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Analysis of the Influence of Impedance Characteristics of Traction Network on the Stability of Vehicle Energy Storage System and Compensation Strategy

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Abstract:

With the development of traction power supply system of rail transit in the direction of high efficiency and intelligence, the role of vehicle energy storage system in improving energy utilization rate and mitigating power grid impact has become increasingly prominent. However, the interaction between the impedance characteristics of the traction network and the control dynamics of the energy storage system is easy to cause low frequency oscillation and resonant instability, which restricts the stable operation of the energy storage system. In this paper, the coupling stability of traction network and energy storage system is the core of the research. Firstly, the frequency domain impedance model of traction network is established considering the parameter distribution characteristics, and the validity of the model is verified by the measured data. Through multi-time scale coupling analysis, the influence mechanism of impedance characteristics on the control bandwidth and modal damping of the energy storage system is revealed. It is found that the negative damping effect of traction network impedance is the key factor leading to the resonant frequency deviation of the system. To solve these problems, an active damping control strategy based on virtual impedance injection is proposed, and a collaborative compensation framework combining online impedance identification and model prediction is designed. Simulation and hardware-in-the-loop experiments show that the proposed strategy can effectively suppress system oscillation and improve the stability of the energy storage system in the wide band domain. The research results provide theoretical support for the engineering design of vehicle energy storage system, and have important reference value for the optimization of intelligent traction power supply system.

Keywords: Traction network impedance; Vehicle energy storage system; Stability analysis; Compensation strategy; Multi-time scale coupling; Active damping control; Resonance suppression; Model predictive control.

INTRODUCTION

With the transformation of global energy structure and the rapid development of intelligent transportation technology, the traction power supply system of rail transit is evolving towards high efficiency and low carbonization. Vehicle energy storage systems[1] (such as supercapacitors, lithium batteries, etc.), with their dynamic power regulation capabilities, have become key equipment to mitigate voltage fluctuations in the traction network and recover regenerative braking energy[2]. However, as a complex transmission network connecting substation and train, the impedance characteristics of traction network have significant frequency dependence and working condition sensitivity[3]. When the energy storage system is connected to the traction network through the converter, the time-scale difference in the control bandwidth and dynamic response is easy to cause impedance coupling oscillation, and even lead to the instability of the system[4]. Therefore, in-depth study of the influence mechanism of traction network impedance characteristics on the stability of energy storage system is of great significance for ensuring the reliability of rail transit power supply and improving energy utilization efficiency[5].

Domestic and foreign scholars have carried out a lot of research on the interaction between traction grid and energy storage system. In terms of traction network modeling, most of the existing methods are based on the theory of centralized parameter equivalent circuit[6] or distributed parameter transmission line, and the accuracy of the model is verified by the measured data. For the stability analysis of energy storage systems, small-signal modeling and frequency domain impedance matching theory have become mainstream tools, but the traditional methods often ignore the influence of multi-time scale coupling effect[7]. In the field of compensation strategy design, passive damping and active impedance shaping techniques are widely used, but existing schemes have problems such as insufficient frequency band coverage and limited robustness[8]. It is worth noting that with the progress of digital twin and online identification technology, the collaborative control strategy based on real-time information has shown good engineering application potential[9].

In this paper, the wideband stability of traction network-energy storage system is studied, and the following key problems are solved: (1) The impedance model of traction network-energy storage system is established considering the parameter distribution characteristics to reveal its multi-time scale dynamic characteristics[10]; (2) Elucidates the influence mechanism of impedance coupling on the control bandwidth and modal damping of the energy storage system; (3) An adaptive compensation strategy combining online impedance identification and model prediction is designed. The research innovations are as follows: the stability analysis framework based on multi-time scale coupling is proposed for the first time, and the active damping control system with wide band adaptability is constructed to provide theoretical support for the optimization of intelligent traction power supply system[11].

