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Research on Constant Current Output of Wireless Charging System for Unmanned Surface Vehicles

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Abstract: A nonlinear state feedback controller is proposed to stabilise the output current of the wireless charging system for unmanned surface vehicles in response to the unstable charging and high waste of power resources caused by mutual inductance changes during the wireless charging process of unmanned surface vehicles. Firstly, the output characteristics of the wireless charging system with LCC-S topology are analysed and its mathematical model is established. Secondly, a state feedback controller is designed to control the output current of the wireless charging system of unmanned surface vehicles. Finally, a simulation model is built in Mtalab to verify the correctness of the control strategy. The simulation results show that the actual output current of the wireless charging system for unmanned vehicles can be quickly stabilised and kept constant under the change of mutual inductance. It also provides some reference for the research of optimal control method of wireless charging system for unmanned surface vehicles.

1. Introduction

As more and more unmanned surface vehicles are hybrid or fully battery-powered, Wireless Power Transfer (WPT) is increasingly becoming a focus of research and application[1-4]. This method can be used to recharge batteries, power equipment on board or directly drive motor drives. Typically, shore power is used to provide power to the ship when it is docked at a dock. Such traditional plug-in charging requires manual connection, and the ship operator may be exposed to the risk of electric shock or some safety hazards. And for unmanned surface vehicles that need to travel quickly to and from the dock, the docking time is very short, so the battery charging time is also very short. The introduction of wireless charging will facilitate the development of automatic and contactless pair charging for unmanned surface vehicles.

When a WPT system is charging, the electrical energy is transmitted through a non-contacting coupling coil that generates a high-frequency magnetic field, which means that the system is susceptible to interference. WPT systems applied to unmanned surface vehicles will continue to have coupling coils that vary horizontally and vertically even when the unmanned surface vehicles are docked in a harbour due to the combined effects of wind, waves, vessel draught and loading and unloading. This will affect the effectiveness of power transmission in the WPT system and leave the system in an unhealthy operating condition for a long time[5].

In order to compensate for this misalignment variation, scholars have successively carried out research in the adoption of composite resonant circuits, control strategies, and coil structures. In terms of composite resonant circuit, Zhang[6] proposed to satisfy the stable charging of the system by introducing a cast cut-off switching adjoint compensation network and combining it with PI control. Liu[7] proposed a dynamic tuning method of wireless charging system using a flux-controllable inductor by adding an additional compensation inductor with an inverter circuit to cope with the power instability caused by mutual inductance changes and detuning of the compensation element. However, this method increases the complexity of the system and will also increase the weight and volume of the system.Vu[8] proposed the control method of switching the network structure by analysing the frequency characteristics of the bilateral LCC compensation network, which achieves the constant current/constant voltage charging mode that does not depend on the load. However, the frequency adjustable range of the WPT system is limited, which results in the method not being flexible and versatile enough.Regarding the use of novel coil structures, Chen[9] placed multiple transmitting coils in the same plane and selectively connected the transmitting coils according to the EV parking position to extend the charging range of the EV in the horizontal plane. Tang[10], on the other hand, achieved omnidirectional charging by using two orthogonal plane helical coils. By increasing the coupling pathways, the location requirement during wireless charging can be effectively reduced, but it also increases the complexity and cost of the system. In addition, as the number of coils increases, the difficulty of the control strategy also increases. In terms of control strategy, Ou[11] proposed a control method based on model predictive control for constant power output of dynamic wireless energy transmission system. The model prediction of the output power is carried out to obtain the optimal duty cycle corresponding to the desired output power, so that the output power is constant. Based on the load and mutual inductance parameter regression of the system, Wang[12] established a wireless charging control model on the state space model, designed a robust controller, and carried out a stability analysis of the system. However, this method only uses the transfer function to describe the input-output relationship of the system, which involves a large number of parameters and cannot describe the dynamic characteristics of the system well, and the performance of the controller is easily affected by the parameter drift.Zhou[13], based on the constant-current characteristics of the bilateral LCC-type resonance topology, carried out the state-averaged modelling of the secondary-side Buck circuit, and designed a multistep compensated control strategy for the sensor sampling delay, to achieve the load voltage of the WPT system. A multi-step compensated control strategy is designed for the sensor sampling time delay, which achieves the fast regulation of the load voltage of the WPT system. However, this method requires real-time acquisition of the inductor current and capacitor voltage of the Buck circuit, and storage and calculation of the target data in the past several acquisition cycles, which makes the control algorithm computationally large, and the cost and space occupation of the hardware implementation is high.

