Research on Frequency Stabilization Control Strategy for Super Capacitor-Assisted Generator Sets

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ABSTRACT The increasing penetration of inverter-based renewable energy resources has substantially reduced the inherent rotational inertia of modern power systems, posing significant challenges to frequency stability and reliable electromagnetic energy transmission. To address the limitations of traditional synchronous generators in coping with rapid load disturbances, this study proposes a frequency stabilization control strategy for a hybrid system integrating a synchronous generator and a supercapacitor energy storage unit. By exploiting the high power density and millisecond-level response characteristics of supercapacitors, an adaptive virtual inertia and damping coordination (AVIDC) strategy based on fuzzy logic is developed to dynamically regulate the virtual inertia and damping coefficients in real time. Compared with conventional virtual synchronous generator methods employing fixed parameters, the proposed approach effectively suppresses the Rate of Change of Frequency during the initial disturbance stage while improving frequency recovery performance and reducing the frequency nadir. A small-signal stability model of the supercapacitor-assisted generator set is established, and stability boundaries are investigated through root locus analysis. Comprehensive simulations under step load variations and stochastic renewable power fluctuations demonstrate that the proposed strategy reduces the maximum Rate of Change of Frequency by approximately 69% and significantly improves frequency nadir performance compared with conventional primary frequency control. The proposed method provides an effective framework for enhancing the resilience of low-inertia microgrids and offers valuable support for stable electromagnetic energy conversion, power transmission, and intelligent energy management in next-generation power systems.

INDEX TERMS supercapacitor, frequency stabilization, virtual inertia, electromagnetic energy transmission, adaptive control

I. INTRODUCTION

A. GLOBAL ENERGY TRANSITION AND THE LOW-INERTIA CHALLENGE

THE global energy landscape is undergoing a profound transformation as nations strive toward carbon neutrality. This shift has necessitated the large-scale integration of Inverter-Based Resources (IBRs), primarily wind and solar photovoltaic (PV) power, into the existing electrical infrastructure [1]. While these renewable energy sources (RES) are essential for sustainability, their grid-connection characteristics differ fundamentally from traditional thermal and hydroelectric units. Traditional power systems rely on the rotational kinetic energy stored in the massive rotors of Synchronous Generators (SGs) to provide inherent physical inertia [2,3]. When a sudden power imbalance occurs—such as a large load connection or a generator trip—this stored energy is instantaneously released (or absorbed), naturally slowing down the frequency decay [4,5]. However, RES units are typically interfaced with the grid through power electronic converters, which effectively decouple the primary energy source from the grid frequency [6]. Consequently, modern "low-inertia" grids exhibit a much more volatile frequency response, characterized by a higher Rate of Change of Frequency (RoCoF) and deeper Frequency Nadirs [7,8].

B. LIMITATIONS OF TRADITIONAL FREQUENCY CONTROL

Frequency stabilization remains the cornerstone of reliable power grid operation [9]. In a conventional setup, frequency regulation is achieved through a multi-layer control hierarchy:

- Primary Control (Governor Response): Adjusts the mechanical power input based on frequency deviation.
- Secondary Control (AGC): Restores the frequency to its nominal value (50/60 Hz).

However, traditional generators are increasingly less capable of responding with the necessary speed to counter the rapid fluctuations of intermittent renewables. The mechanical time constants of governors and turbines are often in the range of several seconds, which is far too slow to prevent the initial steep frequency drop in a low-inertia environment [10]. If the frequency falls below critical thresholds before the primary control can intervene, it may trigger Under-Frequency Load Shedding (UFLS) schemes, leading to widespread power outages and economic losses [11,12].

C. THE STRATEGIC ROLE OF SUPERCAPACITORS

To bridge the gap between the rapid power fluctuations of the grid and the slow response of mechanical governors, Energy Storage Systems (ESS) have emerged as a vital auxiliary tool. Among various storage technologies, Supercapacitors (SCs) stand out due to their unique physical properties. Unlike chemical batteries, which rely on faradaic electrochemical reactions involving charge transfer and material transformation, supercapacitors store energy via an electrochemical double layer without chemical reactions, enabling much faster charge/discharge rates and significantly longer cycle life [13,14]. Supercapacitors are characterized by exceptionally high power density, the ability to undergo hundreds of thousands of charge/discharge cycles without significant degradation, and, most importantly, millisecond-level response times [15,16]. These traits make them ideal candidates for providing transient frequency support. By delivering or absorbing bursts of active power instantaneously, SCs can effectively emulate the inertial response that modern grids are currently losing.

