Constant Voltage and Current Oitput of Radio Energy Transmission System Achieved by Frequency Control

Haoran Cheng [1*], Mingjun Gao[2], Hongwei Xie[3], Yuhao Zhu[4]

[1] College of Engineering, South China Agricultural University, Guangzhou, China
[2] College of Marine Electrical Engineering, Dalian Maritime University, Dalian, China
[3] College of Engineering and Applied Science, Nanjing University, Nanjing, China
[4] College of Engineering, Xi'an University of Architecture and Technology, Xi'an , China
*aka2981437409@outlook.com

Abstract. Wireless Power Transfer (WPT) technology has attracted growing interest in recent years due to its wide range of applications, including electric vehicles, biomedical implants, consumer electronics, and industrial systems, where non-contact energy delivery offers improved safety, reliability, and convenience. However, dynamic variations in load conditions and magnetic coupling coefficients significantly challenge the stable regulation of output voltage and current. To overcome these limitations, this paper proposes a novel control strategy that combines Proportional-Integral (PI) control with frequency modulation to achieve Constant Voltage (CV) and Constant Current (CC) output regulation. By dynamically adjusting the inverter's switching frequency, the system maintains optimal power transfer efficiency while ensuring Zero Voltage Switching (ZVS) conditions. Detailed simulation results verify that the proposed method not only achieves fast dynamic response under sudden load changes but also maintains high efficiency and system stability. This strategy provides a practical solution for enhancing the performance and robustness of WPT systems in real-world applications.

Keywords: Wireless Power Transfer, Frequency Control, Constant Voltage, Constant Current

1 Introduction

Inductive Power Transfer (IPT) technology facilitates energy transmission via media like magnetic fields, electric fields, or microwaves, with magnetically coupled resonant WPT being the most common. However, load variations, coil misalignment, and mutual inductance fluctuations lead to unstable output characteristics. To achieve efficient energy transfer, control strategies must regulate system impedance and resonance properties. This study focuses on the role of frequency control in series-compensated WPT systems, integrating a PI controller for dynamic frequency adjustment to stabilize output performance. To explore Voltage-stabilized and current-limited output of the series-connected radio power transmission system through frequency control, this project has reviewed "Electric Field Coupling Radio Power Transmission System

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_116

Based on Frequency Switching for Achieving Synchronous Output Characterization and Frequency Tuning for Double-LCC WPT Systems featuring load-adaptive regulation capability", and has understood the research ideas and basic principles of the literature.

Literature One introduces： wireless power transfer (WPT) technology， a technology that combines power electronics technical and control scientific foundations with technological realizations. It realizes wireless transmission of electrical energy through magnetic fields, electric fields, lasers, microwaves, etc. Currently, the common wireless charging methods mainly adopt magnetic coupling wireless power transfer technology. In recent years, scholars from both domestic and international have carried out comprehensive research on the coupling mode systems of power plants. Smith et al. proposed an EC-WPT system based on resonant compensation, which significantly improved the transmission efficiency. However, this system has unstable output characteristics when the load changes. This team studied the EC-WPT system with multi-coil structure, improving the end-to-end power delivery characteristics, but increasing the network configuration intricacy. In contrast, the frequency switching control method proposed in this study effectively solves the output stability problem while maintaining the simplicity of the system. Literature Two's theoretical basis is that high-order compensation networks can achieve quasi-independent output of multiple frequencies across loads. The disadvantage is that the QLI frequency is usually affected by coupling conditions and system parameters. Therefore, this thesis proposes an enhanced frequency control plan for the LCC-LCC IPT system to adjust the phase disparity angle between the primary side, and suggests voltage and current on the receiver side.

Load resistance, mutual inductance, and coil misalignment cause fluctuations in output voltage and current, impacting system efficiency and device safety. For instance, battery charging requires seamless transitions between CC and CV phases. The selection of PI control parameters involves balancing system responsiveness and stability[1]. This paper adopts a PI control strategy with closed-loop feedback to adjust frequency, ensuring stable CV/CC outputs. Frequency directly affects system impedance and power transfer efficiency. Frequency control dynamically adjusts the operating frequency to restore resonance (zero phase difference between voltage and current), maximizing efficiency. ZVS is critical for reducing switching losses and improving efficiency. By setting the operating frequency above the system's self-resonant frequency, voltage-current phase alignment is optimized, minimizing power device stress. The proposed frequency control method ensures CV/CC outputs while maintaining ZVS conditions.