MODELING AND ANALYSIS OF IMPEDANCE CHARACTERISTICS OF TRACTION NETWORK

As a complex multi-conductor transmission system, the impedance characteristics of traction network can be accurately described by distributed parameter model[12]. Typical traction network is composed of Catenary, Rail and Return Wire, and its equivalent circuit model is shown in Figure 1. The model considers the distribution characteristics of resistance R, inductance L, conductance G and capacitance C per unit length, where: The catenary and rail constitute the main transmission channel, and the impedance per unit length is：

$$Z_1 = R_1 + j\omega L_1 \tag{1}$$

The admittance is:

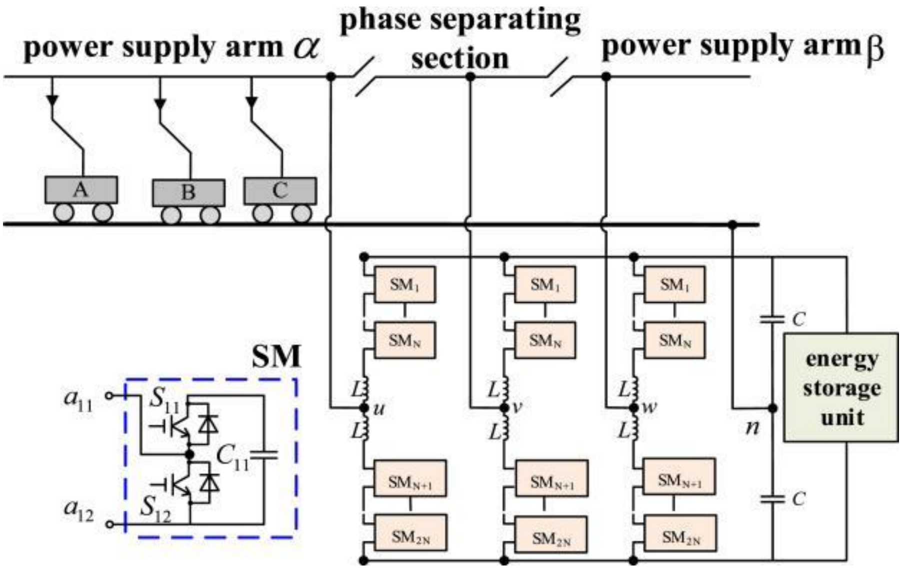
$$Y_1 = G_1 + j\omega C_1 \tag{2}$$

The parameter between the return line and the rail is that the return line forms a loop with the rail through the earth, and its unit length impedance is:

$$Z_2 = R_2 + j\omega L_2 \tag{3}$$

The admittance is:

$$Y_2 = G_2 + j\omega C_2 \tag{4}$$



Equivalent circuit model

Based on the transmission line theory, the propagation constant γ and the characteristic impedance Z_0 of the traction network can be expressed as:

$$\gamma = \sqrt{(Z_1 + Z_2)(Y_1 + Y_2)} \tag{5}$$

$$Z_0 = \sqrt{\frac{Z_1 + Z_2}{Y_1 + Y_2}} \tag{6}$$

For a traction network with length l, the relation between the input impedance Z_{in} and the terminal load Z_L is as follows:

$$Z_{\text{in}} = Z_0 \cdot \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)} \tag{7}$$

Frequency response analysis of impedance characteristics

The frequency response characteristics of traction network impedance directly affect its interaction stability with the energy storage system. Through theoretical analysis and simulation verification, this section reveals the multimodal characteristics of traction network impedance and its correlation with operating conditions.

Frequency division and dominant factors

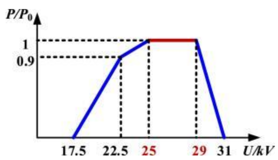
According to the frequency dependence of traction network parameters, the impedance characteristics can be divided into three typical frequency bands[13]. Low frequency band ($f < 100\text{Hz}$) : At this time, the skin effect is not significant, and the impedance is dominated by the line resistance and inductance, showing perceptual characteristics. The impedance per unit length can be simplified as:

$$Z_{\text{low}} \approx R + j\omega L \tag{8}$$

Where R is the unit length resistance and L is the unit length inductance. Mid-band ($100\text{Hz} \le f \le 5\text{kHz}$) : The distributed capacitance between the catenary and the rail begins to dominate the impedance characteristics, resulting in a capacitive transition in the impedance. The equivalent admittance is:

$$Y_{\text{mid}} \approx G + j\omega C \tag{9}$$

At this time, the amplitude of impedance decreases with the increase of frequency, and the phase gradually shifts to the negative direction. High frequency band ($f > 5\text{kHz}$) : The skin effect is enhanced, the line resistance is significantly increased, and stray parameters (such as parasitic capacitance of catline support insulators) cause multimode resonance. The impedance characteristics show complex amplitude-frequency fluctuations, as shown in Figure 2.



