Research on Dual Loop Control Strategy of Dynamic Wireless Charging for Electric Vehicle

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Abstract. This paper focuses on a dynamic wireless charging method of electric vehicles with segmented structure, which uses multiple transmitting coils at the transmitting end to realize wireless power supply for electric vehicles in motion. Based on the structure of the dynamic wireless charging system of the electric vehicle with magnetic coupling resonance, the system is modeled and analyzed by using the equivalent circuit theory, and a control strategy of the transmitting end is proposed, which can effectively solve the problem of coil deviation and dynamic characteristics when the receiving coil and the transmitting coil of the electric vehicle are in the charging process. A double loop controller is designed to adjust the power and current of the transmitting end, which allows the sequence and timely activation of the segmented transmitting coil. Under the condition of no-load and load, the current of the transmitting coil is controlled at the reference value to compensate the power transmission reduction caused by the lateral misalignment of the vehicle and prevent the overload at one time. The system is modeled and analyzed with Simulink software, and the feasibility of the control method is determined.

1. Introduction
Dynamic wireless charging extends the concept of static charging, allowing electric vehicles to charge in real time during driving [1-4]. Ref. [5] proposes a design based on segmented coil, in which only the coil at the best position is energized to ensure higher system efficiency. Due to the rapid increase of the number of transmitting coils in the segmented guide rail, the power supply mode of the transmitting coil chain becomes relatively complex. In order to realize the effective power supply of the transmitting coil chain, it is necessary to locate the electric vehicle accurately, and then activate the corresponding transmitting coil in real time.

Therefore, this paper proposes a control strategy for the transmitter, which can effectively solve the problem of coil offset and dynamic characteristics during the charging process. A dual loop controller is designed to adjust the power and current of the transmitting end, which allows the sequence and timely activation of the segmented transmitting coil. Under the condition of no-load and load, the current of the transmitting coil is controlled at the reference value to compensate the power transmission reduction caused by the lateral misalignment of the vehicle and prevent the overload at one time.

2. System structure and theoretical analysis

2.1. System structure
As shown in Figure 1 is the principle block diagram of dynamic wireless charging system. At the transmitting end, the alternating current (50Hz/60Hz) of the power grid is first converted into direct current, and then converted into high-frequency alternating current (80~100kHz) by inverter, and then transmitted to the transmitting coil to supply energy to the receiving end. The power conversion of the transmitter is realized by the middle power electronic converter and selecting the appropriate compensation circuit. At the receiving end, the receiving coil is connected with the compensation circuit, and the electric energy is obtained through the coupling resonance between the transmitting end and the receiving end. The high-frequency alternating current at the receiving end passes through the rectifier filter circuit, and then it is converted into the appropriate direct current through the DC-DC conversion circuit and sent to the battery.

According to the position of the moving vehicle, the transmitting coil can be continuously energized, and only when the receiving coil is installed can the electric vehicle get the power supply from the transmitting terminal.

2.2. Theoretical analysis
In this paper, the circuit analysis method is used to analyze the reflected impedance, output power and transmission efficiency from the receiver to the transmitter. Figure 2 is the equivalent circuit diagram of the wireless charging system. In the Figure, $U_S$ is the high-frequency inverter voltage source, $I_{P1}$, $I_{P2}$ and $I_S$ are the current of the two loops at the transmitter and the receiver respectively, $L_{P1}$, $L_{P2}$ and $L_S$ are the coupling inductance of the two loops at the transmitter and the receiver respectively, $C_{P1}$, $C_{P2}$ and $C_S$ are the series resonant compensation capacitance of the two loops at the transmitter and the receiver respectively, $R_{P1}$, $R_{P2}$ and $R_S$ are the equivalent internal resistance of the two loops at the transmitter and the receiver respectively, $M_{1S}$, $M_{2S}$ and $M_{12}$ are mutual inductance between transmitting end coil and receiving end coil respectively, and $R_L$ is system load.

From Kirchhoff's law of voltage, the equivalent circuit equation can be obtained as follows:
Among them, $Z_{p1}$, $Z_{p2}$ and $Z_s$ are the impedance of the coil loop at the transmitting end and the coil loop at the receiving end respectively, which are expressed as follows:

$$Z_{p1} = R_{p1} + j\omega L_{p1} - \frac{1}{j\omega C_{p1}}, \quad Z_{p2} = R_{p2} + j\omega L_{p2} - \frac{1}{j\omega C_{p2}}, \quad Z_s = R_s + R_L + j\omega L_s - \frac{1}{j\omega C_s}$$

(2)

Among them, The impedance is usually expressed in complex form, $j$ is the complex part of the impedance, $\omega$ is angular frequency, $\omega = 2\pi f$, and $f$ is the frequency.

