

Research on constant current output control for wireless charging of UAVs

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Abstract. In the context of an increasingly intelligent and modernized society, Unmanned Aerial Vehicles (UAVs), commonly known as drones, have been extensively deployed across various sectors. Despite their broad applications, the operational longevity of UAVs is often constrained by the limitations of their onboard battery capacities, particularly during extensive and prolonged missions. Wireless power supply has emerged as an efficacious solution to this challenge, potentially extending the operational duration of UAVs. However, the wireless charging process for UAVs is subject to various influencing factors, and maintaining a constant current is essential for the long-term health and service life of the UAV's lithium batteries. This paper introduces a constant current output control scheme for the wireless charging of UAVs to mitigate these issues. The primary research focuses on initially formulating the expression for the output current, investigating the impact of mutual inductance perturbation, and various system parameters on the output current. It further delineates the conditions under which the output current remains invariant to load impedance variations. Subsequently, to counteract the perturbations in mutual inductance, the paper proposes a constant-current output control scheme predicated on the estimation of mutual inductance. Specifically, by employing an offline-trained Artificial Neural Network (ANN), the mutual inductance can be estimated solely based on the current measurements from the transmitter side. Finally, to enhance the system's responsiveness to the continuous variation in mutual inductance, a Radial Basis Function (RBF) network is employed as an alternative to the ANN, thereby improving the system's agility.

Keywords: Wireless Charging, Constant Current Output, UAVs, Mutual Inductance Estimation, Radial Basis Function Network.

1. Introduction

1.1. Background and Significance of the Study

Radio energy transmission technology harnesses intangible media such as electric fields, magnetic fields, or acoustic waves to facilitate the wireless conveyance of electrical energy through space. Initially conceptualized by Nikola Tesla in the late 19th century, this technology is lauded as a transformative leap in the realm of energy transmission and accessibility [1]. With the prosperity of society and economy and the progress of science and technology, drones are widely known by people and applied in many occasions, such as agriculture, photography, parcel delivery, mapping and inspection of power lines or pipelines, etc [2-6]. And with the combination of UAVs and technologies such as image processing and intelligent control, UAV operations provide new solutions for intelligent inspection of transmission

grids [7-8]. Typically, the average operational flight duration of a commercial-grade Unmanned Aerial Vehicle (UAV), commonly referred to as a drone, is approximately 30 minutes [1]. Consequently, under conditions demanding extensive range and prolonged operation, the challenge of meeting the endurance requirements for UAV flight is nontrivial, and wireless charging emerges as an effective solution to this endurance dilemma.

However, upon docking at a charging station, the UAV's flight controller is deactivated, which may impede its capacity to stably and safely receive energy amidst complex environmental perturbations, such as during strong wind conditions. Furthermore, lithium-ion batteries, commonly utilized in UAVs, are ideally charged using a constant-current and constant-voltage charging regime to extend battery service life and enhance safety [9-11]. In this context, the precise control of output current at a constant level becomes an integral technological component within the wireless hover charging systems [12-14] designed for UAVs.

1.2. Current status of recent research in wireless energy transmission technology

1.2.1. Current status of foreign research. In 2022, academicians at the University of Perugia, Italy, crafted an avant-garde energy transfer system that adeptly utilizes distinct frequency channels to facilitate the concurrent transmission of energy and information, elucidating the nuances of power transfer dynamics within the system [15]. Advancing their work further, they introduced a streamlined methodology for the analytical and computational determination of the resonant frequency inherent in a planar helical coil. This was complemented by the development and application of software designed to calculate the comprehensive parameters of the coil ensemble.

1.2.2. Status of domestic research. The esteemed Professor Sun Yue and her team at Chongqing University have conducted an in-depth analysis of four magnetic resonance-mode electrical energy transmission system topologies. They have delineated the parametric boundary conditions for the system's transmission coil, which is configured to maintain a constant current and output voltage, as well as a constant voltage [15]. Concurrently, they have investigated the issue of energy loss in resonant mode wireless energy transmission systems and have delved into the strategic planning of inductively coupled wireless energy transmission power supply [16].