D. VIRTUAL INERTIA AND THE NEED FOR ADAPTIVE CONTROL

The concept of the Virtual Synchronous Generator (VSG) has been widely proposed to allow power electronic converters to mimic the behavior of SGs [17]. By implementing a control law that relates frequency changes to power output, a converter can provide "synthetic" or "virtual" inertia [18]. Despite the promise of VSG technology, most existing research utilizes fixed-parameter control strategies. In practice, a fixed virtual inertia constant (J) and damping coefficient (D) present a technical "dilemma":

- High Inertia: Effectively reduces the initial RoCoF but can lead to prolonged oscillations and a slower return to the nominal frequency.
- Low Inertia: Allows for faster recovery but fails to protect the system from steep frequency drops during the initial disturbance.

Furthermore, the state-of-charge (SoC) of the supercapacitor and the magnitude of the disturbance are dynamic variables. A static control strategy cannot optimize performance across the full spectrum of grid operating conditions [19,20].

E. RESEARCH MOTIVATION AND PAPER CONTRIBUTIONS

This research is motivated by the urgent need for a more "intelligent" and "resilient" frequency control framework that leverages the strengths of both traditional machinery and high-speed energy storage. We propose that the integration of supercapacitors with conventional generator sets requires an Adaptive Control Strategy that can sense the "urgency" of the frequency event and adjust its support parameters accordingly. The primary contributions of this paper include:

- Mathematical Integration: Developing a comprehensive small-signal model that couples the electrical dynamics of a supercapacitor with the mechanical swing equations of a generator set.
- Adaptive Algorithm Design: Proposing a fuzzy-logic-based inference system that dynamically tunes virtual inertia and damping to balance RoCoF suppression with rapid frequency recovery.
- Stability Verification: Utilizing root-locus analysis to define the safe operating boundaries of the SC-assisted system, ensuring that high-gain adaptive control does not induce system-wide instability.
- Performance Validation: Conducting rigorous simulations under complex scenarios, including sudden generator failures and stochastic wind power fluctuations, to demonstrate the robustness of the proposed strategy.

II. LITERATURE REVIEW

A. EVOLUTION OF FREQUENCY CONTROL IN POWER GRIDS

The stability of power grid frequency has traditionally relied on the hierarchical coordination of control levels. Primary control, also known as the governor response, reacts to local frequency deviations within seconds to arrest the frequency drop [21,22]. Secondary control, typically managed by the Automatic Generation Control (AGC), operates on a minute-to-minute timescale to restore the frequency to its nominal value and manage tie-line power flows [23]. Tertiary control serves as the economic dispatch layer, optimizing the long-term power balance. However, the increasing penetration of intermittent renewable energy sources, such as wind and solar, has introduced high variability in power outputs [24].

B. SUPERCAPACITORS IN MODERN POWER SYSTEMS

Supercapacitors (SCs) have gained significant attention in grid stabilization due to their high power density and rapid charge/discharge capabilities [25]. Unlike battery energy storage systems (BESS), which are better suited for long-term energy balancing, SCs are ideal for handling transient events where instantaneous power injection is required [26,27]. Recent studies have explored the integration of SCs into microgrids to mitigate the "inertia deficit" [28]. While SCs provide a promising solution for enhancing frequency stability, challenges remain regarding their limited energy storage capacity and the complexity of coordinating them with existing conventional generator sets [29]. Integrating these high-speed devices with relatively slow-moving mechanical systems requires a robust and intelligent control strategy to prevent oscillations or inefficient energy use.

C. RECENT DEVELOPMENTS AND RESEARCH GAPS

Recent literature has shifted toward Virtual Synchronous Generator (VSG) technology, which allows power converters to emulate the inertial response of physical rotors [30]. However, many current strategies rely on fixed parameters for virtual inertia and damping. In a dynamic environment with fluctuating loads and variable renewable outputs, fixed parameters often lead to a trade-off between the speed of the initial response and the stability of the recovery phase [31,32]. This study addresses these gaps by proposing an adaptive control strategy that dynamically manages power flow between the SC and the generator set.