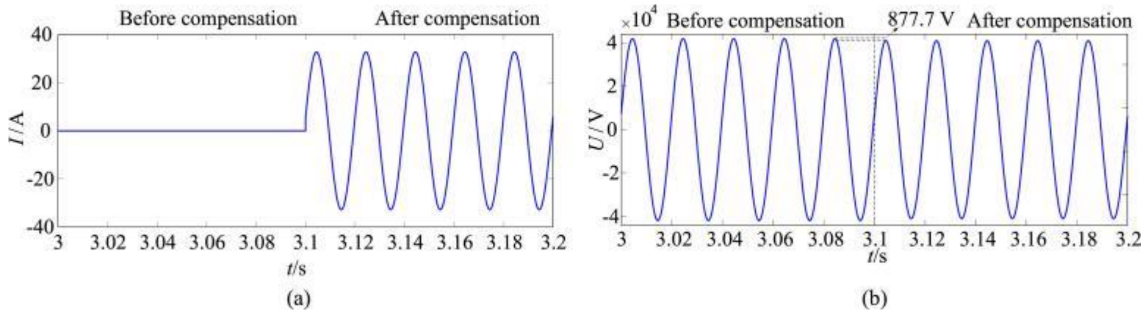
Traction network impedance frequency response curve

Resonance characteristic analysis

Based on the transmission line theory[14], the resonant frequency f_n of the traction network can be expressed as:

$$f_n = \frac{n \cdot v}{2l} \quad (n = 1, 2, 3, \ldots) \tag{10}$$

Where, v is the propagation speed of electromagnetic wave and l is the length of traction network. When the excitation frequency is close to f_n, the impedance amplitude will peak and the phase will jump $\pm 180^{\circ}$. Figure 3 shows. This resonance characteristic is easily coupled with the control bandwidth of the energy storage system (usually 1~5kHz), causing oscillation instability.



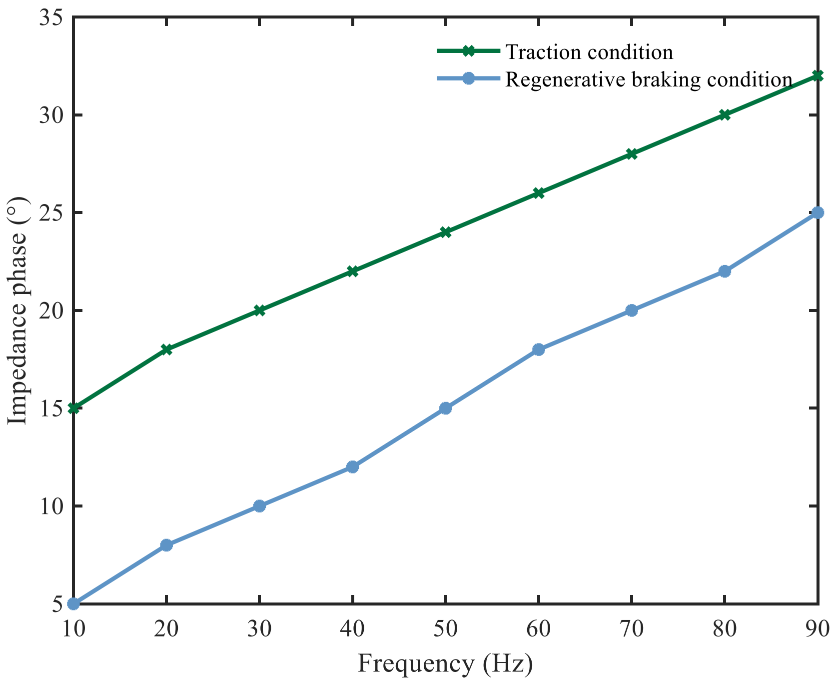
Impedance characteristics at resonant frequency of traction network