1.3. UAV Air Charging Key Research Elements

The aforementioned literature underscores that within the purview of wireless energy transmission applications, sustaining a stable output current at the energy reception end is challenging due to the vicissitudes of coupling effects, load variances, and system parameter fluctuations. The impacts of these perturbations on the output current can be adeptly mitigated through the innovative design of compensatory topologies or current control schemes. However, the preponderance of research has primarily considered the influence of single parameter perturbations. Given the unique characteristics of UAV applications and their operational environments, the UAV hovering wireless charging system confronts a more complex array of challenges than other wireless energy transmission applications. It necessitates a holistic consideration of the interplay between coupling effects, load alterations, and system parameter shifts on the charging current of the system. Thus, the research presented in this paper is centered on the realization of constant current control in wireless charging for UAVs.

1.4. Organizational structure

Chapter 1 primarily elucidates the research backdrop and significance of this treatise, delineates the extant research status of wireless energy transmission, and enumerates the principal research foci of this paper alongside the schematic arrangement of each chapter. Chapter 2 delves into the serial topology and higher-order hybrid topology to analyze the wireless energy transmission model, subsequently scrutinizing the effects of mutual inductance perturbation and parameter perturbation on the output current, and culminating in an analysis of the conditions under which the output current is decoupled

from load impedance. Chapter 3 introduces the artificial neural network model and proposes a mutual inductance estimation scheme predicated on this model as a means to estimate mutual inductance. Chapter 4 introduces the Radial Basis Function (RBF) network and formulates a robust constant current output control strategy to further address the constant current charging conundrum of UAVs. Chapter 5 encapsulates the summation of the research endeavors presented in this paper.

2. Output Analysis of Radio Energy Transmission System

2.1. Modeling Analysis

2.1.1. Series-series type low-order compensation topology. The wireless energy transmission system commonly employs four low-order topologies: the series-series compensation topology, the series-parallel topology, the parallel-series topology, and the parallel-parallel topology. This paper will analyze the mutual inductance model of the wireless energy transmission system as a foundational prototype.

Reactive power is an inherent byproduct of the loosely coupled transformer within a wireless energy transmission system, necessitating appropriate compensation. Reactive power compensation is generally executed in two manners: (1) comprehensive system reactive power compensation, wherein the receiver coil and its compensation capacitance are attuned to fulfill system resonance conditions, irrespective of whether the transmitter and receiver circuits are in parallel or series, followed by the derivation of the transmitter coil's compensation capacitance based on relational equations when the input impedance is purely resistive; (2) separate compensation for the reactive power of the transmitter and receiver coils, ensuring that the reactive power of both the transmitting and receiving coils is nullified, thereby achieving a zero reactive power state for the entire system.

2.1.2. Higher-order hybrid topology. The fundamental archetypes of higher-order hybrid topologies include L-type, T-type, and π -type network configurations. These elemental forms are amalgamated to create the higher-order hybrid topology networks employed within wireless energy transmission systems. Prominent among the hybrid topologies are inductor-inductor-capacitor compensation networks and inductor-capacitor-capacitor compensation networks, which can be dissected to derive expressions for the input current at the transmitter and the current at the receiver. This paper will analyze the inductor-capacitor-capacitor compensation topology as an exemplar.

In accordance with circuit theory, the dynamic circuit equation for the wireless energy transmission system predicated on the inductor-capacitor-capacitor compensation topology is as follows: (The original text was truncated and did not provide the equation.)

$$\begin{cases} L_r \frac{di_n}{dt} + u_{C_r} + i_n R_r = u_p \\ L_p \frac{di_p}{dt} - M \frac{di_s}{dt} + i_p R_p + u_{C_p} = u_{C_r} \\ L_s \frac{di_s}{dt} + i_s R_s + u_{C_s} - M \frac{di_p}{dt} = 0 \\ i_L R_L = u_{C_s} \\ C_p \frac{du_{C_r}}{dt} = i_p \\ C_s \frac{du_{C_r}}{dt} = i_s - i_L \\ C_r \frac{du_{C_r}}{dt} = i_c \end{cases} \quad (1)$$

