

Dynamic Adaptive Planning for Urban EV Charging Infrastructure Towards Social Welfare Maximization

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KEY WORDS: charging planning; electric vehicles; Monte Carlo tree search; spatio-temporal perception reinforcement learning

To investigate how governments can design long-term strategies in dynamic competitive markets, this paper proposes an adaptive planning approach for charging station. From the government perspective, a closed-loop mechanism of “planning-deployment-feedback-replanning” is established. This mechanism generates deployment schemes that adapt to the dynamic evolution of cities.

First, a physical system simulation model is developed by integrating user charging demand, operator revenue, and government constraints, enabling dynamic assessment of station investment benefits. Second, this paper designs a fixed-point iteration (FPI) algorithm to compute steady-state demand and regional price equilibrium. Furthermore, this paper formulates a Markov decision process to optimize the construction process and the layout of charging stations. Finally, this paper proposes a spatiotemporal-aware Monte Carlo tree search-based reinforcement learning (MCTS-RL) method to enhance decision-making in complex urban evolution scenarios. The optimization problem is formulated as:

$$\max_{z \in \mathcal{Z}} S = \sum_{i \in \mathcal{I}_t} \gamma^{t-1} [\eta^{\text{sw}} F_t^{\text{sw}} - \eta^{\text{g}} C_t^{\text{g}}] \quad (1)$$

where, S , F_t^{sw} , and C_t^{g} denote the social welfare function, service capacity function, and government subsidy cost function at planning step t , respectively; η^{sw} and η^{g} represent the weights of social welfare and subsidy costs; $C_{t,i}^{\text{g}}$ is closely related to the operator revenue function in region i , with detailed evaluation provided in Section 1.4. The objective function emphasizes cumulative social welfare maximization while ensuring coordination between process optimization and final spatial deployment.

To improve computational efficiency while maintaining equilibrium accuracy, and to provide an effective interface for deep reinforcement learning training, this paper develops a fast parallel algorithm based on fixed-point iteration. The algorithm simultaneously derives spatial pricing equilibrium and user demand steady state. The update formulas for

queuing delay and spatial price are given as follows:

$$\hat{\lambda}_y = c_y^e + (\sum_{x \in \mathcal{I}} P_{y,x} O_x) / [(\sum_{x \in \mathcal{I}} P_{y,x} O_x - \sum_{x \in \mathcal{I}} P_{y,x}^2 O_x) v \beta^{\text{pri}} \bar{s}] \quad (2)$$

$$\hat{T}_y^w = \bar{T}^w + \alpha^w \bar{T}^w \beta^w (\sum_{x \in \mathcal{I}} P_{y,x} O_x) / (c_y - \sum_{x \in \mathcal{I}} P_{y,x} O_x) \quad (3)$$

where, x and y denote the demand-origin and charging regions; $\mathcal{I}$ is the set of regions; $\hat{\lambda}_y$ is the updated charging price in region y ; c_y^e is the unit electricity cost; $P_{y,x}$ is the probability that an EV from region x selects region y ; and O_x is the potential charging demand. Moreover, v , β^{pri} and $\bar{s}$ denote the utility scale coefficient, price sensitivity coefficient, and average charging demand per EV. In Equ. (3), $\hat{T}_y^w$ and $\bar{T}^w$ denote the updated and free-flow waiting times, respectively; α^w and β^w are the queue-growth parameters; and c_y is the charging service capacity of region y .

With the aim to address complex dynamic evolution, an MCTS-RL algorithm is developed, in which a trained DRL model guides MCTS simulations and the government selects the optimal planning action from the candidate solutions.

Table 1 compares MCTS-RL with four benchmark algorithms in terms of social welfare, relative improvement, and result dispersion. Using multi-source spatiotemporal data from Shenzhen, the case study demonstrates the applicability of the proposed model to real-world scenarios. Among all feasible methods, MCTS-RL achieves the highest social welfare, with the lowest dispersion and superior best- and worst-case performance. Moreover, it enables rapid welfare improvement in the early deployment stages while maximizing cumulative social welfare over the entire planning horizon.

Table 1 Comparison of algorithm performance

Algorithm	Social welfare	Improvement/%	Dispersion
GA	3.08	100	0.25
RL1	3.358	109.03	0.254
RL2	3.433	111.46	0.229
MCTS-RL	3.513	114.04	0.216
GAB	3.601	116.92	0.191

A Multi-Agent Approach to Scheduling Charging and Discharging Operations in Large-scale Electric Vehicle Battery Swapping Stations

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KEY WORDS: battery swapping station; multi-agent; curse of dimensionality; deep reinforcement learning; bucket-based state encoding; attention mechanism

Electric vehicle battery swapping stations (BSS) are critical infrastructure for enhancing the flexibility of modern power systems. However, the optimal scheduling of their charging and discharging operations is a significant challenge due to the high volatility of user demand and the inherent complexity of large-scale systems, making it difficult to achieve both economic efficiency and operational reliability. To address this challenge, this paper proposes a novel scheduling framework based on a multi-agent deep reinforcement learning (DRL) approach, specifically utilizing a grouped Multi-Agent Twin Delayed Deep Deterministic Policy Gradient (MATD3) algorithm.

The operational architecture of the BSS, which includes battery storage, charging/discharging units, and EV user interaction, is depicted in Fig. 1. Initially, a comprehensive mathematical model and a Markov Decision Process (MDP) are established to accurately represent the BSS charging and battery swapping dynamics. To overcome the 'curse of dimensionality' associated with the high-dimensional state and action spaces in large-scale BSS, a centralized decomposition strategy is introduced. As illustrated in Fig. 2, the system is partitioned into multiple subsystems by grouping devices, allowing multiple agents to collaboratively manage the scheduling task. A key challenge in multi-agent systems is overcoming information silos between decision-making subsystems. To facilitate effective collaboration, we design two novel mechanisms: a bucket-based state encoding (BSE) method and an unbalanced attention mechanism. The BSE method efficiently aggregates global battery state-of-charge (SOC) information into a compact representation, while the attention mechanism enables each agent to dynamically focus on the most critical global information. Together, these mechanisms

empower each BSS subsystem to perceive the global state, promoting efficient state sharing and coordinated joint scheduling among agents.