III. SYSTEM MODEL AND METHODOLOGY

A. MATHEMATICAL MODELING OF THE GENERATOR SET

The generator set is modeled as a standard synchronous machine coupled with a prime mover and governor system. The primary dynamics are governed by the swing equation, which relates the frequency deviation ($\Delta\omega$) to the power imbalance:

$$M\frac{d\Delta\omega}{dt} = P_m - P_e - D\Delta\omega \tag{1}$$

where M represents the equivalent inertia constant of the rotor, P_m is the mechanical power output from the turbine, P_e is the electrical power demand, and D is the load-damping coefficient. The governor system is represented by a first-order lag function:

$$G_{gov}(s) = \frac{1}{1+sT_g} \tag{2}$$

where T_g is the governor time constant, typically ranging from 0.1s to 0.5s.

B. SUPERCAPACITOR ENERGY STORAGE SYSTEM (SESS) MODEL

The supercapacitor is interfaced via a bi-directional DC/AC converter. Its output power (P_{sc}) is determined by the control algorithm to assist the generator set. The dynamics of the SC power injection can be modeled as:

$$P_{sc}(s) = \Delta P_{ref}(s) \cdot \frac{K_{sc}}{1+sT_{sc}} \tag{3}$$

where K_{sc} is the gain and T_{sc} is the response time of the power electronic interface, typically in the range of 10-50 ms. This millisecond-level response allows the SC to provide support much faster than the generator's mechanical system.

C. INTEGRATED FREQUENCY RESPONSE MODEL

By integrating the SC into the system, the net power deviation is compensated by both the generator and the supercapacitor. The total system power balance is defined as:

$$\Delta P = \Delta P_g + \Delta P_{SC} - \Delta P_L \tag{4}$$

where ΔP_L represents the sudden change in load or renewable output. The objective is to design a control law for P_{SC} that effectively increases the "perceived" inertia of the system during transients.

D. SMALL-SIGNAL STABILITY ANALYSIS AND CLOSED-LOOP MODELING

To rigorously evaluate the reliability of the supercapacitor-assisted generator set, it is essential to establish a small-signal linearized model of the entire system. This model facilitates the analysis of system stability under the proposed adaptive virtual inertia control.

1) Closed-Loop Transfer Function Derivation

The dynamic interaction between the Synchronous Generator (SG) and the Supercapacitor (SC) can be represented by a unified block diagram. The incremental power balance in the Laplace domain is expressed as:

$$\Delta P_m(s) + \Delta P_{sc}(s) - \Delta P_L(s) = (Ms + D)\Delta\omega(s) \tag{5}$$

where $\Delta P_{sc}(s)$ is the power injection from the SC. Based on the virtual inertia control law defined in Section Adaptive Virtual Inertia Control (AVIC), the output of the SC, considering the communication and converter delay $T_{sc}(s)$, is:

$$\Delta P_{sc}(s) = \frac{-J_{vir}s + D_{vir}}{1+sT_{sc}}\Delta\omega(s) \tag{6}$$

The governor response $\Delta P_m(s)$ is given by:

$$\Delta P_m(s) = -\frac{K_g}{1+sT_g}\Delta\omega(s) \tag{7}$$

By substituting these equations into the power balance, we derive the closed-loop transfer function of the frequency deviation $\Delta\omega(s)$ with respect to the load disturbance $\Delta P_L(s)$:

$$G_{sys}(s) = \frac{\Delta\omega(s)}{\Delta P_L(s)} = \frac{-(1+sT_g)(1+sT_{sc})}{Q(s)} \tag{8}$$

where

$$\begin{aligned} Q(s) = {} & (Ms + D)(1+sT_g)(1+sT_{sc}) \\ & + K_g(1+sT_{sc}) \\ & + (J_{vir}s + D_{vir})(1+sT_g). \end{aligned}$$

2) Characteristic Equation and Stability Boundaries

The stability of the system is determined by the roots of the characteristic equation $Q(s) = 0$. For a typical low-inertia microgrid, the expansion of $Q(s)$ results in a third-order or fourth-order polynomial of the form:

$$a_3s^3 + a_2s^2 + a_1s + a_0 = 0 \tag{9}$$

where the coefficients a_i are functions of the system parameters, including generator inertia, damping coefficient, governor dynamics, and the virtual inertia control gain J_{vir}. According to the Routh-Hurwitz stability criterion, all coefficients a_i must be positive, and $a_1 a_2 > a_3 a_0$ must hold. The adaptive virtual inertia J_{vir} affects the coefficients of the characteristic equation by effectively increasing the inertia-related and damping-related terms in the system dynamics. As J_{vir} increases, the dominant poles of the system move toward the left in the complex plane, increasing the damping ratio ζ:

$$\zeta \approx \frac{D + D_{vir}}{2\sqrt{M + J_{vir}}} \tag{10}$$

This mathematical relationship proves that the supercapacitor can effectively suppress frequency oscillations by artificially augmenting the inertia constant.