A nonlinear state feedback controller is designed to address the problems of low charging efficiency and high waste of power resources caused by mutual inductance changes in the wireless charging process of unmanned surface vehicles. Firstly, the WPT system with LCC-S structure is mathematically modelled and its dynamic characteristics are analysed. Then, design of non-linear state feedback controllers based on mathematical modelling The number of physical sensors is reduced and hardware cost is saved. Finally, the overall wireless power transmission system is analysed using Matlab. The simulation results show that the application requirements of the WPT system can be met under the variation of mutual inductance.

2. Wireless Charging System Analysis and Modelling

The wireless charging system based on the LCC-S compensation network structure is shown in Fig. 1, which is mainly composed of a high-frequency inverter part, a resonant coupling part, and a rectifier filter part. The DC power supply at the transmitting end generates high-frequency alternating current (AC) through the full-bridge inverter circuit, and then the high-frequency magnetic field is generated by the coupling coil through the resonant network to transfer the energy to the secondary coupling coil. The energy passes through the vice-side resonant network and then through the rectifier to supply power to the load.

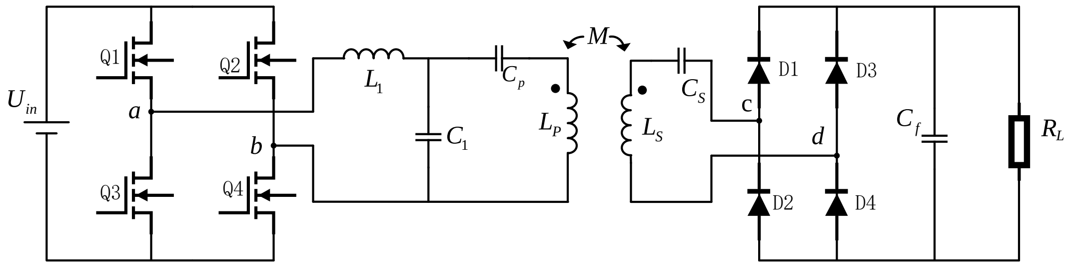

Figure 1: Topology of LCC-S type wireless charging system

2.1. Mathematical Model of LCC-S Wireless Power Transfer System

In this paper, the LCC-S wireless charging system is selected as the research object, and its fundamental equivalent circuit is shown in Fig 2. Where L_P , L_S , respectively, is the self-inductance of the transmitting coil and receiving coil; U_{AB} is the AC voltage after the inverter change; i_1 is the current on the compensation capacitor; i_2 is the current on the primary coil; i_3 is the current on the secondary coil; u_0 is the output voltage; i_0 is the output current; R_0 is the load resistance; Compensating inductance L_1 and compensating capacitance C_1 and C_{f1} constitute the primary resonant network; M for mutual inductance between the coils; the secondary resonant network is a series topology and contains the compensating capacitance C_S . The primary and secondary resonant compensation networks utilise the principle of inductor-capacitor resonance at a specific frequency, eliminating the influence of the coil's own magnetic leakage on the energy transfer, reducing reactive power and improving efficiency.

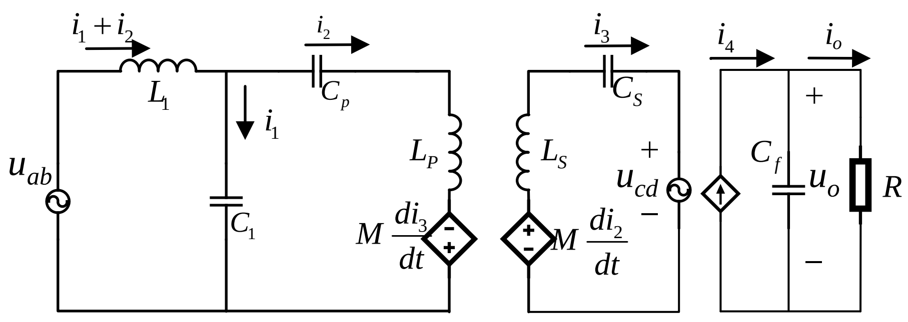

Figure 2: Equivalent circuit of LCC-S WPT

According to Kirchhoff's law the following equation can be obtained:

$$
\begin{cases}
u_{ab} = u_{L_1} + u_{C_1} \\
u_{C_1} = u_{C_P} + \dfrac{di_2}{dt}(L_p - L_m) \\
u_{C_S} = \dfrac{di_3}{dt}(L_s - L_m) + u_{cd} \\
i_4 = |i_3| = \dfrac{u_o}{R} + C_f \dfrac{du_o}{dt} \\
i_3 = C_S \dfrac{du_{C_S}}{dt} \\
i_2 = C_P \dfrac{du_{C_P}}{dt} \\
i_1 = C_1 \dfrac{du_{C_1}}{dt}
\end{cases}
\tag{1}
$$

The rectifier input voltage u_{cd} is the AC voltage that depends on the amplitude of the rectifier voltage u_o and the secondary receiver coil current i_3, and its expression can be written as (2), where the function $\mathrm{sgn}(i_3)$ is defined in (3):

$$
u_{cd} = \mathrm{sgn}(i_3) u_o \tag{2}
$$

$$
\mathrm{sgn}(i_3) = \begin{cases} -1 \; if \;\; i_3 < 0 \\ 0 \; if \;\; i_3 = 0 \\ 1 \; if \;\; i_3 > 0 \end{cases} \tag{3}
$$

Similarly, the absolute value of i_3 can be written as:

$$
|i_3| = \mathrm{sgn}(i_3) i_3 \tag{4}
$$

To determine the wireless charging system of the LCC-S type, Introducing state variables $x = [u_{C_1} \; u_{C_P} \; u_{C_S} \; i_1 \; i_2 \; i_3 \; u_o] = [x_1 \; x_2 \; x_3 \; x_4 \; x_5 \; x_6 \; x_7]$, and by substituting Eqs. (2) and (3) into (1), the system model can be expressed as:

$$
\begin{cases}
\dot{x}_1 = \dfrac{1}{C_1} x_4 \\
\dot{x}_2 = \dfrac{1}{C_S} x_5 \\
\dot{x}_3 = \dfrac{1}{C_S} x_6 \\
\dot{x}_4 = \dfrac{1}{L_1} u - (\dfrac{1}{L_1} + \dfrac{L_s}{\phi}) x_1 + \dfrac{L_s}{\phi} x_2 + \dfrac{M}{\phi}(x_3 + \mathrm{sgn}(x_6) x_7) \\
\dot{x}_5 = \dfrac{L_s}{\phi}(x_1 - x_2) - \dfrac{M}{\phi}(x_3 + \mathrm{sgn}(x_6) x_7) \\
\dot{x}_6 = \dfrac{M}{\phi}(x_2 - x_2) - \dfrac{L_p}{\phi}(x_3 + \mathrm{sgn}(x_6) x_7) \\
\dot{x}_7 = \dfrac{1}{C_f} \mathrm{sgn}(x_6)(x_6) - \dfrac{x_7}{C_f R}
\end{cases}
\tag{5}
$$

Where, $\phi = L_p L_s - M^2$.

2.2. Dynamic Characterisation of Wireless Charging Systems

Wireless charging utilises the principle of magnetic induction coupling between coils for energy transfer. When unmanned vehicles use wireless charging, the charging coils will be deflected and shifted because of the effects of weather, wind and waves. This unaligned characteristic of the charging coils will lead to changes in the air gap between the coils, resulting in changes in the mutual inductance between the charging coils, which will lead to changes in the output current and affect the charging effect. The study of the dynamic transmission characteristics of the wireless charging system is crucial for the design of the controller.