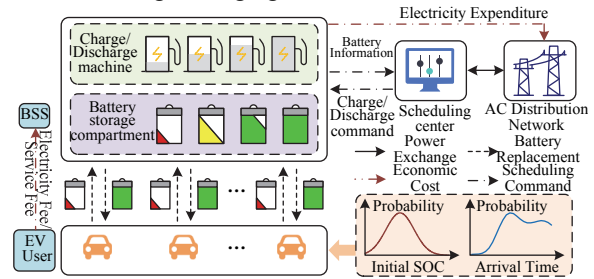


Fig. 1 Schematic diagram of BSS structure and operation mode

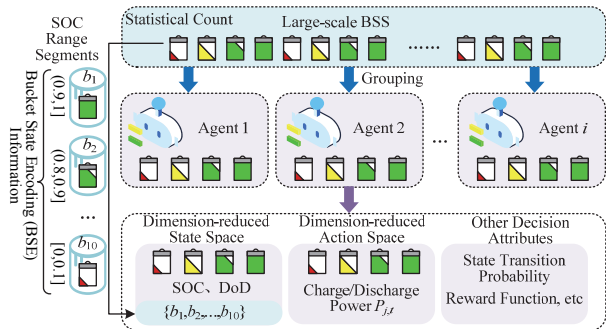


Fig. 2 Diagram of Agent Grouping Control Strategy

The proposed MATD3-based model and algorithm are validated through extensive simulations using real-world operational data from both small- and large-scale BSS. The results demonstrate that our approach possesses superior economic performance and robustness. In large-scale BSS scenarios, the proposed model achieves operational profits at least 2.37% higher than benchmark DRL algorithms and 7.95% higher than traditional model-based optimization methods. Furthermore, it exhibits significantly higher computational efficiency, making it suitable for real-time applications. This work provides a powerful and scalable solution for the intelligent scheduling of large-scale BSS, offering substantial theoretical support and practical guidance for the integration of BSS into future power grids.

Multi-market Mixed-game Trading Strategies for Electric Vehicle Aggregators With Consumption of Renewable Energy

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KEY WORDS: renewable energy; electric vehicle aggregator (EVA); mixed-game; power excess consumption trading; green certificate trading

The present high proportion of renewable energy (RE) in new power systems is indicative of a shift from a ‘sources follow loads’ model to a ‘source, network, load and storage synergy’ model. This indicates that traditional regulatory measures are no longer adequate to meet RE consumption, thus prompting an urgent need to explore user-side response potential. As an important demand-side load, the effective guidance of electric vehicles (EVs) charging behavior has the potential to target RE consumption, flatten RE fluctuations, and enhance the stability of grid operation.

In this paper, a mixed-game model is proposed. First, a Stackelberg game model of government - electric vehicle aggregators (EVAs) is established for the upper-level government so as to develop a long-term RE pricing strategy and a weighting assessment mechanism. The government aims to develop a long-term RE pricing strategy and responsibility weight mechanism to maximize the RE consumption rate and minimize policy costs. Secondly, EVAs, as followers, construct a non-cooperative game model seeking to minimize electricity purchase costs after receiving price information and incentive /penalty factors.

In addition, a multi-market power purchase and sale strategy is formulated, which includes medium- and long-term markets, spot markets, green certificates trading (GCT) and power excess consumption trading (PECT). The bisection method is used to update the pricing strategy based on the updated multi-market purchase and sale strategies of EVAs, thus iteratively solving the Stackelberg equilibrium solutions. Fig. 1 shows the framework diagram of the hybrid game model. The master-slave game with bisection method can be described as:

$$\Omega = \{J^{\text{GOV}}, J^{\text{EVAs}}, S^{\text{GOV}}(p_k^G, \gamma_C, \gamma_Q), S^{\text{EVAs}}(Q_k^G, Q_k^Z, Q_k^H), C_k, C_g, \eta_g\} \quad (1)$$

where J^{GOV} and J^{EVAs} are all the participants of the game;

$S^{\text{GOV}}, S^{\text{EVAs}}$ are strategy sets of different participants; $p_k^G, \gamma_C, \gamma_Q$ represent the long-term renewable energy price, excess consumption reward coefficient and shortfall penalty coefficient respectively; Q_k^G, Q_k^Z, Q_k^H are RE, GCT and PECT purchase volume; C_k, C_g, η_g are objective functions of each subject.

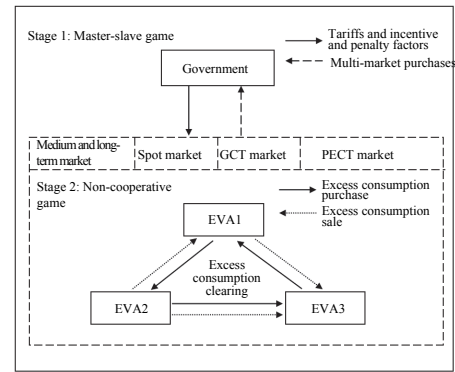


Fig. 1 Framework diagram of the government-EVAs mixed-game

The lower level is constructed as a static Bayesian game among the EVAs since each EVA makes independent decisions and the participants are unaware of the other participants' payoff functions.

In this paper, the proposed method improves the rate of RE consumption by 3.61% compared to a scenario with no consumption assessment mechanism. It also reduces the cost of government policies by 39% compared to a scenario without non-cooperative game including GCT and PECT between EVAs.

In contrast to existing studies, this paper considers the combined impact of government guidance and multi-market coordination, in accordance with the development trend of the electricity market in the context of high RE penetration. And a non-cooperative game between EVAs is constructed, in which each EVA makes decisions in multiple markets. In summary, this paper serves as a reference for government signing of future medium- and long-term RE contracts and for setting consumption assessment coefficients and EVA's power purchase strategy in multiple markets.

A Reconstruction Method for Virtual Power Plant Load Data Based on Federated Learning and Multimodal BERT

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KEY WORDS: virtual power plant (VPP); privacy protection; electricity market; bidirectional encoder representations from transformers (BERT); load data; data reconstruction

Virtual power plants (VPPs) aggregate distributed energy resources and flexible loads to participate in power system operation and electricity markets. The effectiveness of intelligent dispatching and operational decision-making highly depends on the completeness and accuracy of load data. However, communication failures and equipment malfunctions frequently lead to missing load data, while centralized data processing may expose sensitive user information. Therefore, this paper proposes a privacy-preserving load data reconstruction method, termed FLN-BERT-PIN, by integrating federated learning, multimodal Bidirectional Encoder Representations from Transformers (BERT), and differential privacy techniques.