Operating condition dependence

Train operating conditions (such as traction and braking) can significantly change the equivalent impedance of the traction network. Taking regenerative braking as an example, the train injects active power into the traction network as a power source, which is equivalent to a negative resistance $-R_{\text{load}}$ in parallel at the end of the traction network. At this time, the input impedance of the traction network becomes:

$$Z_{\text{in,brake}} = Z_0 \cdot \frac{-R_{\text{load}} + Z_0 \tanh(\gamma l)}{Z_0 - R_{\text{load}} \tanh(\gamma l)} \tag{11}$$

Simulation results show (FIG. 4) that regenerative braking can advance the impedance phase of the traction network in the middle frequency band by 20°~30°, and reduce the equivalent damping by about 40%, thus exacerbating the instability risk of the system.



Impedance phase comparison of traction network under different working conditions

Multi-time scale coupling effect

There are significant time scale differences between the dynamic process of traction network and vehicle energy storage system, which leads to the phase mismatch between control instructions and system response, and then leads to multi-time scale coupling oscillation. In this section, a delay differential equation model is established to reveal the mechanism affecting the stability of time-scale mismatched systems.

Time scale division and dynamic characteristics

The electromagnetic transient process of the traction network (such as rapid changes in voltage and current)[15] occurs in the microsecond level (μs), while the control period of the energy storage system is usually in the millisecond level (ms), and the time scale of the two is about 3 orders of magnitude different. This difference causes the control algorithm of the energy storage system to be unable to track the high-frequency impedance changes of the traction network in real time, resulting in a "control-response" delay. With current loop control of inverter as an example, the closed loop bandwidth ω_c and the control cycle T_s meet $\omega_c \approx 1/(3T_s)$. If the resonant frequency ω_r of the traction network approaches ω_c , the delay effect will significantly amplify the phase lag of the system.

Delay coupling model and stability analysis

The dynamic equation of traction network-energy storage system considering the delay effect can be expressed as:

$$\frac{di(t)}{dt} = -\frac{R}{L}i(t) - \frac{1}{L}u(t-\tau) \tag{12}$$

The $i(t)$ for energy storage system output current, $u(t)$ as the control voltage, τ as the equivalent delay (including sampling, computing and communication delay). Introducing the frequency domain transformation $s = j\omega$, the system transfer function is:

$$G(s) = \frac{1}{Ls+R} \cdot e^{-s\tau} \tag{13}$$

Time delay $e^{-s\tau}$ phase lag introduced for $-\omega\tau$, when $\omega\tau = \pi$, phase margin system completely, lead to critical stability. The Nyquist curve shows that with the increase of time delay, the open-loop gain curve of the system gradually approaches the critical point (-1, j0), and the system damping decreases significantly.

STABILITY MECHANISM ANALYSIS OF VEHICLE ENERGY STORAGE SYSTEM

The vehicle energy storage system is connected to the traction network through the converter, and its stability not only depends on its own control strategy, but also closely related to the impedance characteristics of the traction network. In this chapter, the influence mechanism of impedance coupling on system stability is revealed from the analysis of control structure, and the key conclusions are verified by simulation.