Impedance analysis is used to analyse the equivalent circuit of the WPT system. As shown in Fig 2, the KVL law is used to obtain:

$$\begin{cases} \dot{U}_{ab} = [j(\omega L_1 - 1/\omega C_1)](\dot{I}_1 + \dot{I}_2) - (1/j\omega C_1)\dot{I}_2 \\ j\omega M\dot{I}_3 = j(\omega L_P - 1/\omega C_P - 1/\omega C_1)\dot{I}_3 - (1/j\omega C_1)\dot{I}_3 \\ \dot{U}_{cd} = j\omega M\dot{I}_2 - [j(\omega L_S - 1/\omega C_S)]\dot{I}_3 \end{cases} \tag{6}$$

where $\dot{U}_{ab}$ and $\dot{U}_{cd}$ are in the form of phasors of u_{ab} and u_{cd}, respectively. $\dot{I}_1$, $\dot{I}_2$ and $\dot{I}_3$ are in the form of phasors of i_1, i_2 and i_3, respectively. Assuming that the rectifier is lossless, according to the rule of power conservation, the receiver-side rectifier and the load R_{eq} can be expressed by the equivalent resistance, which is given by:

$$R_{eq} = \frac{8}{\pi^2}R \tag{7}$$

$$\dot{I}_{3rms} = \frac{\pi}{2\sqrt{2}}i_0 \tag{8}$$

$$u_{cd} = \dot{I}_3 R_{eq} \tag{9}$$

Set ω as the resonant frequency of the system, a secondary side resonant network can be under the resonant condition when it satisfies Eq (10).

$$\begin{cases} \omega L_1 = \dfrac{1}{\omega C_1} \\ \omega(L_p - L_1) = \dfrac{1}{\omega C_1} \\ \omega L_s = \dfrac{1}{\omega C_s} \end{cases} \tag{10}$$

After satisfying the resonance condition. Substituting Eqs (9) and (7) into Eq (6) yields:

$$\dot{I}_3 = \frac{\dot{U}_{ab}}{L_1 R_{eq}} \tag{11}$$

From Eq (11), when the wireless charging with LCC-S structure operates at the resonance point, the output current $\dot{I}_3$ on the secondary inductor without rectifier filtering is related to the mutual inductance, compensation inductance and load. The mutual inductance changes dramatically when the coil is offset, which leads to a sharp change in the output current.

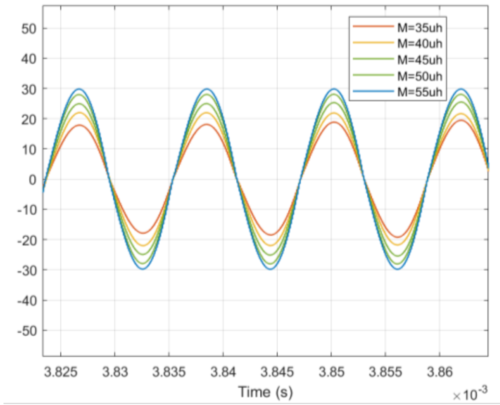

Figure 3: Current variation with different mutual inductance

As can be seen in Fig 3, the current $\dot{I}_3$ in the wireless charging system of LCC-S type. The peak output current differs by 15A under different mutual inductance, which shows the influence of mutual inductance parameters on the output current.

3. State Feedback Nonlinear Controller Design

In a wireless charging system, it is crucial to maintain a stable output current. If the output current is unstable, it will directly affect the charging efficiency and lead to longer charging time. In addition, unstable output current may also lead to overheating or even damage to the internal circuitry of the charging device. Especially for the dynamic wireless energy transmission of unmanned surface vehicles, misalignment between the coupling coils is unavoidable when the transmitting and receiving coils are moving relative to each other, resulting in mutual inductance changes, and thus the output current becomes unstable. Ensuring stable regulation of the output current is important to guarantee the normal operation of the charging system.

3.1. Controller Design

In Eq (5) above, the controller design task becomes more difficult due to the discontinuity of the sign function and the nonlinearity of the mutual inductance M. In order to solve this problem, we adopt a controller design method that uses u_{ab} as the control signal. By establishing the relationship between the current on the compensation capacitor and the output current, we can indirectly control the load charging current C_1 by controlling the current on the compensation capacitor.