In the proposed framework, each client performs model training using local load data and only uploads model parameters for global aggregation, thereby enabling collaborative learning without sharing raw data. Active power, reactive power, and electricity price information are jointly encoded as multimodal input features. The BERT network is employed to capture temporal characteristics and cross-modal correlations of

load data, while a PIN-based optimal candidate selection mechanism is introduced to improve reconstruction accuracy for missing data segments. The core optimization objective of the proposed framework is:

$$\text{mic}(m, n) = \max_{a+b} \frac{I(m, n)}{\log_2 \min(a, b)} \quad (1)$$

where I is the mutual information coefficient between the two variables; m, n are two discrete random variables representing the load data and electricity price, respectively; mic is the maximal information coefficient; $\max$ denotes the maximum correlation; and a, b are the number of grid bins in the directions of m, n , respectively. The combined FLN-BERT-PIN model proposed in this paper is presented in Fig. 1.

The method enables distributed training via federated learning to protect raw user data privacy, while the multimodal BERT effectively captures temporal dependencies and cross-modal correlations in industrial load data. Case studies verify that the proposed method outperforms traditional approaches in reconstruction accuracy, especially under high missing rates, providing a practical solution for privacy-aware missing data recovery in VPP scenarios.

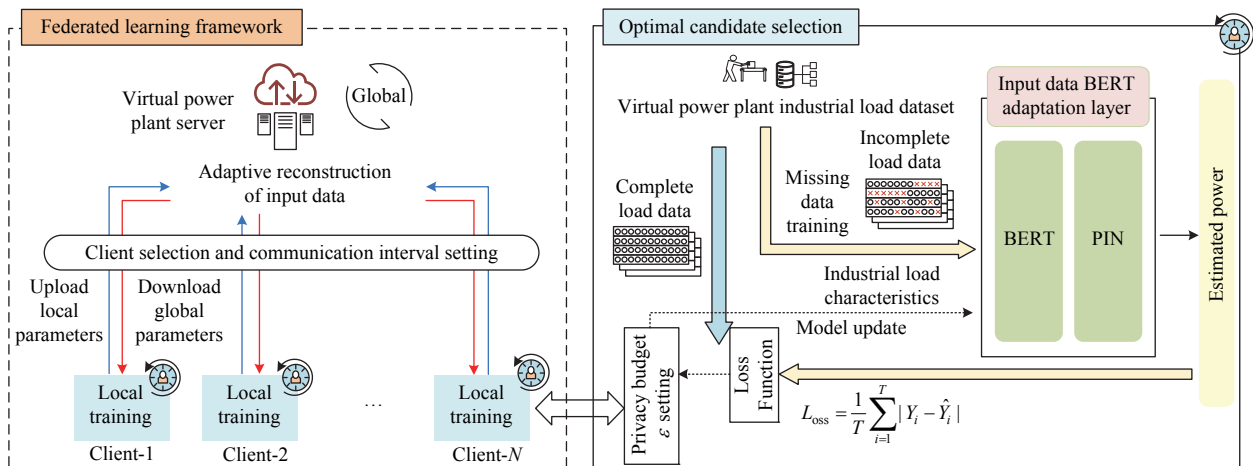


Fig. 1 FLN-BERT-PIN model framework

Deep Reinforcement Learning Based Physical Model Guided VSG Frequency Control Method in Islanded Microgrid Environment

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KEY WORDS: grid-forming (GFM); deep reinforcement learning (DRL); adaptive control; frequency control

To enhance the frequency performance of islanded microgrids dominated by grid-forming(GFM) converters, this paper proposes a deep reinforcement learning method based on physical model guidance: firstly, a small-signal model of VSG with secondary frequency management link is established, then a variable coefficient control is proposed with the small-signal model as a theoretical support, and it is introduced as a physical model into the deep reinforcement learning environment to improve the training efficiency, and then a reward/punishment mechanism is used to realize the VSG frequency adaptive control. Finally, in this paper, the trained model is extended to multiple VSGs cooperative control using reconstruction and migration neural networks.

A deep reinforcement learning control guided by a physical model is utilized to continuously interact with the VSG active loop, as shown in Fig. 1, accumulating maximum rewards through a reward/penalty mechanism to achieve offline training online control. The deep reinforcement learning controller based on physical model guidance is denoted as:

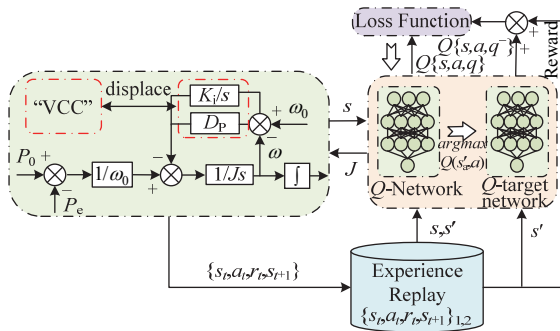


Fig. 1 Deep reinforcement learning controller based on physical model guidance

All the above are single VSG frequency control problems. Thus, this paper proposes to extract the neural network weights and biases, refer to the formulas in the appendix to reconstruct them in Simulink environment using MATLAB Function, and then extend them to multiple VSGs consistent equalization control. This

process is denoted as Fig. 2.

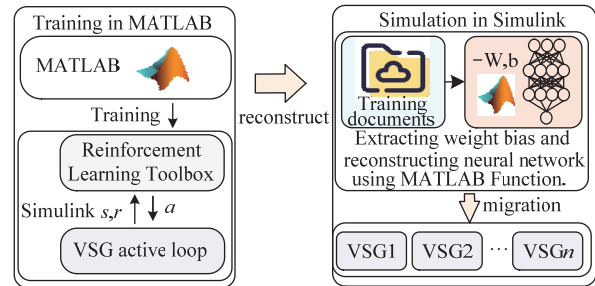


Fig. 2 Network reconfiguration and migration flowchart

The main contribution of this paper is expressed as:

1) The controller proposed in this paper gives certain dynamic properties to the multidimensional parameters of the VSG so that it can respond to the VSG output frequency during the transient process. When the system suffers from different load disturbances, the VSG output frequency can always maintain the optimal output.

2) Being limited by the dimension of deep reinforcement learning (DRL) observations, it is therefore difficult to achieve centrally centralized VSG frequency control. To address the above challenges, in this paper, we first train a single VSG model and then generalize the single VSG frequency control to multiple consistently balanced VSG frequency control using reconfiguration and migration neural networks, which substantially improves the load carrying capability of the structured network-type converter.

3) At present, there are fewer references on the implementation of deep reinforcement learning platform, and this paper solves the problems of inconsistent data structure and communication between simulation and experiment by means of neural network reconstruction and migration.