The total output power of the system is obtained as follows:

$$P_{out} = |I|^2 \cdot R_L = \omega \left( Z_p^2 + 2\omega^2 Z_p M_{12} + \omega^2 M_{12}^2 \right) \left( M_{15}^2 + M_{25}^2 + 2M_{15} M_{25} \right) I_s^2 \cdot R_L$$

(3)

The transmission efficiency of the system is as follows:

$$\eta = \frac{P_{out}}{U_s^2 |I|^2} = \omega \left( Z_p^2 + 2\omega^2 Z_p M_{12} + \omega^2 M_{12}^2 \right) \left( M_{15}^2 + M_{25}^2 + 2M_{15} M_{25} \right) \cdot \frac{R_L}{I}$$

(4)

3. Design of dual loop controller

Figure 3 shows a block diagram of a dual loop controller. The reference current $I_{ref}$ of the transmitting coil will be determined in two ways, by the power obtained from the DC circuit. When the DC circuit power is less than the reference power ($P < P_{ref}$), the reference current can be determined through the reference ammeter. When the DC circuit power is greater than the reference power ($P > P_{ref}$), it indicates that the main power supply is overloaded. The power error is obtained by comparing the DC loop power with the reference power, and the error is transferred to the power control module. According to the power error value and the current $I$ of the transmitting coil, the power controller module can determine the reference current. The current control module calculates the reference value of the inverter output voltage by using the error between the reference current and the measured transmission coil current.

![Figure 3. Control block diagram of dual loop controller.](image)

3.1. Electric vehicle positioning detection module

Figure 4 shows the flow chart of positioning detection. The positioning detection module installed on the vehicle will detect the position of the electric vehicle and measure its lateral offset. When the vehicle is detected, the positioning detection module will generate an analog voltage signal and transmit the output signal to the dual loop controller. When the voltage signal value is equal to the set reference voltage value, it means full alignment; when the voltage signal value is less than or greater than the set reference voltage value, it means left or right misalignment respectively. When it is in the fully aligned state, the single transmitting coil is switched to the normal transmission state. When it is in the left offset state and the right offset state, multiple transmit coils are switched to enter the normal transmission state.
The system is powered on and initialized, and the transmitting coil is waiting for switching for power supply.

Size comparison between $V_m$ and $V_{ref1}$

Offset left status Offset right status

Switch multiple transmitting coils to normal transmission state

Switch single transmitting coil to normal transmission state

Figure 4. Flow chart of electric vehicle positioning detection.

3.2. Power control module

The control block diagram of the power control module is shown in Figure 5. The power control module is required only when the measured DC loop power exceeds the maximum allowable power ($P > P_{ref}$). It prevents further power increase by reducing the current $I$ of the transmitting coil. When the measured power naturally drops below the reference power, the power control module is inhibited.

$$I_{ref} = \sqrt{\frac{P_{ref} \cdot I}{P}}$$

Figure 5. Control block diagram of power control module.

In order to cope with the load dynamic, most of the reference current $I_{ref}$ of the transmitting coil is obtained through the reference voltmeter, which is generated by an adaptive proportional regulator, which associates the reference current of the transmitting coil with its measured value. Among them, the fast dynamic of the proportional regulator allows the power controller to track the DC loop power change caused by the load change and prevent the dual loop controller from overload.

3.3. Current control module

Figure 6 shows a control block diagram of the designed current control module. When the vehicle is detected, the automatic phase increase program is started, and the phase shift angle of the inverter increases linearly from zero, so that the transmitting coil is energized. When the phase-shift angle of the inverter reaches 120°, the program automatically sends a signal to trigger the switch to close and enter the current regulation stage. The phase gain generated by the current error is added into it to regulate the power on state of the inverter.

$$V_{ref} = 4 \cdot \sin(\theta_2/2)\sqrt{\frac{P}{I}}$$

Figure 6. Control block diagram of current control module.