Further, by replacing the rectifier filter circuit and the load in the fundamental equivalent circuit of the LCC-S wireless charging system with R_{eq}, the equivalent diagram shown in Fig 4 is obtained.

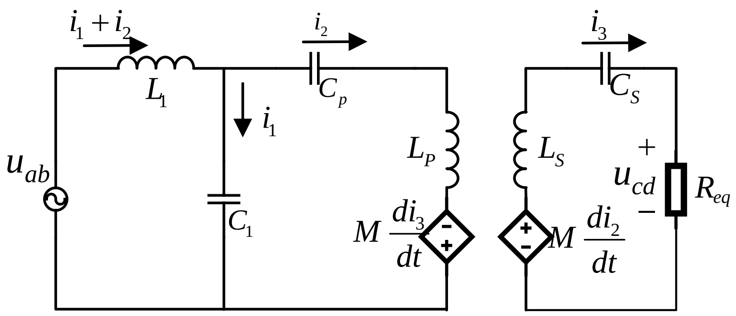

Figure 4: WPT equivalent circuit

It can be obtained from KVL and KCL laws:

$$\dot{I}_1 = \frac{\dot{U}_{ab} M^2}{L_1^2 R_{eq}} + j\frac{\dot{U}_{ab}}{L_1 \omega} \tag{12}$$

$$I_{1rms} = \sqrt{\left(\frac{M}{L_1}\right)^2 + \left(\frac{R_{eq}}{\omega M}\right)^2} I_{3rms} \tag{13}$$

Substituting Eqs (8) and (7) into (13) yields:

$$I_{1rms} = \sqrt{\left(\frac{M}{L_1}\right)^2 + \left(\frac{8R}{\pi^2 \omega M}\right)^2} \frac{\pi}{2\sqrt{2}} i_0 \tag{14}$$

The new reference current expression can be obtained:

$$x_{4ref} = \sqrt{\left(\frac{M}{L_1}\right)^2 + \left(\frac{8R}{\pi^2 \omega M}\right)^2} \frac{\pi}{2} i_{oref} \sin(\omega t + \arctan\frac{L_1 R}{\omega M^2}) \tag{15}$$

The error between the actual charging current and the desired reference current, defined as:

$$\mathrm{e}_1 = i_{oref} - i_o \tag{16}$$

Substituting i_{bref} in the above equation into equation (15), the new error function is obtained as:

$$e_1 = x_{4ref} - \sqrt{\left(\frac{M}{L_1}\right)^2 + \left(\frac{8R}{\pi^2 \omega M}\right)^2} \frac{\pi}{2} i_{oref} \sin(\omega t + \arctan\frac{L_1 R}{\omega M^2}) \tag{17}$$

Theorem 1: For the unmanned surface vehicles WPT charging system (5), the controller is designed as:

$$u = L_1 \dot{x}_{4ref} + (1 + \frac{L_1 L_s}{\phi}) x_1 - \frac{L_1 L_S}{\phi} x_2 - \frac{L_1 M}{\phi}(x_3 + \mathrm{sgn}(x_6) x_7) + L_1 ke \tag{18}$$

Then the closed-loop system controls the asymptotic stabilisation of the system, where k > 0 is the control gain.

Proof: In order to prove the stability of the closed-loop system, a positive definite Lyapunov function is chosen：

$$V_1 = \frac{1}{2} e_1^2 \tag{19}$$

Derivation of the above equation, followed by substituting $\dot{e}_1 = \dot{x}_{4ref} - \dot{x}_4$ with equation (5)

$$\dot{V}_1 = e_1 \left(\dot{x}_{4ref} - \frac{1}{L_1} u_{ab} - (\frac{1}{L_1} + \frac{L_s}{\phi}) x_1 + \frac{L_s}{\phi} x_2 + \frac{M}{\phi}(x_3 + \mathrm{sgn}(x_6) x_7) \right) \tag{20}$$

Bringing the control input (18) into equation (20) yields

$$u = L_1 \dot{x}_{4ref} + (1 + \frac{L_1 L_s}{\phi}) x_1 - \frac{L_1 L_S}{\phi} x_2 - \frac{L_1 M}{\phi}(x_3 + \mathrm{sgn}(x_6) x_7) + L_1 ke \tag{21}$$

Obviously, $\dot{V}_1$ is negatively definite. According to Lyapunov's stability theorem, it is known that the overall closed-loop control system is asymptotically stable. Theorem 1 is proved.