Let the total impedance of the coil circuit at the transmitting end be Z_p and the total impedance of the circuit at the receiving end be Z_s , denoted respectively as:

$$Z_p = j\omega L_p + \frac{1}{j\omega C_p} + R_p \quad (2)$$

$$Z_s = j\omega L_s + R_s + \frac{R_L}{j\omega C_s R_L + 1} \quad (3)$$

Then the expressions for the input current at the transmitter and the current at the receiver can be obtained by the coupling equation as:

$$\vec{I}_{in} = \frac{\vec{U}_p \left(\frac{Z_s}{j\omega C_r} + Z_p Z_s + \omega^2 M^2 \right)}{\left(j\omega L_r + R_r + \frac{1}{j\omega C_r} \right) (Z_p Z_s + \omega^2 M^2) + (j\omega L_r + R_r) \frac{Z_s}{j\omega C_r}} \quad (4)$$

$$\vec{I}_s = \frac{j\omega M \vec{U}_{in}}{Z_s (j\omega L_r + R_r) + (j\omega C_r R_r + 1 - \omega^2 L_r C_r) (Z_s Z_p + \omega^2 M^2)} \quad (5)$$

Further, the output current of the load can be expressed as:

$$\vec{I}_L = \frac{\vec{I}_s}{1 + j\omega C_s R_L} \quad (6)$$

$$= \frac{j\omega M \vec{U}_{in}}{[Z_s (j\omega L_r + R_r) + (j\omega C_r R_r + 1 - \omega^2 L_r C_r) (Z_s Z_p + \omega^2 M^2)] (1 + j\omega C_s R_L)} \quad (7)$$

2.2. Effect of disturbing factors on output current

2.2.1. Effect of mutual inductive disturbances. The inherent variability in the hovering position of a UAV in the aerial realm inevitably leads to fluctuations in the mutual inductance between the UAV and the energy transmitter. Such fluctuations, in turn, impact the constancy of the output current and the stability of the system's performance. Hence, the perturbation of mutual inductance within the wireless energy transmission system stands as a principal factor affecting the steadiness of the output current. In an SS topology, as the coupling coefficient augments, the output current initially surges to a peak value then gradually recedes. Concurrently, the amplitude of the output current variation diminishes with the increment of the coupling coefficient. In contrast, within an inductor-capacitor-capacitor topology, the output current exhibits a monotonic increase with the escalation of the coupling coefficient. When the internal resistance of the resonant inductor at the transmitter is considered negligible, the output current in the inductor-capacitor-capacitor topology bears a linear relationship to the coupling coefficient.

2.2.2. Effect of parameter perturbations. As depicted in Figure 1, within a series-series topology, the system's output current escalates initially with the increase of the primary side's resonant capacitance, reaching its zenith at the system's resonant frequency. Beyond this point, the output current begins to decline. In the inductor-capacitor-capacitor topology, the output current decreases over a certain range as the resonant capacitance of the primary side increases. It can be inferred that alterations in the resonant capacitance at the transmitter side exert a more substantial influence on the output current in a series-series topology compared to that in an inductor-capacitor-capacitor topology.

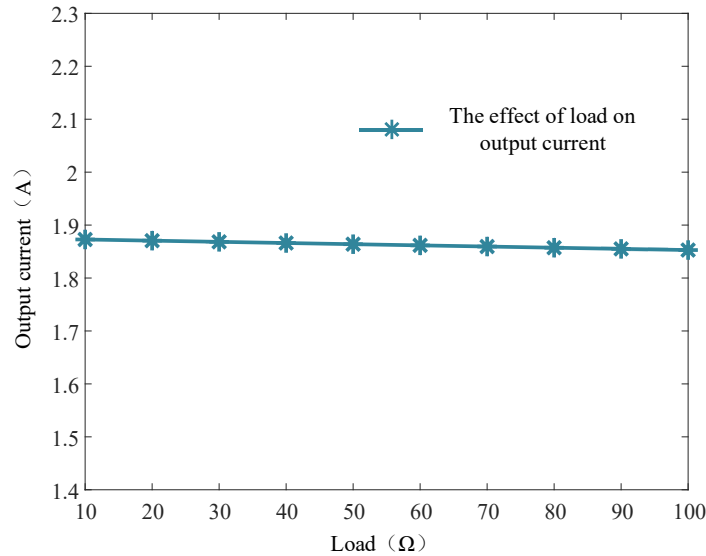


Figure 1. Effect of system parameter perturbation on output current.

