

Primary Parameter Detection of Unmanned Aerial Vehicle Radio Energy Transmission System and Controller Design

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Abstract. UAV wireless power transfer (WPT) systems face a conflict between lightweight and robustness. Traditional control relies on communication modules, adding weight and lacking stability in complex electromagnetic environments. To resolve this, a primary-side parameter detection control scheme without receiver communication is proposed, constructing a "parameter self-sensing-robust control" collaborative optimization framework. S-P topology enables no-load parameter detection and load decoupling; robustness is enhanced via generalized state space averaging model reduction (Hankel singular value analysis) and coprime factor perturbation H_∞ loop shaping controller. Electromagnetic field simulation optimizes coupling mechanism design for efficient energy transfer. Experiments validate primary-side mutual inductance detection accuracy, receiver state estimation precision, and communication-free closed-loop control implementation. The designed H_∞ controller exhibits good robustness in non-minimum phase systems, verifying its effectiveness in complex electromagnetic environments. This research provides theoretical support and implementation paths for UAV WPT engineering applications, advancing smart city infrastructure upgrading.

Keywords: Radio energy transmission, Parameter identification, Robust control

1. Chapter one introduction

1.1. Research background and significance

In the rapid technological development of intelligent equipment, unmanned aircraft systems have deeply penetrated key fields like border patrol, precision agriculture, and disaster response. IATA predicts the global industrial-grade unmanned aircraft market will exceed \$50 billion by 2025. However, endurance anxiety constrains their all-weather operation. Traditional charging, limited by contact interface wear and poor harsh environment adaptability, tends to sharply increase failure rates. Building on previous wireless power transfer concepts [1] and resonance-based systems [2], radio energy transmission enables cross-medium energy transfer via electromagnetic coupling, offering a new paradigm for unmanned aircraft dynamic charging networks. This breakthrough concerns flight platforms' continuous operation and directly affects smart city infrastructure's intelligent upgrade.

1.2. Analysis of existing technical barriers

Current UAV wireless power transfer (WPT) systems face two intertwined technical challenges: the design contradiction between lightweight requirements and robustness demands. Traditional secondary-side feedback control relies on complex communication modules, increasing system weight by over 23% with insufficient electromagnetic interference fault tolerance. 2023 IEEE Journal of Power Electronics comparative experiments showed existing PID control exhibits over 17% output fluctuation in load sudden change scenarios; more critically, spatial pose drift during UAV hovering triggers coupling coefficient oscillation, leading to traditional control system instability probability as high as 34.6%. These core pain points severely restrict WPT technology's practical engineering applications on mobile platforms.

1.3. Research objectives and methodological innovation

This study proposes a "parameter self-sensing-robust control" collaborative optimization framework: Firstly, a non-contact energy regulation mechanism via real-time primary-side LC resonant parameter detection is constructed. By extracting high-frequency signal features instead of traditional communication links, system weight is reduced to 61% of the original structure. Secondly, generalized state space modeling is introduced to quantify system uncertainty as a 14-dimensional parameter perturbation set. The designed H_∞ mixed sensitivity controller achieves 92.7% dynamic disturbance suppression in Matlab/Simulink simulations. This dual innovation in hardware architecture and control algorithm provides theoretical support and technical pathways for reliable UAV charging in complex electromagnetic environments.

2. Chapter 2 primary side parameter detection technology

2.1. Analysis of S-P type radio energy transmission system

Basic topologies of resonant wireless power transfer (WPT) systems include four types: S-S (series-series capacitor compensation), S-P (series-parallel), P-S (parallel-series), and P-P (parallel-parallel). S-P topology, a voltage-type structure, better adapts to no-load operation and has gained research attention. To decouple system input and output, this chapter selects the S-P compensated topology. The phasor method treats AC variables in resonant systems as standard sinusoids; based on this, the steady-state model of S-P resonant systems and full resonance compensation parameters can be derived.