In this paper, artificial intelligence (AI) is introduced into the frequency of grid-forming (GFM) type converter, which provides a theoretical basis and practical guidance for the stable operation of high proportion new energy power systems.

Bi-level Collaborative Regulation-operation Optimization Method for E-SOP Security Concerning DC-link Calculation

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KEY WORDS: E-SOP; DC-link calculation; device-node security; multi-dimensional security margins; bi-level collaborative optimization

High penetration of distributed generators leads to severe spatiotemporal source-load imbalance, thereby intensifying risks at critical nodes and undermining defensive capabilities through the power tidal effect. Although energy storage system-integrated soft open point (E-SOP) can effectively compensate for spatiotemporal power deficits, existing researches often employ idealized E-SOP models, which ignore voltage and current fluctuations in expanded DC-links, and lack dynamic node security margins, leading to distorted resilience assessments and local optima.

This paper proposes a bi-level collaborative regulation-operation optimization method for E-SOP security

concerning DC-link calculation. As Fig. 1 shows, this paper develops a refined E-SOP model embedding dynamic DC-link characteristics to quantify internal power equilibrium, and establishes a model concerning device-node security with multi-dimensional margins to track power impacts on operational boundaries. Based on the proposed bi-level collaborative optimization framework in Fig. 2, E-SOP site selection and dispatch strategy are optimized. In the modified IEEE 123-node system, the effectiveness is verified, providing an innovative solution for the distribution network with flexible interconnection.

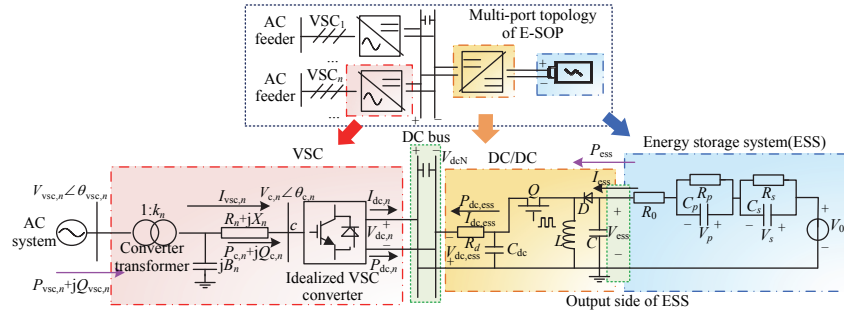


Fig. 1 Refined equivalent circuit of E-SOP

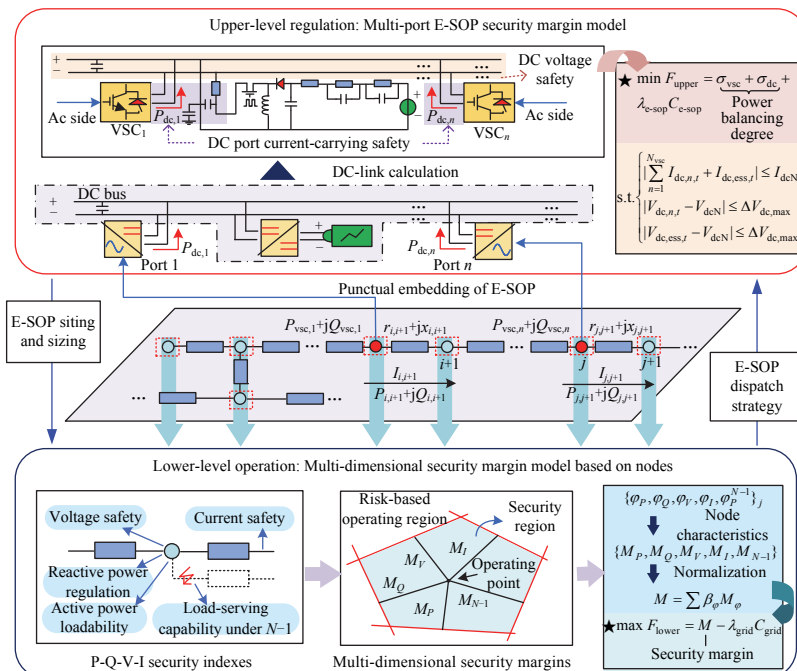


Fig. 2 Framework of collaborative regulation-operation optimization method for E-SOP security

Energy Management Strategy for Photovoltaic-energy Storage-direct Current-flexible Buildings Considering Multiple Comfort Levels of Heterogeneous Load Clusters

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KEY WORDS: load heterogeneity; load clustering; multiple comfort levels; photovoltaic-energy storage-direct current-flexible (PEDF); non-dominated optimization

In buildings, the large and heterogeneous load groups make it difficult to establish a unified regulation method and standard. Given the heterogeneity of a large number of loads in terms of environmental parameters, load parameters, and operating periods, it is extremely challenging to conduct unified modeling for these loads. To address this issue, this paper clusters the operating curves of these loads and establishes fitting models for similar loads to enable unified regulation.

The clustering performance of the traditional k-means clustering algorithm cannot meet the requirements of refined load modeling. Therefore, an improved clustering algorithm based on dynamic time warping and secondary clustering for load operating periods is proposed in this paper. In the initial clustering, the operating periods are not taken into account. Only the heterogeneity of environmental and load parameters is considered, and the dynamic bending distance is used as the basis for selecting cluster centers. After the initial clustering is completed, secondary clustering is performed on the operating periods of the loads. The number of clusters is increased, and the cluster centers are recalculated. By traversing within the maximum possible number of clusters, the appropriate number of clusters and fitting model parameters are sought with the best clustering effect and the best model fitting effect as the goals.

All the loads included in each load model are

regulated through a unified control sequence. However, the impact of numerous operating loads on the environment within buildings is complex. It is not singular but involves multiple-parameter coupling, which poses challenge to establishing a unified regulation standard. Therefore, an “economy - multiple comfort” coupling model is proposed. The coupling relationship of “economy- multiple comfort” for the loads is depicted in Fig. 1, as presented in this paper. The “economy - thermal comfort-auditory comfort” coupling model for air-conditioning loads, the “economy-air-quality comfort - auditory comfort” coupling model for fresh-air loads, and the “economy-visual comfort” coupling model for lighting loads are included in this model. Through this model, the non-dominated sorting genetic algorithm II (NSGA-II) is used to perform multi-objective optimization scheduling of “economy-multiple comfort” for the loads within the building.