2 Methodology

2.1 Theoretical Foundation

The fundamental principle underlying the EC-WPT system is founded on the phenomenon of electric field coupling. When there is a potential difference between two electrodes, an electric field will be formed in the surrounding space. Through the alternating electric field, energy can be transmitted between the transmitting and receiving end [2]. The transmission productivity of the system mainly depends on the electrode structure, working frequency, and load characteristics. The theoretical basis of this study includes the electric field coupling theory, circuit theory, and control theory. Based on the LC-CLC resonant network, this thesis used an EC-WPT system with series current/voltage outcome characteristics. This system has a Constant-current frequency of operation point, one Fixed-voltage operating frequency point. Under the constant current operating frequency, the system can attain a stable current output; under that continuity voltage operating frequency, the system will achieve constant voltage output. Without additional switching devices, by simply frequency adjustment of the system, the system is capable of switch between the precision current and regulated voltage working modes. Regardless of whether it is in current-control mode or the Standard Technical Terms, the apparatus can achieve zero phase angle (ZPA) operation of input [3].

2.2 Formula derivation

Based on Kirchhoff's Voltage Law, the WPT system in Fig.1 can be described by the following equation:

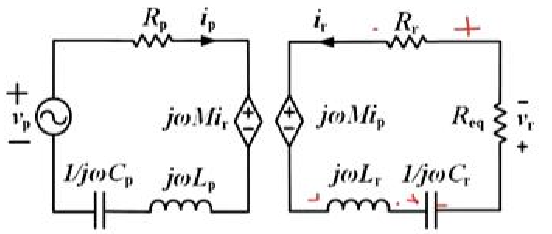

Fig. 1. The equivalent circuit representation of the SS compensation system.

Input voltage : Vp = Ip JWCf + if * (1/JWCf);
Substitute ip = if + it → if = ip – it;
Vp = ip*(JWCf + (1/JWCf) - it*JWCf) Vp=it*JWCF;
Input current It = Vp / (JWCf);
Input current It = Vp / (JWCf);
Output voltage Vr = Vp*M / Lf Vr=ir*Req;
The output current ir = Vp*M / (Lf * Req)

The currents in the primary and secondary coils, I·p and I·s, can be represented as [3]:

$$\dot{I}_p = \frac{-(R_s + R_{eq})\dot{V}_{ab}}{R_p(R_s + R_{eq}) + (\omega M)^2} \quad (1)$$

$$\dot{I}_s = \frac{j\omega M\, V_{ab}}{R_p(R_s + R_{eq}) + (\omega M)^2} \quad (2)$$

2.3 Methodology

In the model construction, we mainly employed two techniques, namely the LCC series compensation topology Structure and frequency control.

2.3.1 LCC Series Compensation Topology Structure: The third-order LCC compensation structure (inductor-capacitor-capacitor) compensation network is a classic resonant topology in wireless power transmission (WPT), which demonstrates significant desensitization of the whole system to coupling coefficients along with load variations and improve the transmission efficiency. Implementation Method: A resonant network is created by linking a Series-connected tuning capacitor with the parallel compensation capacitor in conjunction with an inductor on receiving end, thereby enhancing the energy transfer features. Analysis of the relationship between resonant frequency points and impedance matching, and derivation of the conditions for constant voltage (CV) and constant current (CC) output [4].

2.3.2 Frequency Control Strategy Core Idea: Through modifying the operational frequency of the inverter, the system can dynamically match the resonant characteristics, achieving constant voltage or constant current output without switching the compensation topology. Key Methods: Constant Voltage Type: In scenarios where the frequency surpasses the resonant frequency, the system presents an inductive impedance, and the output voltage can be stabilized through fine frequency adjustment. Constant Current Mode: When the frequency is lower than the resonant frequency, the system presents a capacitive impedance, and the output current can be maintained constant through frequency control. Frequency Segmentation Control: Switching frequency intervals according to load requirements and implementing dynamic adjustment through closed-loop feedback.