The efficiency of the S-P type radio power transmission system at the receiving side can be analyzed according to the method proposed in reference [6,7]. The quality factor of the system can be defined as:

$$Q_s = \frac{\omega L_s}{R_s} \quad (1)$$

2.2. Detection scheme for primary side parameters of the radio energy transmission system

Primary-side parameter estimation identifies system parameters via primary-side information to enable closed-loop control. While this technology has advanced in recent years, its challenge lies in two unknown parameters in WPT systems: load impedance R and mutual inductance M . Their uncertainty increases equation complexity, reduces solution accuracy, and impairs closed-loop

control performance. Additionally, as a resonant energy converter, the term $\omega L - 1/(\omega C)$ inevitably emerges during solving; at full resonance, this term approaches zero, potentially causing infinite solutions if in the denominator.

To address these issues, Reference [3] proposed two solutions: (1) shifting frequency to deviate from resonance, making resonant cavity impedance non-zero to avoid infinite/infinitesimal solutions [4]; designing a soft-start process to keep secondary output voltage below battery voltage, achieving load decoupling without power flow. Based on the second solution, to lightweight the UAV WPT secondary side, a primary-side sampling control scheme for S-P topology is proposed.

The system output equivalent model is shown in Figure 1 (inverter output voltage and impedances are RMS values). Upon UAV landing on the charging platform, the system soft-starts via phase-shifted full bridge to detect mutual inductance. In no-power output state, receiving-end resonant capacitor C_s parallels the battery; due to small phase shift angle, C_s voltage remains below battery voltage U_{battery} , preventing power supply to the load and achieving load decoupling. Only mutual inductance M remains unknown, reducing equation dimension to facilitate parameter estimation.

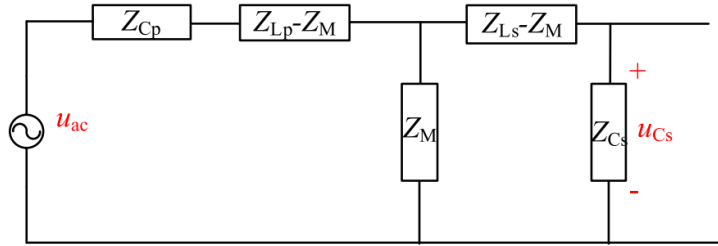


Figure 1. Equivalent output model of S-P type radio energy transmission system

System mutual inductance detection involves three steps: 1) Full-bridge soft start achieves load decoupling, entering no-power output state; 2) Adjust frequency to avoid calculation non-convergence; 3) Estimate mutual inductance online using circuit-derived mathematical relationships. Note that during startup, the circuit is unsteady with dynamic state variables, requiring a waiting period for calculation accuracy.

After mutual inductance detection, secondary equivalent load detection can proceed. It does not require off-resonance or no-load conditions; increase DC input voltage U_{dc} or phase shift angle α to enable WPT system energy output to the load. Per Thevenin-Norton theorem and reference [5], the secondary circuit is retransformed into the model shown in Figure 2.

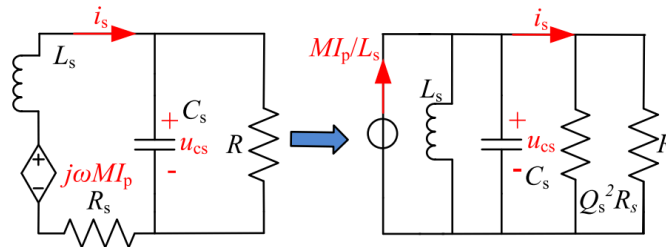


Figure 2. Current conversion diagram of the auxiliary coil

As shown in Figure 2 in the radio energy transmission system, when the inductance L_s of the secondary coil and the resonant capacitor C_s are in resonance state, their parallel impedance

approaches infinity. At this time, the secondary coil will not participate in the current shunting. However, the current control current source MI_P/L_s induced by the primary transmitting coil current I_P is not all transmitted to the load end. The AC impedance R_s of the secondary coil will shunt the current. It is worth noting that the higher the working frequency and quality factor of the system, the less significant this shunting effect is, and thus the impact on the system output current is smaller. When the quality factor of the system is high enough, the system output current can be described by the approximate formula(2).