4. Simulation Analysis

The objective of this section is to illustrate and analyse the performance of the proposed WPT charger controller. According to the methodology introduced in the literature[14], a sliding mode observer is established using a mathematical model and combined with the controller to simulate the closed-loop control block diagram of the wireless charging system for unmanned surface vehicles shown in Fig. 5 in MATLAB/Simulink software. The relevant parameters are shown in Table 1

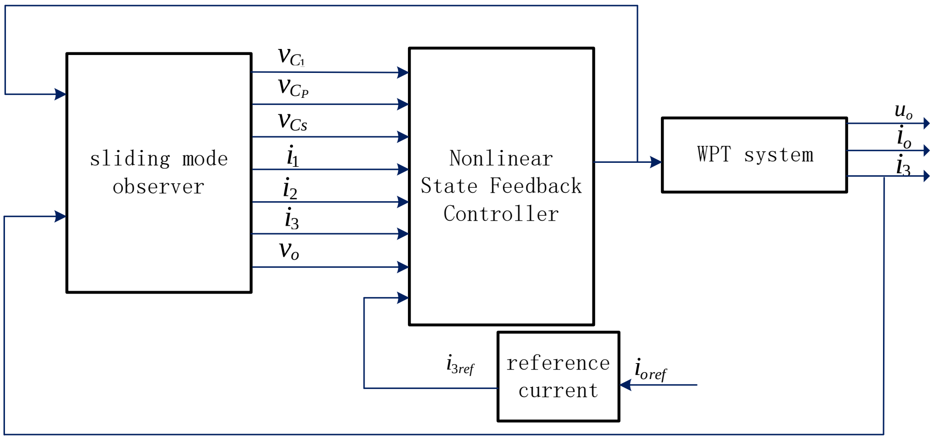

Figure 5: Closed-loop control block diagram of wireless charging system for unmanned surface vehicles

Table 1: System parameter

Parameter	Value	Parameter	Value
Primary Coil Inductors L_p	554 μh	compensation capacitor C_S	37.729 nF
Side Coil Inductance L_s	94 μh	coil mutual inductance M	20 μH
Compensating Inductance L_1	30.4 μh	load resistance R	10Ω
compensation capacitor C_1	115.32 nF	operating frequency f	85 KHz
compensation capacitor C_P	6.69 nF	filter capacitor C_f	470 μF

The coupling degree of mutual inductance in the wireless charging process is changing at any time, in order to observe the unmanned surface vehicles wireless charging system on the mutual inductance of the change of the anti-interference, add a perturbation at 10ms, at this time, the mutual inductance of the mutation from 20uh to 25uh, at this time, the current output waveform is shown in Figure 6.

According to the simulation output waveform, it can be seen that the output of the system can keep the output current stable, and the system has a strong anti-interference ability.