2.3. Load-independent conditions for output current

2.3.1. Tandem-Tandem Topology. When the product of frequency and mutual inductance is sufficiently large, under the assumption that the internal resistance of the receiving and transmitting ends is negligible, the system's output current remains independent of the load resistance. However, in practical systems, the internal resistance of the coils cannot be overlooked. Moreover, when the mutual inductance between the transmitter and receiver coils is minimal, it becomes challenging to satisfy these conditions. Consequently, changes in load impedance will affect the system's output current, with an increase in load leading to a monotonic decrease in output current.

2.3.2. Higher-order hybrid topology. When the inductance of the receiving coil and the resonant capacitance achieve parallel resonance and the internal resistance of the receiving coil is disregarded, the output current can be rendered independent of the load impedance. In practical scenarios, the internal resistance of the receiving coil is non-negligible, and an increase in load results in a monotonic decrease in output current. Notably, in the inductor-capacitor-capacitor topology, the output current diminishes more gently with an increase in load. Therefore, the impact of load perturbation on the system's output current is less pronounced in the inductor-capacitor-capacitor topology than in the series-series topology.

3. Constant Current Output Control Based on Mutual Inductance Estimation

During UAV operations, the coupling effect between the transmitting and receiving coils is subject to fluctuations due to deviations in the flight control system's position control or the harsh working environment, such as strong winds. Compared to other parameter perturbations, mutual inductance perturbation persists throughout the entire operation and is the predominant disturbance in the UAV hovering wireless charging system. Thus, addressing the mutual inductance perturbation issue is pivotal to achieving a constant-current output in UAV hovering wireless charging.

3.1. Artificial neural network model

The architecture of the Backpropagation (BP) neural network encompasses an input layer, one or more hidden layers, and an output layer, with each layer consisting of numerous neuron nodes. The nodes between layers are interconnected via weights, and each neuron node undergoes a projection. The computation of a single neuron node, when scaled to the entire neural network, forms the process of forward propagation in the BP neural network model. The final input sample is processed by the neural network to yield the corresponding output. If the output deviates from the desired value, the weights are updated through an error backpropagation process. The cycle of forward calculation and error backpropagation is repeated until the error function meets the predefined requirements, thereby completing the BP neural network training process.

3.2. Mutual inductance estimation with variable coupling effects

As illustrated in Figure 2, the schematic diagram of the proposed scheme is integrated into the wireless energy transmission system. Initially, upon system startup, the system operates for a predetermined duration to achieve a stable state. Once in a steady state, the transmitter current is sensed by a current sensor. Given the presence of detection errors in the current sensor and the analog-to-digital converter, the detected currents are averaged. The averaging process occurs after sensing 20 sets of transmitter currents. It is crucial to note that even under stable operation, the transmitter current will exhibit inevitable minor fluctuations. Therefore, a scheme initiation signal is established, activating the mutual inductance estimation scheme only when the deviation of the system's transmitter current exceeds 1%. In the proposed mutual inductance estimation scheme, the mean-processed transmitter detected current is normalized and fed into the BP neural network, and the output of the BP neural network is then inversely normalized to obtain the estimated mutual inductance value.

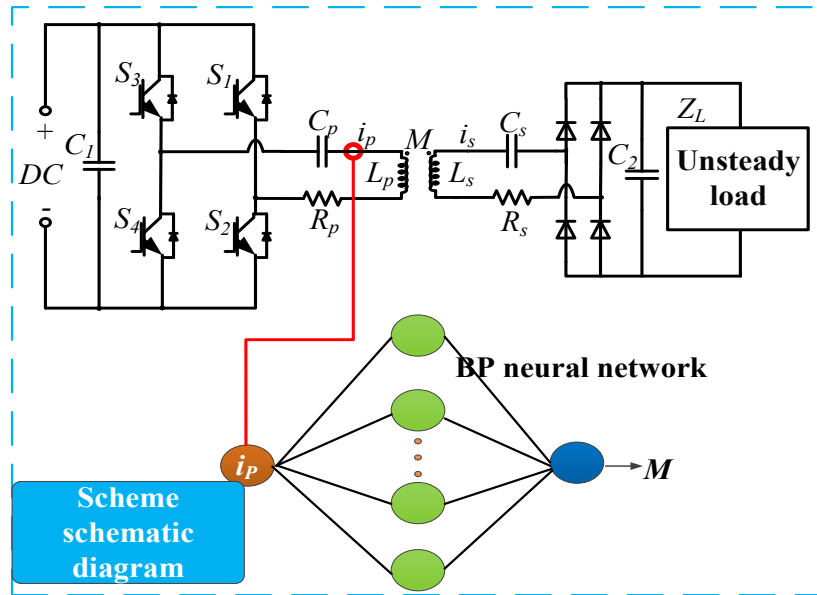


Figure 2. Schematic diagram of offline training process of BP neural network.