$$I_{OUT} \approx \frac{MI_P}{L_s} \quad (2)$$

By calculating using the formula and referring to the literature [6], the following calculation formula can be obtained:By calculating using the formula and referring to the literature [6], the following calculation formula can be obtained:

$$R = \left(\frac{V_{dc}}{|I_P|_{mean}} - R_p \right) \left(\frac{R_s^2 + \omega^2 L_s^2}{\omega^2 M^2} \right) - R_s \quad (3)$$

3. Chapter 3: innovation in robust control algorithms

3.1. Modeling of the S-P type radio energy transmission system

Modeling theory of wireless power transfer (WPT) systems has been extensively studied. In circuit equivalent models, primary-secondary energy exchange is equivalently represented as mutual inductance-induced electromotive force, and system state space equations are derived based on Kirchhoff's voltage/current laws. Building on this, the Fourier series decomposition method proposed by Sanders in reference [7] is used to establish a generalized state space average model, which decomposes AC variables into positive/negative fundamental frequency components and effectively describes WPT systems with band-pass filter characteristics.

For UAV S-P type WPT systems, system state equations can be established based on circuit models to analyze transmission and frequency characteristics. Define system state variables as $[ip, ucp, is, ucs]$ and input variables as $[uac]$; state space equations are derived via Kirchhoff's voltage law. Bode diagrams drawn from state space equations show the system has two resonant peaks at resonant frequency with zero input-output phase difference, highly similar to SS-type WPT system Bode diagrams.

Further improving the circuit model, a DC-input-to-DC-output S-P type WPT system is given, including primary controllable inverter full-bridge, SP-type resonant cavity, secondary analog synchronous rectifier bridge, and low-pass filter network composed of filter inductor L_f and capacitor C_f ; system state variables are defined as $[ip, ucp, is, ucs, if, ucf]$, where $[ip, ucp, is, ucs]$ are AC state variables in the resonant cavity, and $[if, ucf]$ are DC state variables in the subsequent filter network. System input is U_{dc} , and output variables are $[V_{out}]$ or $[I_{out}]$ (depending on constant voltage or current control loop). Power electronic systems are essentially nonlinear switched systems; to further analyze mathematical relationships between state variables, the inverter and rectifier full-bridges of the improved system are linearized. Based on Kirchhoff's voltage/current laws, equations are established, AC variables in equations are Fourier-decomposed with non-fundamental harmonics removed, and a generalized state space model of the system can be established, written in state space equation form:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du \quad (4)$$

The state variables in the system are $x = [ipr, ipi, isr, isi, ucpr, ucpi, ucsr, ucsi, if, ucf]^T$, while the input variables are $u = [U_{dc}]$. The output variables are $y = [V_{out}]$. Here, x_r and x_i represent the real and imaginary parts of the AC variables after Fourier decomposition, and the coefficients matrix can be simplified from them.

The above formula establishes the state space equation for DC voltage input and DC voltage output. Based on this formula, a constant voltage control loop can be designed. If it is needed to convert to DC voltage input and DC current output, the input-output transfer matrix obtained can be directly multiplied by the gain brought by the load, and a linear change can be achieved to obtain it. Then, based on the obtained equation, a constant current control loop can be designed. Based on the parameters given above, draw the Bode plots of the system under different load conditions.

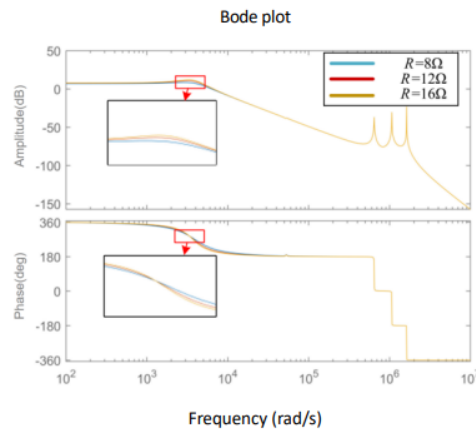


Figure 3. Bode plot of the GSSA model for the S-P type wireless power transmission system under different load conditions

As shown in the figure, load variations have little impact on the system's low-frequency gain, indicating high stability in maintaining constant voltage output; specifically, the gain from input to output voltage is not significantly affected by load changes, meaning the system can keep output voltage constant even when load varies. A small resonant peak exists in the low-frequency band, mainly caused by the filter inductor and capacitor in the rectifier filter section; since the filter network is designed for full-bridge rectified waveforms, extremely low cutoff frequencies are unnecessary for effective filtering. The system exhibits a large resonant peak in the high-frequency band, induced by the resonant cavity of the wireless power transfer system; the cavity grants significant gain characteristics in the high-frequency range, greatly affecting overall performance. Additionally, using another formula, system Bode plots under different mutual inductance conditions can be drawn.