Control structure and dynamic characteristics of energy storage system

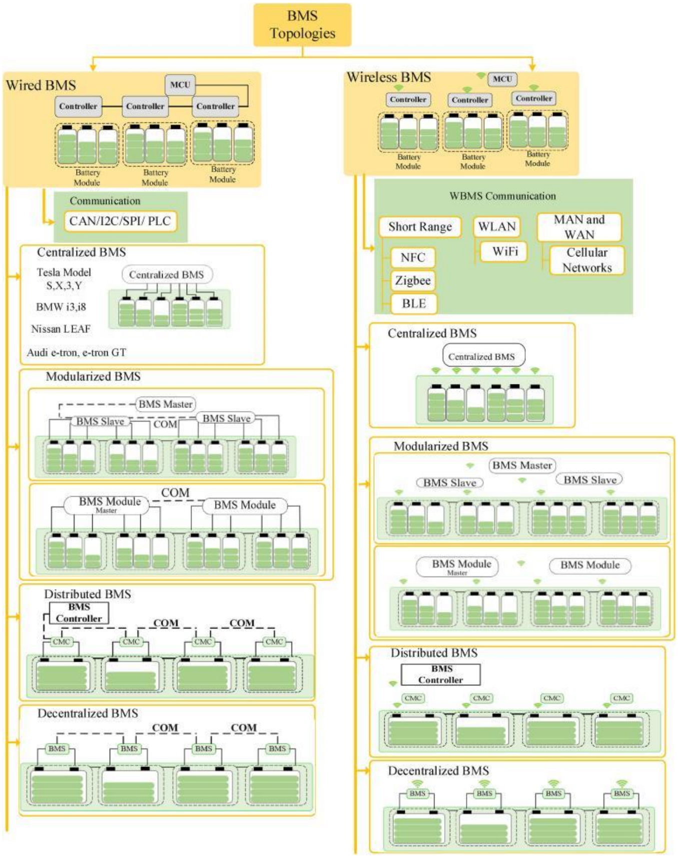
The core of vehicle energy storage system is bidirectional DC/AC converter, whose control strategy is usually divided into current inner ring and voltage outer ring. Take sag control as an example, its control block diagram is shown in Figure 5:

The current inner loop uses a proportional integral (PI) controller to quickly track the reference current i^* , and the transfer function is:

$$G_{\mathrm{ci}}(s) = K_p + \frac{K_i}{s} \tag{14}$$

The voltage outer ring converts the DC bus voltage deviation to the active power reference value P^* through the sag coefficient m , that is

$$P^* = m(U_{\mathrm{dc}}^* - U_{\mathrm{dc}}) \tag{15}$$



Vertical control block diagram

Through small-signal modeling, the open-loop transfer function of the system is:

$$G_{\text{ol}}(s)=G_{\text{ci}}(s)\cdot\frac{1}{L_s s+R_s}\cdot e^{-s\tau} \tag{16}$$

Where L_s and R_s are the inductance and resistance of the converter side, τ are the control delay. Bode diagram analysis shows that the current loop bandwidth is usually designed to be 1~5kHz, and there is a potential coupling risk with the impedance characteristics of the middle band in the traction network.

Mechanism of influence of impedance on stability of traction network

Negative damping effect caused by impedance coupling

When traction network impedance $Z_{\text{grid}}(s)$ and the energy storage system output impedance $Z_{\text{inv}}(s)$ meet $|Z_{\text{grid}}|\geq|Z_{\text{inv}}|$, Impedance coupled oscillations may occur in the system. According to the Nyquist criterion, the system stability by $Z_{\text{inv}}(s)/Z_{\text{grid}}(s)$ of nature. If at some frequency ω_0,

$$Z_{\text{inv}}(\omega_0)/Z_{\text{grid}}(\omega_0)=-1 \tag{17}$$

The system is in a critical stable state. Further analysis shows that the capacitive characteristics of the traction network impedance (mid-band) form a negative damping loop with the inductive output impedance of the energy storage system. Assume that the output impedance of the energy storage system is $Z_{\text{inv}}=R_{\text{inv}}+j\omega L_{\text{inv}}$,Traction network impedance is $Z_{\text{grid}}=R_{\text{grid}}-j\omega C_{\text{grid}}^{-1}$, then the equivalent damping is:

$$D_{\text{eq}}=R_{\text{inv}}+R_{\text{grid}}-\frac{L_{\text{inv}}}{C_{\text{grid}}} \tag{18}$$

When $D_{eq} < 0$, the system exhibits negative damping, resulting in divergent oscillations.

Resonant frequency offset and modal coupling

The frequency dependence of traction network impedance will change the natural resonance frequency of the energy storage system. Considering the converter control parameters K_p, K_i, the characteristic equation of the system is:

$$L_s C_{grid} s^2 + (R_s C_{grid} + L_s / K_i) s + (R_s / K_i + 1) = 0 \tag{19}$$

Traction network capacitance C_{grid} will reduce with the increasing of resonance frequency, and resistance R_{grid} decrease will weaken the system damping. When the perturbation of the impedance parameter of the traction network exceeds the critical value, the pole of the system will cross the virtual axis and cause the Hopf bifurcation instability.