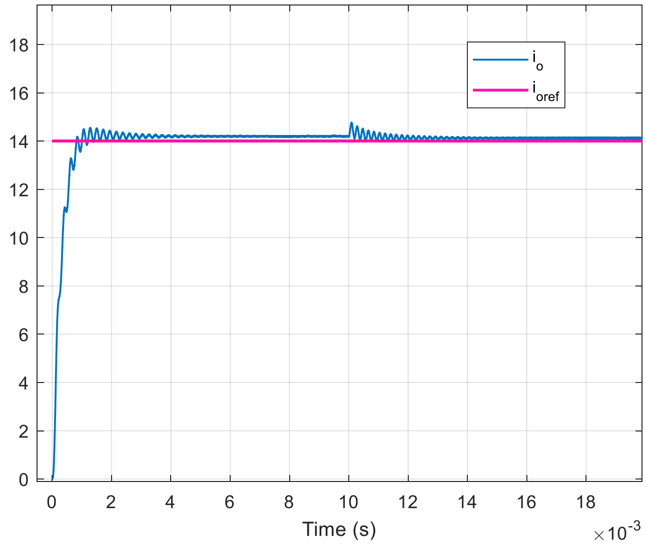

Figure 6: Simulated waveform of output current when mutual inductance changes

5. Conclusions

In order to solve the problems of output current fluctuation and transmission energy efficiency degradation caused by wind and wave disturbance of wireless charging system of unmanned surface vehicles in the marine environment, a state feedback controller is designed in this paper. This paper firstly analyses the wireless charging output characteristics and establishes a mathematical model of the wireless charging system by establishing the equivalent circuit of the WPT system. Considering that in the practical application of electric vehicle wireless charging system, the change of mutual inductance will lead to the change of power transmission, which will affect the stability of the system. This paper proposes a closed-loop state feedback controller based on the accurate mathematical model. This control method can make the wireless charging system ensure the output current of the system is constant under the change of mutual inductance. The feasibility of the control strategy is finally verified using simulation software implementation.

References

[1] Wang W, Wang S, Liu X F, et al. Design and optimization of novel solenoid magnetic coupler for electric boats wireless charging[J]. Journal of Power Supply, 2024, 3(13): 1-18.

[2] Miller J M, Jones P T, Li J M, et al. ORNL experience and challenges facing dynamic wireless power charging of EV's[J]. IEEE Circuits & Systems Magazine, 2015, 15(2): 40-53.

[3] Aditya K, Pradhan S, Munsi A. Feasibility study on megawatt-level fast charging system for shore power supply using wireless power transfer technology [J]. Electrical Engineering, 2023: 1-15.

[4] Tavakoli R, Pantic Z. Analysis, design and demonstration of a 25-kW dynamic wireless charging system for roadway electric vehicles[J]. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2017, 6(3): 1378-1393.

[5] Guidi G, Suul J A, Jenset F, et al. Wireless charging for ships: High-power inductive charging for battery electric and plug-in hybrid vessels[J]. IEEE Electrification Magazine, 2017, 5(3): 22-32.

[6] Zhang W J, Qin W, Song J C, et al. Development of constant current and constant voltage wireless charging system with mutual inductance identification function in primary side[J]. Electric Machines and Control, 2021, 25: 52-60.

[7] Liu H, Li Z J, Tian Y H, et al. Dynamic tuning method for wireless charging system based on the magnetic flux controllable inductor[J]. Journal of Harbin University of Science and Technology, 2023, 28(05): 11-18.

[8] Vu V B, Tran D H, Choi W. Implementation of the constant current and constant voltage charge of inductive power transfer systems with the double-sided LCC compensation topology for electric vehicle battery charge applications [J].

IEEE Transactions on Power Electronics, 2017, 33(9): 7398-7410.
[9] Chen J, Li R, Yu S, et al. Anti-offset high-voltage wireless power transfer system based on many-to-one topology[J]. Electronics, 2023, 12(8): 1898.
[10] Tang Z Q, Guo F, Lai Y T, et al. Research on quasi omnidirectional wireless charging with multiple transmitting coils [J]. Transducer and Microsystem Technologies, 2023, 42(03): 27-30, 35.
[11] Ou S P, Zhang H Y, Lu D J. Dynamic wireless power constant power charging of electric vehicle[J]. Chinese Journal of Power Sources, 2021, 45(4): 528-531
[12] Wang L Y, Yue Y, Wang L F, et al. Wireless charging control for electric vehicle based on parameters perturbation of load and mutual inductance[J]. Automation of Electric Power Systems, 2018, 42(15): 178-185, 267.
[13] Zhou Z, Zhang L, Liu Z, et al. Model predictive control for the receiving-side DC–DC converter of dynamic wireless power transfer [J]. IEEE Transactions on Power Electronics, 2020, 35(9): 8985-8997.
[14] Gong C, Hu Y, Gao J, et al. An improved delay-suppressed sliding-mode observer for sensorless vector-controlled PMSM [J]. IEEE Transactions on Industrial Electronics, 2019, 67(7): 5913-5923.