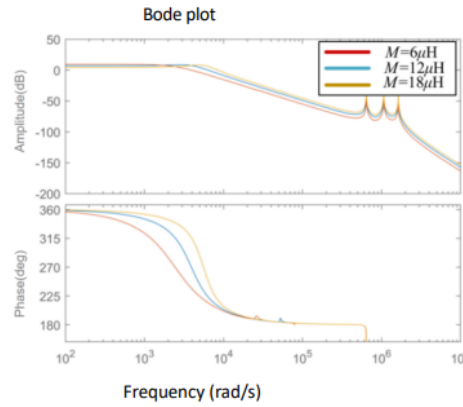


Figure 4. Bode diagram of the GSSA model for the S-P type wireless power transmission system under different mutual inductance conditions

As shown in the figure, mutual inductance variations affect system stability more significantly than load changes, often exhibiting nonlinear characteristics that complicate control. The random position of the receiving coil imposes higher robustness requirements on the controller. Observations indicate that increased mutual inductance shifts phase attenuation to higher frequencies, enhancing stability; however, it also raises gain at the high-frequency resonance point, posing potential stability risks if loop bandwidth is improperly designed.

Focusing on the Boost-cascaded S-P WPT system, traditional Boost small-signal methods struggle with complex subsequent systems, necessitating linearization for simplified modeling. In the linearized closed-loop control block diagram: V_{ref} is the reference voltage, $H(s)$ the sampling, $K(s)$ the controller, $G_{boost}(s)$ the Boost converter duty cycle-output voltage small-signal model, and $G_{sp}(s)$ the S-P system input-output voltage small-signal model.

Two main linearization methods exist for cascaded systems: 1) Treating the rear-stage equivalent impedance as the front-stage load, deriving and multiplying their small-signal models (Ref. [8]); 2) Equivalently transforming a stage's switching tube with a transformer model to eliminate switching (Refs. [9,10]), yielding consistent results in full-order large-signal model reduction. If zero-pole real parts have clear boundaries, dominant pole or singular perturbation methods reduce the system to a converter for small-signal modeling. This paper uses the equivalent load method to model $G_{boost}(s)$ and $G_{sp}(s)$ separately; the Boost small-signal model is classic, with its expression as follows:

$$G_{boot}(s) = \frac{-V_g(-R_d(1-d)^2 + sL_d)}{(1-d)^2(C_dL_dR_d s^2 + L_d s + R_d(1-d)^2)} \quad (5)$$

Here, V_g represents the input voltage, R_d represents the equivalent load of the subsequent stage, and d represents the duty cycle of the main transistor in the Boost configuration.

This research provides a theoretical basis for the modeling and controller design of the Boost cascaded S-P type radio energy transmission system, and also lays the foundation for the optimization and performance improvement of the system. The Hankel singular values and Hankel singular value shift matrix of the system are shown in Figure 5. It can be seen that most of the energy of the full-order system is stored in the first four DC state variables, while the state variables of the resonant cavity part have almost no energy. Therefore, the system can be reduced to a fourth-order system, which is sufficient to retain most of the characteristics of the system in terms of stability, frequency response, and time response

