Q_p$ and $Q_s$ and $k$.](image)

![Fig. 4. Interleaved boost PFC main circuit and control circuit](image)

| Table II. System simulation parameters |
|---------------------------------------|
| Parameter | Value | Parameter | Value | Parameter | Value |
| $L_p$ | 156 µH | $C_2$ | 1714 µF | $U_{in}$ | 220 V |
| $L_s$ | 156 µH | $f$ | 85 kHz | $R_L$ | 50 Ω |
| $C_p$ | 22.47 nF | $k$ | 0.3 | $C_s$ | 22.47 nF |
| $L_2$ | 87.28 µH | $L_1$ | 87.28 µH |

![Fig. 5. The system simulation circuit](image)
291.49%, respectively, which is beneficial to an improvement of the transmission characteristics.

5. Experimental design and experimental analysis

The experimental platform of the SP-WPT system is shown in Fig. 8. The MOSFET (APTM50HM75STG) was used in the inverter circuit. The rectification devices (H3P150FYB and DSEI60-06A) were used on the transmitting side and the receiving side, respectively.

According to Fig. 8, in order to acquire the better transmission characteristics of the system, \( Q_p \) and \( Q_s \) are both chosen as 151.48 in the experiment. The system parameters are shown in Table III.

5.1 Load experiment

The load characteristics experiment was conducted to analyze the system transmission characteristics when the load changes. The output waveform and the input waveform of the system with traditional AC-AC converter and the PFC high-frequency converter are measured by an oscilloscope (TBS1202B) with \( R_L = 75 \Omega \), \( R_L = 50 \Omega \), and \( R_L = 25 \Omega \), as shown in Figs. 9–11, respectively. And the output power and the transmission efficiency of the system with different load are calculated, as shown in Fig. 12.

In Figs. 9–11, there is a phase difference between the output voltage and the current in the traditional system, but the phase of the output voltage remains the same with the phase of the output current and THD is reduced in the designed system with the resonant state. In Fig. 12, the output power and the transmission efficiency of the system can achieve 3 kW and above 80% with \( R_L = 50 \Omega \). Compared with the traditional system, the designed system is good for the electromagnetic energy exchange, improves the transmission characteristics to a certain extent and reduces the large amount of the inverter current on the transmitting side.

![Fig. 6. Waveforms of input voltage and current on the power supply side of the system.](image)

![Fig. 7. Harmonic analysis of system input current.](image)

![Fig. 8. SP-WPT system experiment platform.](image)

![Fig. 9. Experimental waveform under load \( R_L = 75 \Omega \).](image)

![Fig. 10. Experimental waveform under load \( R_L = 50 \Omega \).](image)

![Fig. 11. Experimental waveform under load \( R_L = 25 \Omega \).](image)

![Fig. 12. Comparison of system transmission characteristics of two converters with load changes.](image)

| Parameter | Value      | Parameter | Value      | Parameter | Value      |
|-----------|------------|-----------|------------|-----------|------------|
| \( L_p \) | 156 \( \mu \)H | \( Q_p \) | 151.48     | \( U_{in} \) | 220 V      |
| \( L_s \) | 156 \( \mu \)H | \( Q_s \) | 151.48     | \( R_L \) | 50 \Omega   |
| \( f \)  | 85 kHz     | \( k \)    | 0.3        | \( D \)    | 15 cm      |
5.2 Frequency experiment
The working frequency $f$ is affected by external factors such as the load variation [30]. The frequency characteristics experiment was conducted to analyze the system transmission characteristics when the working frequency changes.

According to the application, the frequency range of the system was selected as $84 \text{kHz} - 86 \text{kHz}$ and the measurement was tested once every 0.2 kHz. The frequency experimental results are shown in Fig. 13.

At the resonance frequency 85 kHz, the designed system obtains the maximum output power of 3059 W and a maximum transmission efficiency of 88.2%. The output voltage and the output current remain in the same phase with little THD (shown in Fig. 14), and the system remains in the resonance state. Compared with the traditional system, the output power and the transmission efficiency increase 186 W and 3.2%.

5.3 Waveform experiment
The experimental waveform of the system is mainly used to test the input voltage and output voltage and current waveform of the high-frequency converter with PFC, so as to observe whether it meets the design requirements.

The PFC drive pulse waveform test, as shown in Fig. 15, is basically consistent with the simulation results. The PFC output voltage and input current waveform test as shown in Fig. 16. It can be seen that the output DC voltage of PFC is basically maintained at about 390 V, with an error of 2.5% compared with the theoretical value of 400 V. The high-frequency inverter drive pulse waveform test is as shown in Fig. 17. It can be seen that the two groups of switching tubes are interleaved with each other by 180°, and the maximum switching voltage is less than 20 V. The high-frequency inverter soft switch waveform test as shown in Fig. 18. The soft switching technology can effectively reduce the loss of switching devices. To sum up, the dual-boost PFC designed in this paper meets the design requirements.

6. Conclusions
The main goal of this paper was to solve the harmonic effect on the transmission characteristics of an MCR-WPT system with SP structure. The equivalent circuit model of the system was established. With the harmonic current component, the transmission characteristic formula of the MCR-WPT system is derived. The relationship between THD, quality factors $Q_p$ and $Q_s$, and the coupling coefficient $k$ was analyzed by a simulation method.

A dual-boost PFC circuit was developed to finish harmonic suppression of the input current. Double closed loop control, which includes outer loop voltage control and inner loop current control, was finished to reduce the harmonic effect.

A simulation platform of the designed system was built, and the load experiment, frequency experiment and waveform analysis experiment were carried out by the designed experimental platform. Compared with a traditional system, the results show that the THD and the harmonic current are reduced, and the power factor of the power supply side and the transmission characteristics of the designed system are improved.

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