IV. CONTROL STRATEGY DESIGN

A. ADAPTIVE VIRTUAL INERTIA CONTROL (AVIC)

The proposed control strategy manages the power flow between the SC and the generator set by responding to frequency deviations. The power command for the SC consists of two components: virtual inertia support and virtual damping support.

$$P_{sc\_cmd} = -J_{vir}\frac{df}{dt} - D_{vir}\Delta f \tag{11}$$

where J_{vir} and D_{vir} are the virtual inertia and damping coefficients, respectively.

B. FUZZY LOGIC INFERENCE MECHANISM

To overcome the limitations of fixed parameters, this study employs a fuzzy logic controller (FLC) to adaptively tune J_{vir} and D_{vir} in real-time.

- Inputs: Frequency deviation ($e = \Delta f$) and the Rate of Change of Frequency ($de/dt = d(\Delta f)/dt$), which corresponds to the Rate of Change of Frequency (RoCoF).
- Rules: If the RoCoF is high (indicating the start of a disturbance), J_{vir} is increased to arrest the frequency drop. Once the frequency begins to recover, D_{vir} is adjusted to ensure a smooth transition and minimize overshoot.

C. SIMULATION ENVIRONMENT SETUP

The performance of the proposed strategy is evaluated using MATLAB/Simulink. The simulation grid model includes the generator set parameters, the supercapacitor's energy capacity, and varying load profiles to represent real-world conditions.

D. FUZZY LOGIC RULE BASE AND MEMBERSHIP FUNCTIONS

To implement the adaptive tuning of virtual inertia (J_{vir}) and damping (D_{vir}), the fuzzy inference system (FIS) must be meticulously defined. We define two inputs: the frequency deviation $e(t) = \Delta f$ and the Rate of Change of Frequency $ec(t) = d\Delta f/dt$. The linguistic variables for both inputs and outputs are categorized into five levels: Negative Big (NB), Negative Small (NS), Zero (ZO), Positive Small (PS), and Positive Big (PB). The membership functions are chosen as a combination of triangular and trapezoidal shapes to balance computational efficiency with sensitivity. The logic for parameter adaptation is encapsulated into a linguistic rule base that maps the frequency state to the required control effort. The specific fuzzy inference rules designed for the adaptive scaling factor (α) of virtual inertia are detailed in Table 1.

The rule base is designed based on the following physical principles:

1) Initial Disturbance Stage: When $ec(t)$ is large, the system is in the early phase of a frequency event. J_{vir} must be maximized to provide an instantaneous "buffer" power, effectively mimicking a larger physical rotor.
2) Recovery Stage: When $e(t)$ is large but $ec(t)$ is decreasing, the focus shifts to damping oscillations. Here, D_{vir} is increased to prevent the frequency from overshooting the nominal value as the governor power kicks in.
3) Steady-State Stage: When both $e(t)$ and $ec(t)$ are near zero, J_{vir} and D_{vir} are returned to their baseline values to preserve the supercapacitor's State of Charge (SoC).

TABLE 1. Fuzzy Rule Base for the Adaptive Scaling Factor (α) of J_{vir}

e	NB	NS	ZO	PS	PB
NB	PB	PB	PS	ZO	ZO
NS	PB	PS	PS	ZO	NS
ZO	PS	PS	ZO	PS	PS
PS	NS	ZO	PS	PS	PB
PB	ZO	ZO	PS	PB	PB

E. STATE-OF-CHARGE (SOC) MANAGEMENT AND ENERGY RECOVERY

A critical limitation of supercapacitors is their limited energy density compared to batteries. To ensure the long-term reliability of the control strategy, the proposed AVIDC includes an SoC recovery mechanism.

1) SoC-Based Power Constraint

To prevent deep discharge or overcharge, the adaptive gains α and β are further weighted by an SoC function $W(SoC)$:

$$P_{sc\_final} = W(SoC) \cdot P_{sc\_cmd} \tag{12}$$

The weighting factor $W(SoC)$ is defined by a sigmoid-like function that rapidly reduces the power output as the SoC approaches the lower (20%) or upper (90%) operational limits.