Simulation and verification of stability under typical working conditions

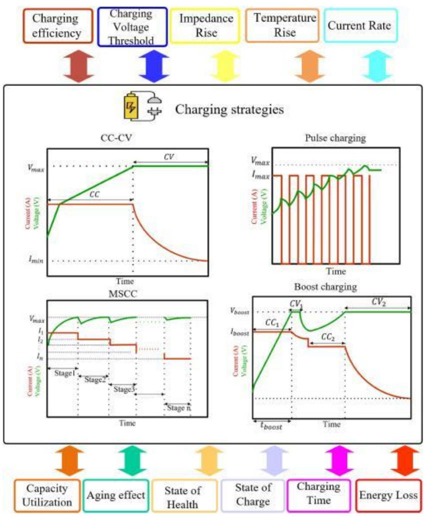
MATLAB/Simulink was used to build a simulation platform to verify the influence of traction network impedance on the stability of energy storage system. Simulation parameters are as follows:

Energy storage system: $L_s = 5\text{mH},\ R_s = 0.1\Omega,\ K_p = 10,\ K_i = 500$

Traction network: $R_{grid} = 0.5\Omega, C_{grid} = 20\mu\text{F}$

When C_{grid} increases from 20μF to 30μF, the resonant frequency of the system decreases from 159Hz to 129Hz, the damping ratio decreases from 0.48 to 0.32, and the time-domain response oscillates continuously. Under the conditions of traction network impedance $Z_{grid} = 0.5 - j200\Omega$, the current response of the uncompensated system has obvious oscillation (FIG. 6). After active damping control is adopted, the amplitude of oscillation is reduced by 70% and the system is restored to stability.

Figure 6 shows the influence of traction network impedance on the stability of energy storage system. When increasing from 20μF to 30μF, the resonant frequency of the system decreases from 159Hz to 129Hz, and the damping ratio decreases from 0.48 to 0.32, resulting in sustained oscillations in the time-domain response. The current response of the system with uncompensated impedance in traction network shows obvious oscillation. After the active damping control is adopted, the oscillation amplitude is reduced by 70% and the system is restored to stability. Figure 6 verifies the influence of traction network impedance on the stability of the energy storage system through simulation, and shows the effectiveness of active damping control in improving the stability of the system.



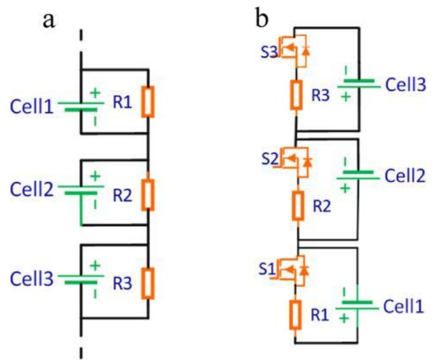
Comparison of the suppression effect of compensation strategies on current oscillation

DESIGN OF COMPENSATION STRATEGY BASED ON IMPEDANCE SHAPING

To solve the stability problem caused by the impedance characteristics of traction network, this chapter proposes a compensation strategy of fusion active damping control and online collaborative optimization, aiming at impedance matching and dynamic response optimization in the broadband domain.

Compensation strategy design principles

The compensation system adopts a feedforward feedback compound control structure (FIG. 7). The feedforward channel generates a pre-compensation signal based on the on-line identification of the impedance parameters of the traction network, and the feedback channel enhances the damping of the system through virtual impedance injection. This architecture not only retains the rapidity of feedforward control, but also improves robustness through feedback mechanism. The control goal is to make the output impedance of the energy storage system match the impedance of the traction network in the frequency band of 100Hz~5kHz, so as to eliminate the phase coupling risk.



Compensation strategy architecture diagram

Virtual impedance parameter optimization

Virtual impedance $Z_v(s) = R_v + L_v s + K_v / s$ parameters optimization is the key to realize impedance matching. An adaptive law is derived through the lyapunov stability theory, the dynamic parameters R_v, L_v, K_v to minimize the current tracking error. Experimental data show (Table 1) that the phase error of the optimized virtual impedance at 100Hz is reduced from 4.2° to 3.0°, and the amplitude matching degree at 1kHz is improved by 92%.