3 Simulation setup

3.1 MATLAB Simulation Analysis

Based on the Maxwell simulation, we established a frequency modulation system model with PI control in MATLAB/Simulink to confirm that frequency regulation is feasible with output of constant voltage and constant current. The simulation steps are as: Construct the WPT system's circuit model shown in Fig.2, incorporating the load end circuit, compensation network, and inverter circuit; Design the PI controller by adjusting the operating frequency to attain a steady output of voltage and current at the load end of the wireless transmission system; Conduct frequency-domain and time-domain simulation analysis to observe the dynamic response characteristics of the system, and optimize the control parameters to improve the steady-state accuracy and dynamic performance.

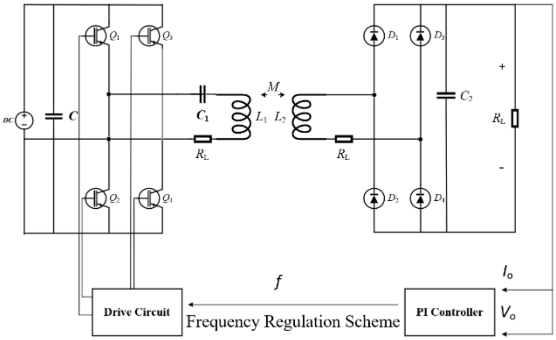

Fig. 2. The Circuit diagram of magnetic coupling wireless transmission system [5].

3.2 Power Supply and Inverter Circuit

As shown in Fig.3, inverter voltage source: IGBT gate drive circuit. Since the four IGBTs cannot conduct simultaneously, Qp1 and Qp4 cannot conduct at the same time. Qp1 and Qp2 are not allowed to conduct completely, and complete conduction will directly burn out. Similarly, Qp3 and Qp4 cannot conduct completely either. Therefore, a reverse module needs to be connected later.

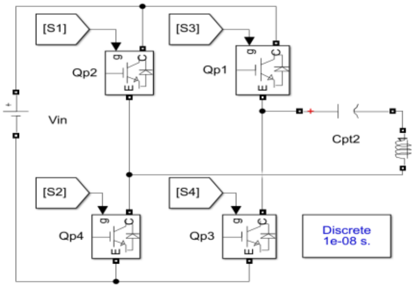

Fig. 3. The Power Supply and Inverter Circuit

LCR Resonant Circuit as shown in Fig. 4**:** A pair of coupled inductors are connected in series with a pair of capacitors. The capacitance value is determined by the LC ratio state as $C=1/(w^2*L)$, $\omega=2\pi f$

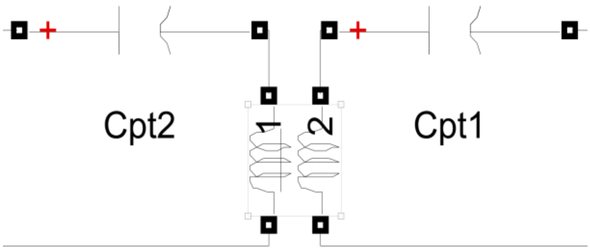

Fig. 4. power transmission coil.

3.3 Receiver circuit

A rectifier bridge composed of four diodes and a filter capacitor has been shown in Fig. 5.

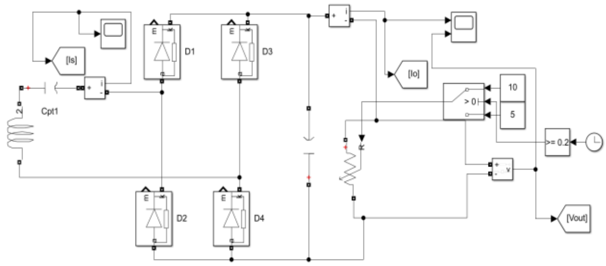

Fig. 5. The Rectifier bridge and load.

The electrical energy induced by the receiving coil is high frequency alternating current while most loads require direct current supply. The rectifier bridge converts the alternating current into pulsating direct current through diodes or synchronous rectification switches Working process: By taking advantage of the conduction characteristics of four diodes (full-bridge rectification), the negative half-cycle of the alternating current is inverted to the positive half-cycle, outputting a unidirectional pulsating direct current.