4. Simulation verification analysis

In order to verify the effectiveness of the designed dual loop controller, according to the aforementioned dual loop controller, a system simulation circuit is built in Simulink to verify the charging effect of the dual loop controller. The simulation parameter settings are consistent with Table 1. The reference value of the current of the transmitting coil is assumed to be $I_{ref}=50$A, the power limit
of the transmitting end is set to $P_{ref}=3\ kW$, and the transmitting end is less than the maximum power (4kW) that can be transmitted by the system to achieve full alignment.

| System parameter                  | Launcher    | Receiver    |
|-----------------------------------|-------------|-------------|
| Resistance                        | 0.3Ω        | 0.2Ω        |
| Inductance                        | 19.7uH      | 19.7uH      |
| Capacitance                       | 178.013pF   | 178.013pF   |
| Mutual Inductance                 | 3.94uH      |             |
| Resonant Frequency                | 85kHz       |             |
| Coupling Coefficient              | 0.2         |             |
| Transmission Distance             | 200mm       |             |
| Load                              | 10Ω         |             |

Two groups of coupling coils are set at the transmitter and the receiver. Among them, the inductance and coupling coefficient of the two groups of coils are the same. The simulation of dynamic wireless charging is realized by setting a delay on-off switch at the transmitter to alternately change the on position. Figure 7(A) and (B) respectively represent the current of the transmitter coil and its RMS value.

![Image](image1.png)

**Figure 7. Current curve of transmitting coil in dynamic wireless charging system.**

From Figure 7, it can be concluded that it takes about 0.001s for the transmitter to supply power stably to the system. When the continuous switching coil at the transmitter changes the system parameters, the adjustment of the dual loop controller makes the power supply current error of the system within ±0.1A. Therefore, the designed dual loop controller has small charging current error and small charging fluctuation, which can realize load balance charging.

The current charging condition of the load is obtained through signal detection. Figure 8(A) and (B) are the curves of load current and power change at the receiving end of the dynamic wireless charging system.

![Image](image2.png)

**Figure 8. Control effect of dual loop controller.**

It can be seen that when the system parameters change with the continuous switching coil at the transmitter, the current at the receiver is kept within 42–48A, and the constant current suitable for the load can be obtained directly through the rectifier filter at the receiver.
5. Conclusion and Prospect
This paper focuses on the use of multiple transmitting coils at the transmitting end to realize wireless power supply for electric vehicles in motion. A double loop controller is designed to adjust the power and current of the transmitting end. The control allows the sequence and timely activation of the segmented transmitting coil. Under the condition of no-load and load, the current of the transmitting coil is controlled at the reference value to compensate for the power transmission reduction caused by the lateral misalignment of the vehicle and prevent the primary overload. The simulation results show the feasibility of the positioning control method, and ensure the continuity and stability of dynamic radio energy transmission.

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References
[1] Mi, C.C., Buja, G., Su, Y.C., et al. (2016) Modern advances in wireless power transfer systems for roadway powered electric vehicles. IEEE Transactions on Industrial Electronics, 63(10): 6533-6545.
[2] Shin, J., Shin, S., Kim, Y., et al. (2014) Design and implementation of shaped magnetic-resonance-based wireless power transfer system for roadway-powered moving electric vehicles. IEEE Transactions on Industrial Electronics, 61(3): 1179-1192.
[3] Chopra, S., Bauer, P. (2013) Driving range extension of EV with on-road contactless power transfer—a case study. IEEE Transactions on Industrial Electronics, 60(1): 329-338.
[4] Miller, J.M., Jones, P.T., Li, J.M., et al. (2015) ORNL experience and challenges facing dynamic wireless power charging of EV's. IEEE Circuits and Systems Magazine, 15(2): 40-53.
[5] Sun, Y., Tian, Y., Su, Y.G., et al. (2015) High-efficiency power distribution scheme for online powered system of electric vehicles. Journal of Southwest Jiaotong University, 48(2): 236-242.
[6] Song, K., Zhu, C.B., Li, Y., et al. (2015) Wireless power transfer technology for electric vehicle dynamic charging using multi-parallel primary coils. Proceedings of the CSEE, 35(17): 4445-4453.
[7] Zahid, Z.U., Dalala, Z.M., Zheng, C., et al. (2015) Modeling and control of series-series compensated inductive power transfer system. IEEE Journal of Emerging and Selected Topics in Power Electronics, 3(1):111-123.
[8] Covic, G.A., Boys, J.T. (2013) Modern trends in inductive power transfer for transportation applications. IEEE Journal of Emerging and Selected Topics in Power Electronics, 1(1): 28-41.
[9] Colak, K., Asa, E., Bojarski, M., et al. (2015) A novel phase-shift control of semibridgeless active rectifier for wireless power transfer. IEEE Transactions on Power Electronics, 30(11): 6288-6297.
[10] Miller, J.M., Onar, O.C., Chinthavali, M. (2015) Primary-side power flow control of wireless power transfer for electric vehicle charging. IEEE Journal of Emerging and Selected Topics in Power Electronics, 3(1): 147-162.