4. Model-free constant current output control based on online training

This chapter begins by introducing the Radial Basis Function (RBF) neural network model and comparing it with the traditional BP neural network. Subsequently, a robust constant current output control strategy utilizing the RBF neural network is proposed. Finally, the RBF network is optimized to suit the unique characteristics of UAV hovering wireless charging.

4.1. RBF network model

A quintessential configuration of the RBF neural network is depicted in Figure 3. The network is structured into three layers: an input layer, a hidden layer, and an output layer. The hidden layer employs radial basis functions as its activation function; the connection between the input and hidden layers is linear, while the connection from the hidden to the output layer is weighted. Similar to the BP neural network, the network's output can be articulated as:

$$O_j = \sum_{i=1}^m W_{ij} h_i$$

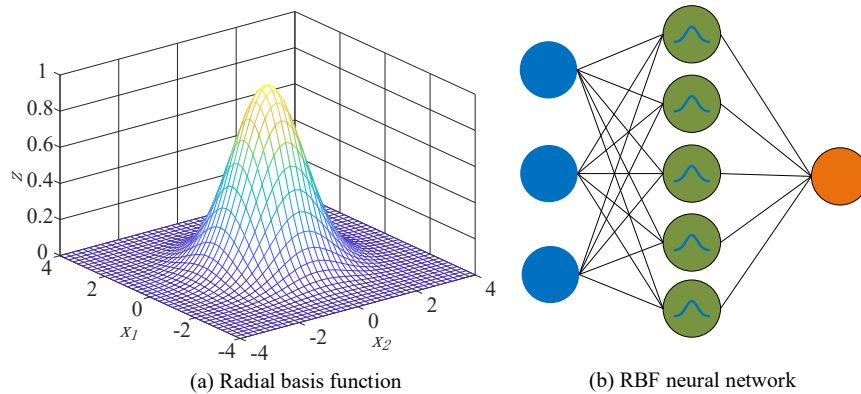


Figure 3. Schematic diagram of radial basis function and RBF neural network.

The Radial Basis Function (RBF) neural networks offer several distinct advantages over the traditional Backpropagation (BP) neural networks, particularly in the context of UAV wireless charging systems:

1. **Superior Approximation Accuracy:** The RBF networks are renowned for their enhanced capacity to approximate nonlinear functions with greater precision than BP neural networks. This is attributed to the radial basis functions that map inputs into a higher-dimensional space, facilitating the identification of an optimal fitting surface. Empirical evidence from this and other scholarly works substantiates the superior approximation accuracy of RBF networks for nonlinear functions [17].

2. **Rapid Performance:** RBF networks exhibit faster computational performance compared to BP networks. This is due to the localized response characteristic of the RBF networks, which is a stark contrast to the global response typical of BP networks.

3. **Efficient Use of Computational Resources:** RBF networks are more economical in terms of computational resources. Unlike BP networks, where full connectivity is required between adjacent layers, RBF networks connect only the implicit and output layers through weights, thereby reducing the overall computational overhead.

Given these advantages and considering the unique demands of UAV hovering wireless charging systems, this chapter advocates for the adoption of RBF neural networks in lieu of BP neural networks, proposing a robust constant current output control scheme designed to exhibit enhanced dynamic performance.

4.2. Robust constant current output control

In practical operating scenarios, the mutual inductance between the UAV's receiving and transmitting coils is subject to inevitable fluctuations due to the challenges associated with maintaining constant coil positioning. Furthermore, system parameters may deviate from nominal values as a result of environmental influences and internal heat generation. These perturbations can lead to variations in the output current, which can compromise the charging performance for hovering UAVs. To ensure the efficacy of the wireless charging system, it is imperative to address the following three pivotal technical challenges:

1. How to promptly address the effects of continuous changes in coupling coefficients?
2. How to accurately track varying desired charging currents?
3. How to effectively compensate for perturbations arising from parameter drift?