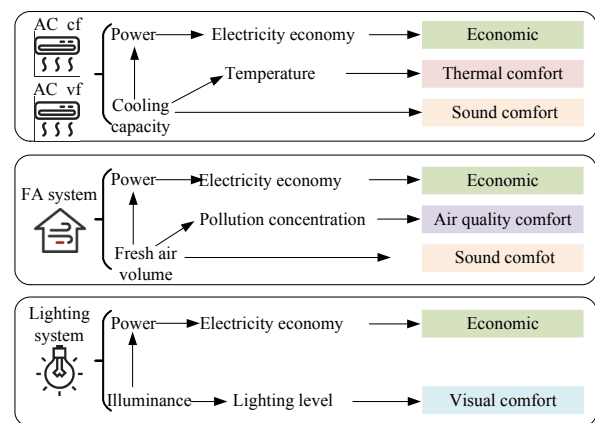


Fig. 1 Schematic of the coupling relationship between economy and multi-dimensional comfort

Evaluating Multi-dimensional Regulation Capability of Central Air Conditioning Considering Carbon Emissions and Apparent Temperature

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KEY WORDS: carbon emissions; apparent temperature; central air conditioning; regulation capability assessment

As the penetration of renewable energy continues to increase, random, intermittent, and continuous power fluctuations become increasingly prominent. Central air conditioning (CAC) loads offer multi-timescale regulation potential. However, existing methods mainly use air temperature to characterize CAC operation and adopt a fixed 15-min interval for regulation capability assessment, while apparent temperature (AT), low-carbon operation, and multi-dimensional regulation capability are not considered.

To improve assessment accuracy, an AT-based correction model for CAC operating characteristics is developed. AT is calculated using measured air temperature (MT), relative humidity, and wind speed. The CAC on/off cycles, operating states, and baseline power are corrected to better reflect occupants' thermal comfort, as shown in Fig. 1.

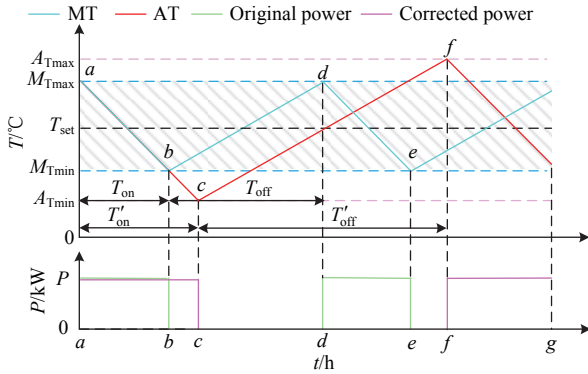


Fig. 1 Impact of AT and MT on CAC operating characteristics

A low-carbon CAC operation model considering carbon emissions is developed. Subject to AT limits and on/off constraints, part of each cooling cycle is advanced or delayed based on the electricity carbon emission factor. This shifts CAC operation to low-carbon periods and reveals the effects of carbon emissions and electricity prices on the operating baseline, as shown in Fig. 2.

On this basis, fast, residual, and sustained regulation capability assessment models are established. The fast model evaluates the maximum up- and

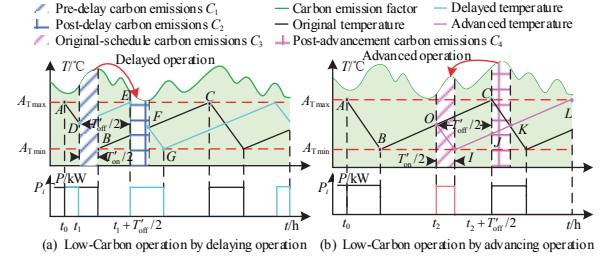


Fig. 2 Power of CAC under low-carbon operation

down-regulation power within a specified response time. The residual model updates temperature, operating state, and power after successive commands. The sustained model establishes the relationship between regulation power and response duration, obtaining the power-duration capability boundary, as shown in Fig. 3.

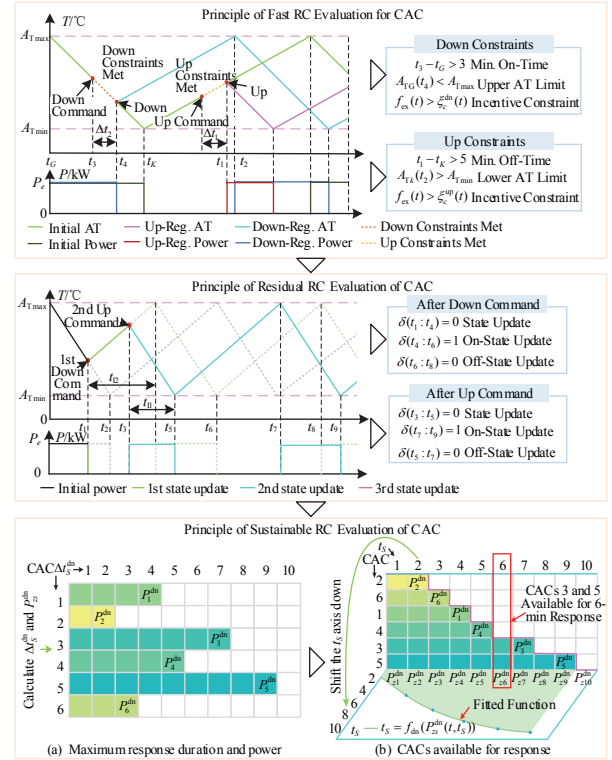


Fig. 3 Principles of Multi-dimensional RC Evaluation for CAC

Overall, the proposed method integrates AT-based correction, low-carbon operation, and multi-dimensional regulation capability assessment, supporting CAC participation in multi-timescale control.

Oscillation Center Migration Characteristics and Active Stability Control of Virtual Synchronous Generator Grid-connected System

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KEY WORDS: virtual synchronous generator; electromechanical transient simulation model; current limiting constraint; oscillation center; active stability control

Most existing studies on virtual synchronous generator (VSG) grid-connected systems lack comprehensive analysis of how current limiting constraints induce oscillation center migration and affect system stability. This paper establishes an electromechanical transient simulation model of the VSG grid-connected system that takes into account the dual constraints of current limiting and internal electromotive force (EMF) amplitude. For VSG grid-connected systems with different short-circuit ratios, the law is analyzed by which the current limiting constraint causes changes in the equivalent internal EMF amplitude, thereby leading to the migration of the system's oscillation center. In response to the positional characteristics of the oscillation center migration, an active stability control strategy based on VSG states and wide-area branch responses is proposed.