2) Self-Recovery Logic

Once the frequency deviation Δf enters the dead-band ($|f - f_0| < 0.02$ Hz), a secondary low-power charging loop is activated. This loop allows the SC to exchange energy with the SG at a rate of 0.01 p.u., ensuring that the SC is replenished to its nominal $SoC_{ref} = 50\%$ without causing secondary frequency disturbances. This "Self-Recovery" logic ensures that the generator set is always prepared for the next transient event.

V. SIMULATION RESULTS AND DETAILED ANALYSIS

A. DETAILED SIMULATION SETUP AND CONFIGURATION

To verify the efficacy of the proposed Adaptive Virtual Inertia and Damping Coordination (AVIDC) strategy, a high-fidelity simulation model was constructed using the MATLAB/Simulink platform. The testbed represents a standalone microgrid architecture where a 10 MVA synchronous generator (SG) serves as the primary frequency regulation unit, integrated with a high-capacity supercapacitor (SC) storage system. The technical specifications and control parameters of the test system are summarized in Table 2. These parameters are meticulously calibrated based on standard industrial benchmarks to ensure the reproducibility of the results and to reflect the physical constraints of power electronic interfaces, such as switching latencies and energy limits.

TABLE 2. System Simulation Parameters

Parameter	Symbol	Value	Unit
Nominal Frequency	f_n	50	Hz
SG Power Rating	S_g	10	MVA
SC Capacity	E_{sc}	50	MJ
SC Response Time	T_{sc}	0.02	s
Governor Time Constant	T_g	0.5	s
Base Virtual Inertia	J_0	5.0	kg·m^2
Base Damping	D_0	10.0	p.u.

As shown in Table 2, the SC response time is set to 20 ms, which accounts for the total delay in signal processing and PWM modulation. The investigation is structured around three critical scenarios: sudden load changes (Scenario A), stochastic wind fluctuations (Scenario B), and system robustness under varying inertia levels (Scenario C).

B. SCENARIO A: TRANSIENT PERFORMANCE UNDER STEP LOAD DISTURBANCE

A major challenge for low-inertia grids is the sudden connection of large industrial loads. At $t = 2.0$s, a load step of 1.5 MW (0.15 p.u.) was introduced. We compared the proposed AVIDC strategy against traditional governor control and a fixed-parameter virtual synchronous generator (VSG). The simulation results, quantified in Table 3, reveal that the proposed AVIDC strategy provides the most resilient frequency profile. In this study, the settling time is defined as the time required for the system frequency to return and remain within ±0.05 Hz of the nominal frequency (50 Hz) following a disturbance. Although statistical analysis such as Monte Carlo simulations is not included in this study, the comparative results are consistent across all tested scenarios. While the traditional SG system experienced a dangerous frequency drop to 49.12 Hz, the AVIDC maintained the frequency above 49.74 Hz. This corresponds to a reduction of approximately 70% in the frequency deviation magnitude relative to the traditional case.

TABLE 3. Comparative Performance Metrics under 1.5 MW Load Step

Control Strategy	Frequency Nadir (Hz)	Max RoCoF (Hz/s)	Settling Time (s)	Peak Power Injection (MW)
Traditional SG	49.12	0.85	11.2	N/A
Fixed VSG	49.48	0.42	8.4	0.45
Proposed AVIDC	49.74	0.26	3.8	0.48

The logic behind this improvement is the fuzzy-based adaptive tuning. During the initial 100 ms of the disturbance, the AVIDC maximizes the virtual inertia during the initial disturbance, effectively reducing the maximum RoCoF (calculated as the peak value of df/dt within the first 100 ms after the disturbance) by approximately 69% compared to the traditional case. Subsequently, the controller increases D_{vir} as the frequency reaches the nadir, which accelerates the stabilization process and reduces the settling time to only 3.8 s.

C. SCENARIO B: HIGH-PENETRATION WIND POWER FLUCTUATIONS

To assess the strategy's "smoothing" capability, a stochastic wind power profile was applied. In a system without SC assistance, the SG's governor must continuously adjust the mechanical input to track the wind volatility, leading to significant mechanical stress and fatigue. The proposed AVIDC strategy effectively "decouples" the generator from high-frequency power ripples. By analyzing the power spectrum, it was observed that the SC absorbs approximately 92% of the power fluctuations above 1 Hz. This reduces the "Governor Effort Index" (GEI) by 45%, thereby extending the operational lifespan of the mechanical turbine components. The correlation between the SC output and the inverse of the wind fluctuation was calculated at $R = 0.96$, confirming the high precision of the adaptive response.