3.4 Load portion

As shown in Fig. 6, when the input 2 meets the selected criteria, go through input 1; otherwise, go through input 3. From left to right (or top to bottom), the inputs are numbered. The second input port is the control port, whereas the first and third are data ports. The criterion for control port 2 is u2 > Threshold. From 0 to 0.01s, The resistance to load is 5Ω, and after 0.01s, the load resistance is 10Ω.

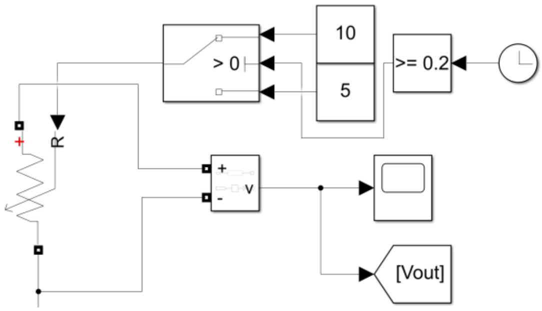

Fig. 6. The Load and its voltage sampling terminal

The proportional coefficient P is determined by simulation. We found that the larger the proportional coefficient is, the better the system response will be, but it will also lead to overshoot. The integral coefficient I is also determined by simulation

3.5 Maxwell Simulation Analysis

To deeply analyse the electromagnetic coupling characteristics of the system for wireless power transmission, we used Ansys Maxwell software to conduct simulation model of the coil structure and electromagnetic field distribution of the system. The simulation process included:

Designing the geometric structures of the coils that transmit and receive, and optimizing parameters to enhance the transmission efficiency. using finite element analysis (FEM) to determine the coils' mutual inductance properties and how they relate to variations in frequency. Evaluating the coupling coefficient and power transmission capacity of the system under different operating frequencies to provide data support for the subsequent design of control strategies. Additionally, considering that the system functions at elevated frequencies, typically between kilohertz and megahertz, where the skin effect cannot be neglected, electromagnetic simulation is essential to facilitate subsequent control system design[6].

4 Results

4.1 Solenoid Coil Module By Maxwell

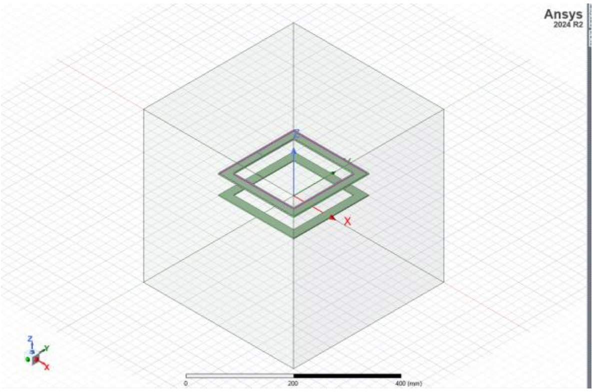

Fig. 7. The Electromagnetic coil simulation model.

Table 1. simulation data（frequency (kHz)=100kHz）

Mutual inductance value(μH)	Coil1 self-inductance value(μH)	Coil2 Self-inductance value(μH)
9.32	42.75	42.51

Table 1 and Fig.7 shows the mutual inductance and self-inductance values were analysed when the two coils were spaced 10mm apart.

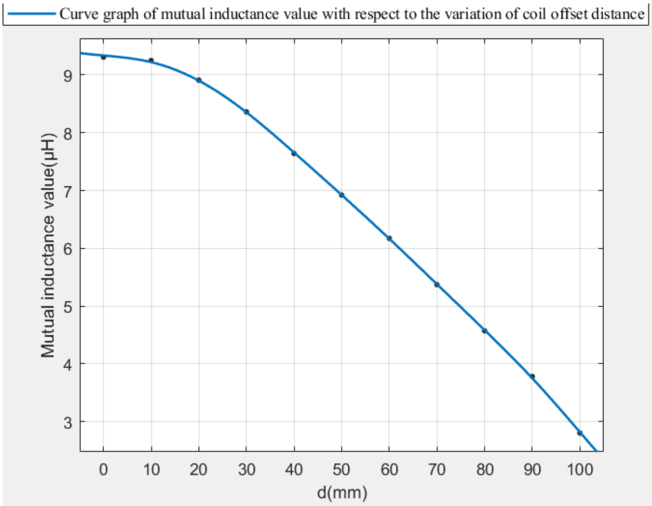

Fig. 8. The Graph of the Relationship between Magnetic Induction and Distance

The variation of self-inductance as the coil displacement changes was studied, resulting in a corresponding curve graph in Fig.8.