Fig. 1(a) and Fig. 1(c) present the migration of the oscillation center position coefficient $\lambda_{\min}$ and the minimum system voltage $U_{\min}$ for grid-connected systems with $SCR=3.0$. Fig. 1(b) and Fig. 1(d) present the migration of the oscillation center position coefficient $\lambda_{\min}$ and the minimum system voltage $U_{\min}$ for grid-connected systems with $S_{CR}=1.5$. The results illustrate that under current limiting conditions, the oscillation center migrates from the grid side towards the VSG side as the virtual power angle increases.

Unlike traditional systems where the oscillation center remains fixed usually, the VSG's equivalent internal EMF amplitude dynamically changes due to current limiting, causing the oscillation center to migrate. Two scenarios are identified: migration into the VSG itself or remaining within the transmission network.

In Fig. 2, an active stability control framework is proposed. It utilizes VSG state monitoring to trigger power reference reduction. Concurrently, it employs a wide-area branch response index (sBTTC) to locate and

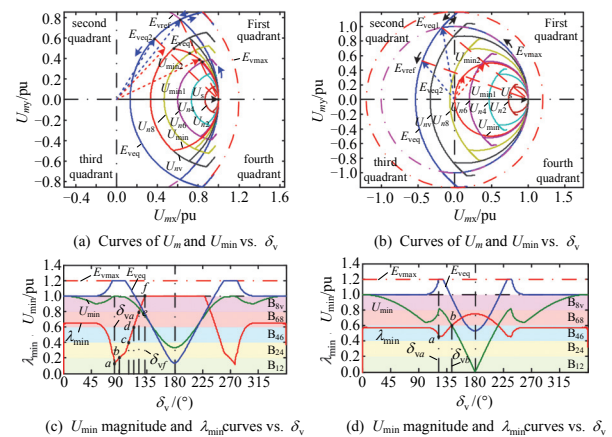


Fig. 1 U_m , $\lambda_{\min}$ and $U_{\min}$ corresponding to SCR=3.0 and SCR=1.5

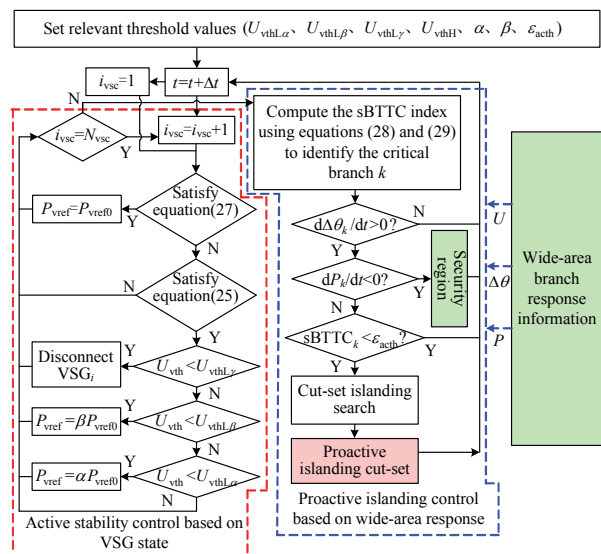


Fig. 2 Active stability control strategy for system including VSGs

sever the critical network cut-set when the oscillation center migrates within the grid.

The impact of key factors—current limiting level I_{vmax} and SCR on the migration characteristics are analyzed, and corresponding stabilization methods are proposed. Simulations on a modified IEEE 10-machine 39-bus system verify the correctness of the oscillation center migration analysis and the effectiveness of the proposed active control strategies in maintaining the stability of main grid.

Iterative Calculation Method of Short-circuit Current of Power Grid Connected with Inverter-based Resources Considering Non-smooth Features of Fault Model

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KEY WORDS: inverter-based resources(IBRs); fault equivalent model; short-circuit current calculation; non-smooth; iterative algorithm

The increasing proportion of inverter-based resources (IBRs) in power grid has introduced novel characteristics to short-circuit current calculation method, and causes convergence problem in conventional algorithms, needing new development of computational approaches.

The output characteristics of IBRs during the low voltage ride-through (LVRT) are determined by the LVRT control strategy. Its fault equivalence model is the voltage-controlled current source model. The steady-state output current under the typical control strategy is:

$$\begin{cases} I_d = I_{dref}, I_q = 0 & U_{PCC} > 0.9 \\ I_d = \min\{I_{dref}, \sqrt{I_{max}^2 - I_q^2}\} \\ I_q = \min\{K(0.9 - U_{PCC}), I_{max}\} & U_{PCC} \leq 0.9 \end{cases} \quad (1)$$

This study analyzes the fault equivalent models under typical LVRT control strategies for IBRs. These models exhibit control strategy switching transients and nonlinear current-limiting characteristics, which contribute to non-smooth features in the equations of short-circuit current calculation. Then, mathematical expressions for the short-circuit current calculation that accounts for nonlinear and non-smooth behaviors are established.

In order to better solve nonlinear problems, gradient algorithms such as the Newton-Raphson (NR) method are adopted to replace the fixed-point iterative algorithm for solving equations. However, when using gradient-based algorithms to solve non-smooth equations, new convergence problems will be faced. This paper presents a typical example and proves that when the true solution of the equation system considers non-smooth points, gradient-based algorithms will generate numerical oscillations or even non-convergence problems. Among them, the convergence result of the example of solving non-smooth equations by the NR

method is shown in Fig. 1.

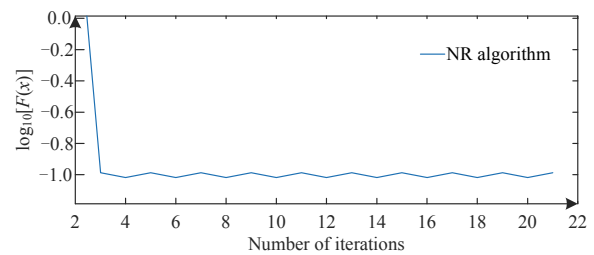


Fig. 1 Relationship between the unbalance of equations and the number of iterations

NR algorithm may exhibit numerical oscillations when solving these equations. The non-smooth feature of control strategy switching is identified as the primary cause of convergence failures. A new Trust Region Gradient updated with quasi-Newton technique algorithm (TRGN) is proposed, which uses quasi-Newton intercept approximation instead of gradient and combines trust region to solve non-smooth equations. This algorithm can ensure global convergence of short-circuit current calculation in high proportion new energy grids and broaden the application scope of the traditional quasi-Newton algorithm.