4.2.1. Control strategy. This chapter introduces a constant-current control scheme that leverages an online-trained RBF neural network. The output current I_L can be sensed at the receiving end by a current sensor and subsequently transmitted to the DSP controller at the transmitting end via a communication link. The measured output current, converted to its root mean square (RMS) value, serves as one of the input signals for the RBF network. Concurrently, the desired current I_{L_exp} and the phase angle $\alpha(i-1)$ from the preceding activation stage are selected as additional input signals. The RBF neural network processes these input signals to output the phase-shift angle α_i . This phase-shift angle, once stored in the phase-shift register, enables the DSP controller to regulate and output PWM signals, thereby adjusting the output voltage of the GaN-based inverter and controlling the output current accordingly. Moreover, the control scheme utilizes the error between the desired current and the output current to adjust the parameters of the RBF neural network in real-time. As the effects of the aforementioned perturbations manifest as fluctuations in the output current, the online-trained RBF neural network can adjust its parameters in response to these errors, thereby bolstering the robustness of the wireless hover charging system.

4.2.2. RBF Network Optimization. Building upon the control scheme flowchart presented in the preceding subsection, this chapter proposes an RBF network optimization method tailored to meet the unique requirements of the UAV hovering wireless charging system. The optimization method

encompasses data-enhanced kernel function centroid optimization, initial weights optimization, and the establishment of error limits. The specific implementation methods are as follows:

1. Kernel Function Center Optimization Based on Data Enhancement: This optimization technique sets the kernel function center corresponding to the desired current as a constant value.

2. Initial Weight Optimization: Given that the control scheme in this chapter modulates the network parameters through online training, the magnitude of the initial weights significantly influences the initial training velocity. Consequently, the initial weights (W) of the RBF network are calculated using the following equation:

$$W_i = ec_{\min} + i \frac{ec_{\max} - ec_{\min}}{2} \quad (8)$$

where $ec_{\min}$ is the minimum value after phase angle normalization in the generated data of Method 1; $ec_{\max}$ is the maximum value after normalization; and i is the number of nodes in the hidden layer of the RBF network.

3. Setting the Error Limit: Even in the absence of perturbations, the output current may exhibit fluctuations within a certain range. When the output current deviates from the desired value, the RBF neural network-based control scheme will suppress the deviation of the output current by adjusting the network parameters and, consequently, the output phase shift angle.

5. Conclusion

The emergence of aerial hovering wireless charging for Unmanned Aerial Vehicles (UAVs) has introduced a sophisticated solution adept at surmounting the demands of vast operational scopes and enduring flight missions, which have historically strained the battery capacities of UAVs. Considering the ubiquitous integration of lithium-ion batteries as the UAVs' power repositories, the necessity for a wireless charging infrastructure that exercises constant-current output control is both apparent and paramount. Such precise control is essential for prolonging the batteries' service lifespan and for reinforcing the integrity and safety of UAV operations.

However, the UAV hovering wireless charging system is enveloped by a complex ecosystem of challenges, primarily emanating from external environmental vicissitudes and internal system instabilities. The system is acutely vulnerable to a multitude of perturbations, ranging from relentless fluctuations in mutual inductance and undulating load dynamics to shifts in the desired current and the meandering progression of system parameters. These disturbances pose a significant threat to the efficacy and equilibrium of the wireless charging regimen.

In response to these multifarious challenges, the current scholarly endeavor unveils a pioneering compensation topology, ingeniously crafted to neutralize the impact of load impedance on the output current. This topology is predicated on the tenet that the output current should remain steadfast, unaltered by variations in load, thus ensuring a perpetual and dependable flow of energy to the UAV.

Moreover, to augment the system's robustness and its alacrity, this discourse advocates for an avant-garde model-free constant-current output control mechanism. This mechanism distinguishes itself by transcending the constraints of traditional frameworks, which are often tethered to preconceived models. By liberating itself from such dependencies, the system acquires an enhanced dexterity to nimbly adjust to the mercurial demands of real-time operational exigencies. The deployment of this control mechanism is projected to substantially refine the UAV hovering wireless charging system's nimbleness and robustness, ensuring a perpetual and secure conduit for power delivery—even amidst the vicissitudes of continuous mutual inductance variations, load oscillations, desired current alterations, and system parameter drifts.

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