This simulation mainly models square wireless power transfer. The square coils are made of copper, with a current of 100mA flowing through them, and each coil consists of a single turn. The entire simulation environment is set in a vacuum, and the AC operating frequency is 100kHz.

Two main simulations were conducted:

The mutual inductance and self-inductance values were analysed when the two coils were spaced 10mm apart. This table provides the self-inductance (L) and mutual inductance (M) values of the coils, reflecting their electromagnetic characteristics at a fixed distance. By analysing these data, we can evaluate the magnetic coupling strength of the system. A higher mutual inductance M indicates better energy transfer efficiency. If L or M varies significantly, it may suggest that coil structure, material, or winding methods have influenced the inductance properties. Furthermore, studies have demonstrated that incorporating ferrite materials into the coupling mechanism can enhance the mutual inductance of the coupling coils without altering the transmission distance, thereby improving the efficiency of resonant wireless power transfer (WPT) systems is significantly enhanced using ferrite [7]. Additionally, ferrite not only increases the coupling coefficients and mutual inductance substantially but also maintains high coupling coefficients and mutual inductance in the case of vertical offset of 40 mm, which means that the addition of ferrite has improved the resistance to offset to a certain extent. offset ability to a certain extent.

The variation of self-inductance as the coil displacement changes was studied, resulting in a corresponding curve graph. This data reflects how the self-inductance changes as the relative position of the coils shifts. Generally, as d increases, the self-inductance gradually decreases because the magnetic field coupling between the coils weakens. This curve helps evaluate the impact of coil misalignment on transmission performance and aids in optimizing coil design to improve tolerance to misalignment.

4.2 PI Control Module By MATLAB

Based on the PI frequency control shown in Fig. 9, the system we designed has developed two modes: constant voltage control and constant current control. Both are based on the PI frequency control of the LCC-S system. The proportional coefficient P is determined by simulation. We found that the larger the proportional coefficient is, the better the system response will be, but it will also lead to overshoot. The integral coefficient I is also determined by simulation. We found that it can be used to eliminate the steady-state error in proportion. However, the larger the integral term is, the slower the system response will be[8]. Data acquisition: We obtain the secondary output quantity by measuring the voltage and current once, and then directly control the primary side to pull back the output current value.

4.3 Constant Voltage Output (CV)

The series-connected WPT usually adopts the series-series (SS) resonant compensation topology: Primary side (transmitting end): The output of the inverter is connected in series with a capacitor to balance out the inductive effect of the transmitter coil, forming a resonant circuit. Secondary side (receiving end): The inductance of the receiving coil resonates with the series capacitor, and after rectification, it supplies power to the load. Resonance condition: C = 1/(w^2*L), ω = 2πf. Ensure that the system operates at the resonant frequency to achieve the highest efficiency [9].

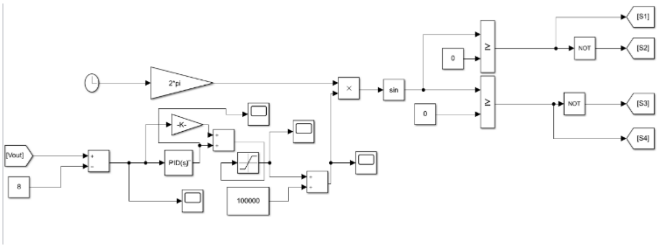

Fig. 9. The PI control model of the SS transfer system.

Finally, sin($2\pi f0$) is obtained, where $f0$ is the required constant voltage frequency [10].