Finally, using the IEEE 118-bus system as a case study, this paper compares the convergence performance of the TRGN algorithm with the gradient algorithm and the fixed-point iteration algorithm. As shown in Table 1. The results demonstrate that the proposed algorithm not only maintains robust convergence characteristics but also effectively addresses the solution of non-smooth equations.

Table 1 Impact of IBRs capacity on algorithm

I_{IBRi}	Algorithm Name					
	Fixed-point algorithm		NR algorithm		TRGN algorithm	
	Number	Times	Number	Times	Number	Times
0.02	22	0.677	5	0.314	8	0.253
0.04	∞	∞	6	0.295	10	0.242
0.06	∞	∞	∞	∞	11	0.246
0.08	∞	∞	∞	∞	12	0.267
0.1	∞	∞	8	0.329	15	0.265

Optimization and Simulation Synergetic Approach for Power System Critical Inertia Requirement Assessment

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KEY WORDS: inertia requirement; inertia estimation; inertia alarming; frequency security; low-inertia system; electronic power system

Inertia forms the foundation for AC power systems frequency stability, rendering critical inertia requirement (CIR) assessment vital for low-inertia risk management in new-type power systems. The CIR is defined as the minimum system inertia level required to ensure that the rate of change of frequency (RoCoF) and frequency deviation during post-disturbance transients remain within security limits, governed by frequency stability criteria. Safeguarding frequency security during low-inertia scenarios represents a critical scientific challenge demanding urgent resolution. Accurate CIR assessment serves as a prerequisite for identifying and managing low-inertia risks in new-type power systems, enhancing the capability of grid operation and planning departments to issue security alerts and implement precise inertia-level control.

CIR assessment constitutes a multivariable-coupled problem subject to constraints including primary frequency regulation (PFR) capability and frequency security requirements. As the microscopic essence of power systems, unit commitment not only determines the system inertia level but also governs PFR capability, rendering inertia levels derived without physical operational constraints merely numerical solutions.

To address existing methods' limitations in concurrently handling PFR coupling dynamics, accurate post-disturbance frequency calculation, and computational efficiency, this paper establishes an optimization and simulation synergetic approach for CIR assessment from three perspectives: steady-state existence, transient security and numerical criticality, as illustrated in the Fig. 1. The feasible inertia points (FIP) optimization searching focuses on the steady-state operational feasibility within regional power grids. Leveraging known system parameters and operational criteria, it deduces FIPs and their corresponding operating states, thereby providing a steady-state dataset for transient frequency simulations. The transient security simulation evaluates post-disturbance frequency dynamics. Using the FIP obtained from the optimization subproblem as inputs, it dynamically updates the

participation of frequency regulation resources (e.g., generator dispatch, reserve capacity) in a multi-machine frequency response simulation model. This approach simulates system frequency trajectories coordinating inertia and PFR capabilities while validating key frequency indicators. As a bridge between subproblems, the adaptive CIR correction module enables proactive assessment and enhances iterative computation efficiency, constituting a critical element of the framework.

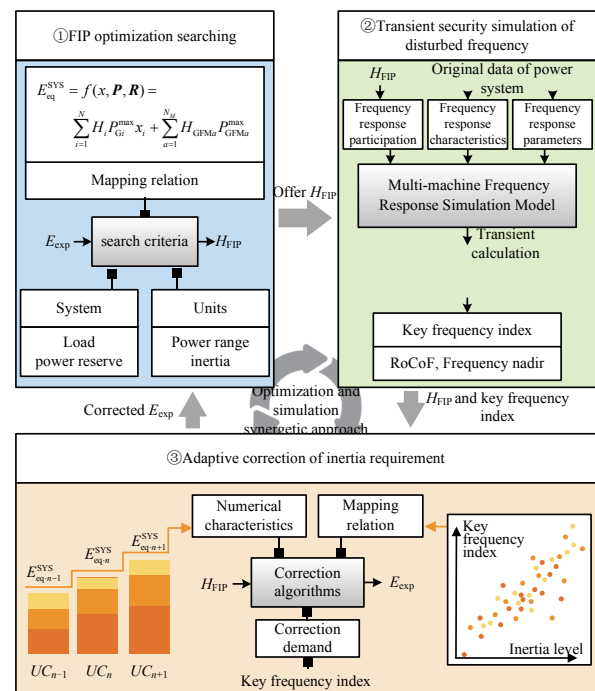


Fig. 1 Synergetic framework for CIR assessment

The effectiveness and accuracy of the proposed framework were validated on an actual regional power grid. Compared to conventional methods, our approach incorporates steady-state operational constraints and accurately replicates post-disturbance frequency response characteristics, achieving rapid and precise CIR assessment. Therefore, the framework provides a modular, easily implementable, and reliable solution for CIR assessment, which provides calculation tools for security warning and precise control of system inertia level, balancing both accuracy and practicality in assessment results.

Mechanism of DC Bias Generation and Engineering Suppression Methods for VSC-HVDC Transmission Systems

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Key words: VSC-HVDC, DC bias, asymmetric bridge arm parameters, DC bias suppression

In the three-phase six-arm topology of the MMC, each bridge arm primarily consists of an arm reactor and submodules of the converter valve. When there are deviations in the equipment parameters of each bridge arm, the original symmetry assumptions and modeling methods no longer stand. This paper establishes a mathematical model for the DC component of the arm current under asymmetric bridge arm parameters, such as resistance, reactance, capacitance, as well as the number of submodules, and analyze the DC bias under the influence of different factors. Taking the case where the equipment parameters of the upper arm in phase A deviate as an example, the corresponding relationship between the DC bias voltage and current in the MMC is illustrated in Fig. 1.