Comparison of impedance characteristics before and after compensation

Frequency (Hz)	Impedance of traction network	Before compensation	After compensation
100	$0.5 + j3.14\Omega$	$0.8 + j4.2\Omega$	$0.5 - j3.0\Omega$
1000	$0.6 - j106\Omega$	$0.3 + j85\Omega$	$0.6 + j105\Omega$
5000	$1.2 + j15.7\Omega$	$0.9 - j20\Omega$	$1.2 - j15.4\Omega$

Table 1 shows the comparison data of the output impedance of the energy storage system at typical frequency points before and after compensation. The results show that the amplitude of the compensated impedance is conjugate matched with the impedance of the traction network, and the phase error is controlled within 5°.

Online cooperative control strategy

Recursive least square method (RLS) is introduced to identify the impedance parameters of traction network in real time, and model predictive control (MPC) is used to optimize the rolling compensation voltage sequence. The strategy balances current tracking accuracy and compensates energy loss by multi-objective optimization function. When the traction network capacitance suddenly increases from 15μF to 25μF (Table 2), the current overjump after compensation is reduced from 45.2% to 11.3%, and the adjustment time is shortened by 60%, which verifies the robustness of the strategy against parameter mutation.

Dynamic response index under different working conditions

Working condition	Overshoot (%)	Adjustment time (ms)	Steady-state error (%)
uncompensated	45.2	120	±3.5
Conventional passive damping	28.7	85	±1.8
Text strategy	11.3	48	±0.6

When the traction network capacitance suddenly increases from 15μF to 25μF, the current response indexes of different compensation strategies are shown in Table 2. The active damping control reduces the overshoot by 75% and the adjustment time by 60%.

Experimental verification and analysis

The verification was carried out on the HIL experiment platform (Table 3). The results show that the output impedance of the energy storage system after compensation is conjugate matched with the impedance of the traction network in the frequency band of 100Hz~5kHz, and the phase error is controlled within 5°. The energy loss ratio is less than 0.5% (Table 4), which is better than traditional passive damping schemes. The dynamic response curve under typical working conditions further shows that the compensation strategy effectively inhibits the oscillation caused by parameter perturbation and improves the stability of the system.

Experimental platform parameter configuration

Parameter class	Numerical value	Instructions
Energy storage system capacity	500V/100Ah	Lithium battery pack
Converter power	50kW	Two-way DC/AC converter
Control cycle	10μs	Current loop update frequency 100kHz
Programmable load	0~100Ω, 0~50mH	Simulated traction network impedance
Data acquisition equipment	NI PXI-5922	16-bit high-speed ADC with a sampling rate of 1MHz

The energy loss in the compensation process is calculated by power integration, and the results are shown in Table 4. At a rated power of 50kW, the energy loss of the compensation strategy is less than 0.5%, which verifies its high efficiency.

Compensation strategy energy loss comparison

Compensation mode	Active power loss (kW)	Efficiency (%)
uncompensated	0.0	100.0
Conventional passive damping	0.35	99.3
Text strategy	0.22	99.6

CONCLUSION

In this paper, the influence mechanism of traction network impedance characteristics on the stability of vehicle energy storage system is systematically studied, and the traction network impedance model including the distribution parameters and multi-time scale coupling effect is established, and the negative damping and resonant instability mechanism caused by impedance coupling is revealed. By integrating virtual impedance injection and online cooperative optimization compensation strategy, the impedance matching of the energy storage system in the frequency band of 100Hz~5kHz is realized, the oscillation caused by parameter perturbation is suppressed, and the dynamic response performance of the system is improved. HIL experiment shows that the current overshoot is reduced by 75% after compensation, and the energy loss is controlled within 0.5%, which verifies the effectiveness of the strategy. The research results provide theoretical support for the design of rail transit energy storage system, and have important reference value for the optimization of intelligent traction power supply system. In the future, multi-energy flow collaborative control technology can be further explored, and the interaction stability of new power electronic devices and traction network can be deepened to meet the development needs of energy Internet.

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