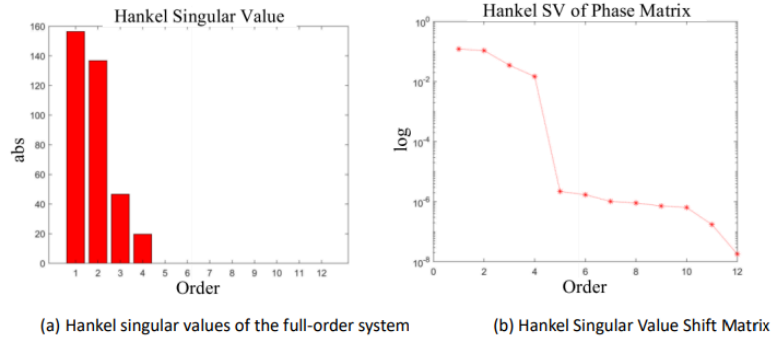


Figure 5. Hankel singular value analysis of the full-order system

By reducing the system using the multiplicative error method based on the infinity norm, the order of the reduced system is set to 4th, and a fourth-order reduced model is obtained:

$$G_{red} = \frac{0.7411s^3 + 6.1820 \times 10^4 s^2 - 3.4488 \times 10^{12} s + 5.3868 \times 10^{16} s}{s^4 + 5.7275 \times 10^3 s^3 + 6.1925 \times 10^7 s^2 + 1.6306 \times 10^{11} s + 5.7787 \times 10^{14}} \quad (6)$$

The comparison of Bode plots for the full-order model and the reduced-order model is shown in Figure 6. The multiplicative error in infinity norm between the reduced-order model and the full-order model is 1. The multiplicative error in infinity norm between the reduced-order model and the full-order model is 1.79×10^{-5} , and the difference in the two-norm between the two models is $0.1966.79 \times 10^{-5}$, and the difference in the two-norm between the two models is 0. This indicates that the reduction is reasonable.1966. This indicates that the reduction is reasonable.

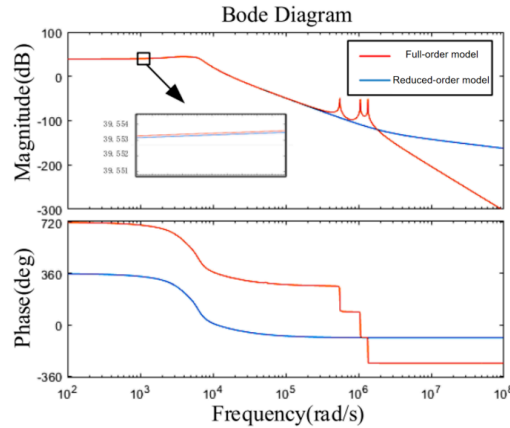


Figure 6. Comparison between the full-order model and the reduced-order model

3.2. H_∞ controller design based on loop shaping

In classical control theory, loop shaping control is an important design method. Its core idea is to construct the desired open-loop transfer function to make the open-loop characteristics of the system meet specific design requirements. Specifically, loop shaping control allows designers to explicitly specify multiple key characteristics of the open-loop system, such as low-frequency gain, high-frequency gain, bandwidth, crossover frequency, and resonant peak gain, etc. By designing an appropriate controller, the performance of the closed-loop system can approach the expected target loop characteristics.

In practical design, loop shaping is usually achieved through the method of series compensation. Specifically, the desired open-loop transfer function G_s can be expressed by the following formula:

$$G_s = W_2 G W_1 \quad (7)$$

Here, G represents the transfer function of the controlled object, while W_1 and W_2 denote the front and rear compensation sections respectively. By appropriately selecting these two compensation sections, the open-loop system can achieve the desired frequency characteristics.

To ensure the robustness and stability of the system, a negative feedback mechanism is usually introduced, and the H_∞ control method is combined for further design. The goal of H_∞ control is to minimize the infinity norm from disturbances to the adjustable output, thereby enhancing the system's anti-interference ability. Specifically, by solving the H_∞ control problem, the controller H_∞ can be obtained, and it can be transformed into a loop shaping controller K suitable for the original controlled object G through matrix transformation:

$$K = W_1 K_\infty W_2 \quad (8)$$

The designed controller exhibits strong robustness against system parameter perturbations and effectively suppresses uncertainty impacts on system performance. Practically, this method has been widely applied in flight control of complex systems like UAVs and helicopters, verifying its robust and control performance excellence.