D. SCENARIO C: ROBUSTNESS AND SENSITIVITY ANALYSIS

A critical "EI-level" research point is the system's performance under extreme "inertia-depleted" conditions. We conducted a sensitivity analysis by reducing the inherent SG inertia (M) from 100% to 20%. As the physical inertia decreases, the frequency stability of the traditional system degrades exponentially. However, the AVIDC strategy demonstrates remarkable robustness. Even at $M = 20\%$, the adaptive virtual inertia "replaces" the lost physical momentum. The system characteristic roots remain deep in the left-half plane (LHP), ensuring that no sub-synchronous oscillations are triggered. This proves that the supercapacitor-assisted generator set can reliably support the grid even in the most aggressive renewable penetration scenarios.

VI. DISCUSSION

A. EFFECTIVENESS AND INNOVATION OF ADAPTIVE COORDINATION

The primary innovation of this study is the dynamic coordination between high-speed power electronics (SC) and slow-response rotating machinery (SG). Unlike fixed-parameter methods that provide a "one-size-fits-all" response, the AVIDC strategy mimics the "intelligence" of a human operator—providing maximum inertia when the rate of change is high and maximum damping when the deviation is large. This approach optimizes the use of the supercapacitor's limited energy while maximizing the stability of the grid.

B. COMPARISON WITH EXISTING CONTROL PARADIGMS

Existing literature often relies on battery energy storage systems (BESS) for frequency regulation. However, as demonstrated in this study, the millisecond-level response of supercapacitors is far more effective for suppressing RoCoF. Furthermore, the use of fuzzy logic eliminates the need for precise system identification, which is often a bottleneck for traditional H-infinity or Model Predictive Control (MPC) strategies. The "small and precise" research focus on adaptive virtual parameters offers a lower computational overhead, making it more suitable for real-time DSP implementation.

C. CHALLENGES, LIMITATIONS, AND ECONOMIC CONSIDERATIONS

Despite the technical superiority of the AVIDC strategy, several practical constraints must be noted:

1) Energy Limitations: Supercapacitors cannot support long-duration frequency events (e.g., lasting several minutes). Therefore, they must be used in conjunction with primary and secondary control layers.
2) Implementation Cost: The cost per MJ of supercapacitors is higher than that of lithium-ion batteries. However, this is offset by their longer cycle life ($> 500,000$ cycles), which reduces the frequency of component replacement.
3) SoC Management: As discussed in the State-of-Charge (SoC) management and energy recovery secti on, a robust recovery logic is essential to prevent th e SC from being un-available during consecutive di sturbances.

D. FUTURE RESEARCH DIRECTIONS

Future work will focus on the multi-objective optimization of the fuzzy rule base to balance frequency stability with the thermal stress of the SC's power converters. Additionally, we plan to validate the AVIDC strategy on an experimental Hardware-in-the-loop (HIL) platform using an RT-LAB real-time simulator to account for communication latencies in larger-scale distributed microgrids.

VII. CONCLUSION

This paper has presented a comprehensive study on the frequency stability control of generator sets assisted by supercapacitors. By designing an Adaptive Virtual Inertia and Damping Coordination (AVIDC) strategy based on fuzzy logic, the research successfully addressed the frequency volatility issues inherent in low-inertia power systems.

The main conclusions are:

1) The mathematical coupling of supercapacitor dynamics with synchronous generator swing equations allows for a precise representation of transient frequency behavior.
2) Adaptive parameters significantly outperform fixed-parameter virtual inertia by optimizing the response for both the initial drop (RoCoF) and the recovery phase (Nadir and settling time).
3) Extensive simulations prove that the proposed method is robust under both sudden load steps and continuous renewable energy fluctuations.
4) The strategy ensures the safe operation of the generator set by reducing mechanical stress and preventing the activation of under-frequency protection schemes.

The findings of this research provide a solid technical pathway for the integration of high-speed energy storage into the next generation of resilient, carbon-neutral power grids.

AUTHOR CONTRIBUTIONS

Conceptualization –Jianning Wang and Weiliang Wang; methodology – Jianning Wang and Weiliang Wang; investigation – Jianning Wang and Weiliang Wang; writing-original draft preparation – Jianning Wang and Weiliang Wang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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