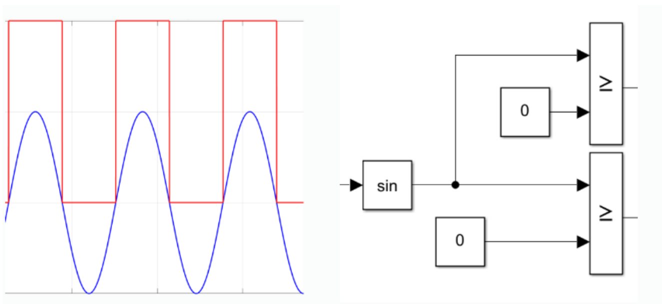

Fig. 10. The Waveform and output principles in CV mode.

Fig.10 compares a constant value with a triangular wave to achieve control by changing the duty cycle. First, an input triangular wave is generated, and then the level is changed according to the set threshold. Under constant voltage condition, P is set to 8, then when the output voltage is greater than 8V, a high level is output, and vice versa.

4.3.1 Waveform And Result

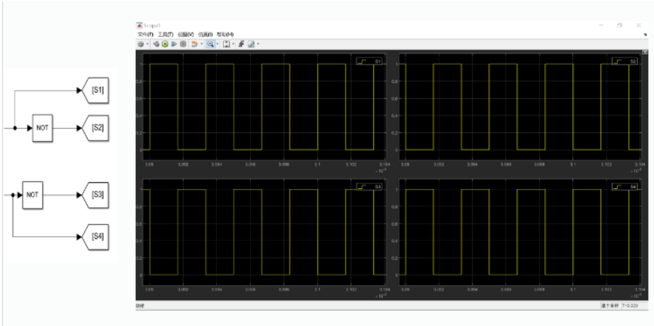

Fig. 11. The Actual Waveform in CV mode of the SS transfer system.

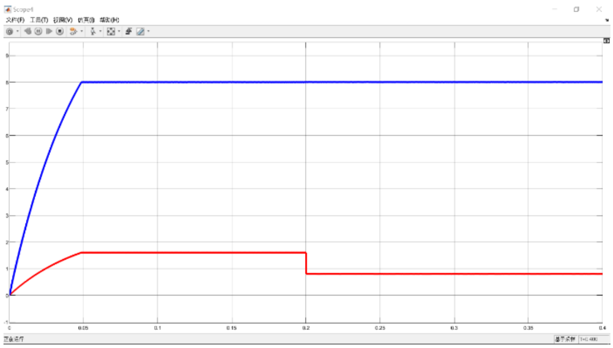

Fig. 12. The Actual Waveform about the relationship between voltage and time in CV mode of the SS transfer system.

Fig.11 and Fig.12 illustrates the MATLAB Simulink Constant voltage output Simulation. During the design process, before successful debugging, the voltage output image showed a small amount of ripple. By adjusting the size of the PI controller and stabilizing capacitor appropriately, this problem was solved. Now stabilized at 8V, the voltage across the load has reached its ideal value. At 0.2s, the load resistance value changes while the voltage at both ends remains unchanged.

4.4 Constant Current Output (CC)

Constant current output characteristic: In the resonant state, a stable current output is achievable through the S-S compensation system. When the load changes, the system output current remains unchanged, which makes it particularly suitable for scenarios requiring constant current charging[11].

4.4.1 Waveform and Result: Fig.13 and Fig.14 shows the Constant current output（CC）Simulation. After reaching the theoretical constant current output value of 2A, the load changes within 0.2s, and the current value slightly changes in a short period of time but immediately returns to the stable value before. Theoretical and simulation results show nearly identical trends.

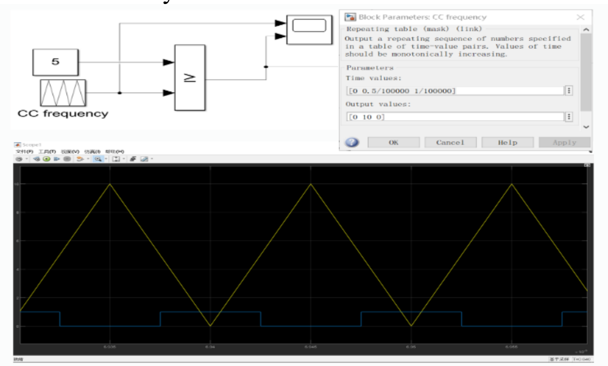

Fig. 13. The Actual Waveform in CV mode of the SS transfer system.