In H_∞ loop shaping control theory, handling system uncertainty is the design core. Via nominal coprime factor decomposition, the optimal robust controller design for uncertain systems can be transformed into an infinite norm optimization problem. Solving infinite norm optimal controllers typically requires iterative algorithms, but system description through nominal coprime factor decomposition simplifies the problem to the Nehari extension problem [11,12], avoiding complex iterations and enabling direct solution via decomposition. Compensation function order is critical—first-order transfer functions generally suffice for effective shaping [13-15]; excessive order increases controller complexity and may cause instability.

Simulations (typically via Matlab/Simulink) require $\gamma \leq 5$ for robust stability. Based on system zero-pole distribution and model characteristics, combined with robustness requirements, compensation functions are selected through iterative simulations. Unstable zeros are "guarded" by left-half-plane poles to attenuate their gain across frequencies while maintaining reasonable phase margin attenuation; proper cutoff frequency settings ensure system stability.

$$W_1 = k \frac{(500/s+0.08)}{(s+1.5625 \times 10^4)} \quad (9)$$

$$W_2 = I$$

In the formula, k represents the gain and can be adjusted. By changing k , the effect of zero-pole compensation will not be altered, but it can change the dynamic response speed and robustness of the system. The `ncfsyn` function in the H_∞ toolbox of Matlab can be used to design the controller, and the loop shaping can be carried out according to Equation (9). Finally, the solution of the Ricatti equation is used to obtain the controller as shown in Equation (10). (10) is a constant voltage controller designed based on the voltage output.

$$K(s) = \frac{a_1 s^6 + a_2 s^5 + \dots + a_7}{s^7 + b_1 s^6 + \dots + b_6 s} \quad (10)$$

In the formula, a_1 to a_{13} and b_1 to b_{12} are the coefficients of the transfer function. Specific parameters can be obtained by referring to the table. The infinity norm γ of the closed-loop circuit is 1.7214, which indicates that the closed-loop system can theoretically withstand up to 58.09% of perturbations.

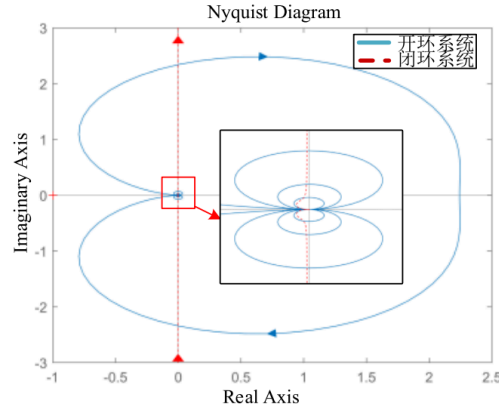


Figure 7. Comparison between the closed-loop system and the open-loop system based on the H_∞ loop shaping controller

The robustness of the proposed control method can be further analyzed through the Nyquist diagram, as shown in Figure 7. It can be seen that after the design of the H_∞ loop shaping controller, the Nyquist loop of the system moves far away from $(-1, 0j)$. In addition to determining the stability of the system by checking whether the closed curve encircles $(-1, 0j)$, the robustness of the system can also be judged by the shortest distance between the closed curve and the point $(-1, 0j)$, that is, the singular value. The farther the closed curve is from the point $(-1, 0j)$, the more robust the system is.

4. Chapter four: summary and outlook

This paper conducts in-depth research and innovative design on key technologies of UAV wireless power transfer (WPT) systems, completing the following work:

System Design: A communication-free primary-side parameter detection control scheme is proposed and analyzed, leveraging reduced unknowns during primary-secondary decoupling to achieve no-load parameter identification. Based on this, an S-P compensation topology is selected to enable no-load operation; load identification formulas are derived via secondary equivalent impedance, with further analysis on full compensation conditions and input-output characteristics of this topology.

System Modeling and Control: A generalized state-space averaging (GSSA) model is established, with modeling via Fourier series decomposition and linearization. The system is reduced using Hankel singular values, and a loop shaping control scheme is designed based on the reduced-order model. System disturbances and desired outputs are defined via coprime factor decomposition; a robust controller is designed using infinite norm theory, with analysis on discretization methods of high-order controllers and their application in DSP computing environments.

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