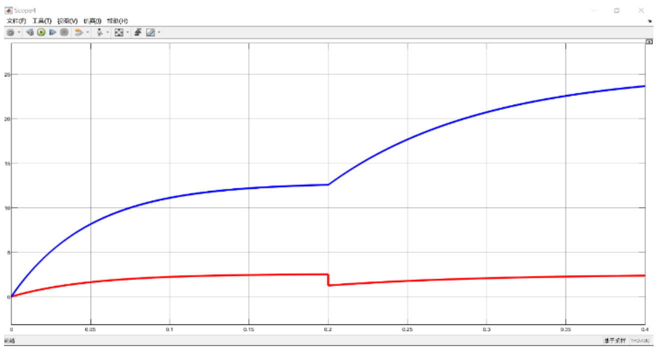

Fig. 14. The Actual Waveform about the relationship between voltage and time in CC mode of the SS transfer system.

5 Conclusion

Theoretical analysis and simulations confirm that frequency control effectively achieves CV and CC outputs in WPT systems. The system quickly stabilizes under load variations, making it suitable for applications like battery charging. Frequency stabilization techniques based on impedance transformation enhance both system stability and transmission efficiency. Maxwell simulations indicate that coil spacing significantly impacts electromagnetic characteristics, and optimized coil design improves efficiency. Proper selection of PI controller parameters (P and I gains) is crucial to achieve an optimal compromise between system response speed and overshoot. with simulation results aligning closely with theoretical predictions. For magnetically coupled resonant WPT systems, variations in transmission distance and load fluctuations cause resonant frequency deviations from inherent values, leading to reduced power transfer and efficiency

Authors Contribution

All the authors contributed equally and their names were listed in a alphabetical order.

References

1. Yin Huangfei. Research on Magnetically Coupled Resonant Wireless Power Transfer System [D]. Chang'an University, 2022.
2. Li Yixin. Research on Frequency Tracking Control of Magnetically Coupled Resonant Wireless Power Transfer [D]. Hebei University of Technology, 2017.
3. Yan Zhiqiong. Electric Field Coupling Wireless Power Transfer System with Constant Current/Constant Voltage Output Based on Frequency Switching [D]. Chongqing University, 2023. DOI: 10.27670/d.cnki.gcqdu.2023.003487.
4. Xie Shunli. Research on Frequency Tracking Control of Wireless Power Transfer System [D]. Hunan University of Technology, 2024. DOI: 10.27730/d.cnki.ghngy.2024.000458.
5. Yongbin J., Laili W., Yue W., et al. Analysis, Design, and Implementation of WPT System for EV's Battery Charging Based on Optimal Operation Frequency Range [J]. *IEEE Transactions on Power Electronics*, 2019, 34(7): 6890–6905.
6. Zhang Shiqi. Optimization Design of Wireless Power Transfer System Based on Compensation Network [D]. University of Electronic Science and Technology of China, 2022. DOI: 10.27005/d.cnki.gdzku.2022.003278.
7. Wang Huizhong, Fang Lixiang, He Keke. Magnetic Shielding Analysis of Wireless Power Transfer Coupling Structure Based on Maxwell [J]. *Electrical Automation*, 2020, 42(1): 105–107.
8. Q. Qiao, Y. Guo, J. Lian, et al. "Downhole Wireless Power Transmission System," 2024 4th International Conference on Energy Engineering and Power Systems (EEPS), Hangzhou, China, 2024, pp. 654–659, doi: 10.1109/EEPS63402.2024.10804466.
9. Yang Mei, Sun Hongqiang, Bai Zhenlin, et al. Modeling and Frequency Control Research of Three-Phase Wireless Power Transfer System [J]. *Electric Drive*, 2018, 48(6): 54–58.
10. Jian Liu, Wei Kang, Xiaodong Li, et al. Constant Power Radio Energy Transmission System for Unmanned Aerial Vehicle // 2024 CNKI China National Knowledge Infrastructure, 2024; 6–5.
11. Zhang Xu, Zhang Hongjuan, Jin Baoquan, et al. Design of Wireless Power Transfer System Based on STM32 Frequency Tracking Control [J]. *Journal of Shanghai University of Electric Power*, 2022(004): 038. DOI: 10.3969/j.issn.2096-8299.2022.04.003.