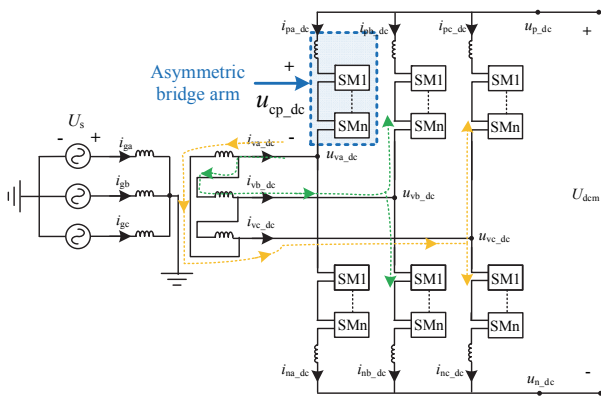


Fig. 1 Corresponding relationship between DC bias voltage and current of MMC

Based on the average switching function model, the DC bias current can be mathematically derived and expressed as:

$$\begin{cases} i_{p_dc} = \frac{U_{dcm}}{F_p} \\ i_{n_dc} = \frac{U_{dcm}}{F_n} \end{cases} \quad (1)$$

$$i_{v_dc} = i_{n_dc} - i_{p_dc} \quad (2)$$

To optimize the long-term operating conditions of the transformer and mitigate DC magnetic bias risks, this section introduces a DC bias suppression control loop into

the controller to suppress the DC current component on the valve side of the converter transformer. The control block diagram is illustrated in Fig. 2.

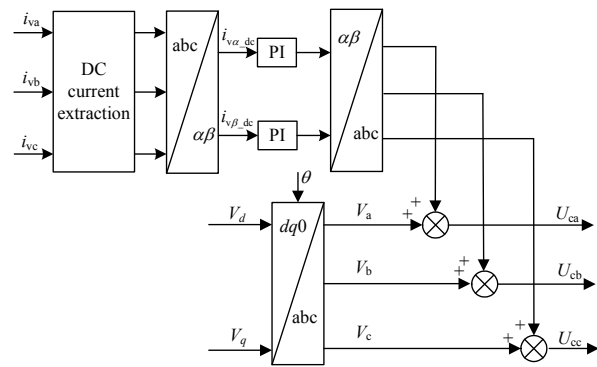


Fig. 2 Two-degree-of-freedom DC bias current suppression strategy

The DC bias current suppression strategy proposed in this paper has been implemented in the Baihetan-Jiangsu ± 800 kV UHVDC (Ultra-High Voltage Direct Current) transmission project. According to field commissioning results, the activation of the suppression strategy effectively mitigates the DC bias current on the valve side of the converter transformer, while also reducing audible noise and vibration levels in the converter transformer, as shown in Fig. 3.

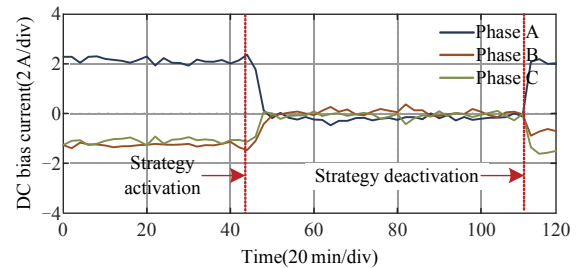


Fig. 3 DC current of P1 VSC1 before and after strategy

The proposed DC bias suppression strategy has demonstrated remarkable effectiveness in engineering applications. After field commissioning, the DC bias current is rapidly reduced, accompanied by significant decreases in transformer noise and vibration levels, which has led to a substantial improvement in the transformer's operating environment.

Feeder Selection Method Tolerating Transformer Error in Asymmetric Distribution Network Based on Arc-suppression Component Compensation

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KEY WORDS: improved zero-sequence admittance method; arc suppression coil; asymmetric distribution network; fault feeder selection

The zero-sequence admittance method is not affected by the grounding resistance, and the fault feeder selection result is reliable. In engineering practice, due to the influence of parameter asymmetry and transformer error, the accuracy of the feeder selection results is low. Although the influence of parameter asymmetry on zero-sequence admittance method has been effectively solved, the problem of low fault feeder selection accuracy in the background of transformer measurement error has not been well solved, which is the most difficult and the last problem to be solved that affects the engineering application of zero-sequence admittance method.

In order to eliminate the influence of the phase angle measurement error of the current transformer on the zero-sequence admittance method, this paper proposes an asymmetric distribution network fault feeder selection method based on the compensation of arc components. The method effectively amplifies the phase difference of the measured zero-sequence admittance between the fault feeder and the normal feeder, achieving reliable feeder selection in the distribution. The zero-sequence current after compensation of arc current is used to replace the zero-sequence current for zero-sequence admittance method, and the measured remaining zero-sequence admittance of the normal feeder and the fault feeder can be obtained.

When the arc suppression coil is in the state of overcompensation, the distribution range of the zero-sequence admittance angle of the normal feeder and the fault feeder is shown in Fig. 1.

When the arc suppression coil is in the state of overcompensation, the fault feeder selection criterion is: the feeder with the remaining zero-sequence admittance angle above the boundary line $l(22.5^\circ \sim 202.5^\circ)$ is determined as the fault feeder, and the feeder with the remaining zero-sequence admittance angle below the boundary line $l(-157.5^\circ \sim 22.5^\circ)$ is determined as the normal feeder.

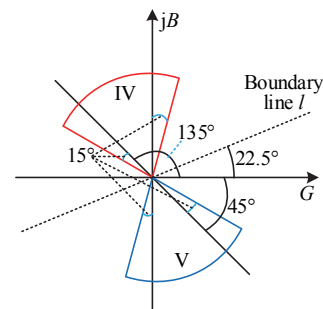


Fig. 1 The distribution range of the zero-sequence admittance angle of the normal feeder and the fault feeder

The key to the implementation of the proposed fault feeder selection method in this paper lies in the accurate acquisition of the required compensation arc current of each feeder, that is, the acquisition of the feeder distribution coefficient. This paper proposes a method to measure the distribution coefficient of the feeder by projecting the transient zero-sequence current component on the transient zero-sequence voltage and the transient current component of the arc suppression coil on the transient zero-sequence voltage. The projection diagrams of the transient component are shown in Fig. 2.

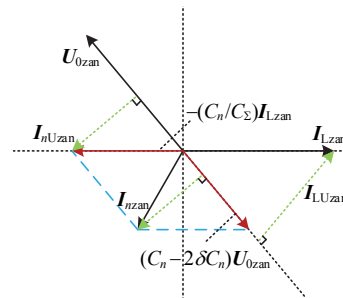


Fig. 2 The projection diagrams of the transient component

Compared with other fault feeder selection methods, the method proposed in this paper is not affected by transition resistance, parameter asymmetry, and current transformer measurement error, and it better feeder selection reliability and sensitivity. At the same time, the fault feeder selection method still applies to arc faults, and the selection accuracy can reach 100%.

Rotor Speed Control Strategy of Energy Storage Doubly-fed Condenser for System Frequency Trajectory Optimization

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KEY WORDS: energy storage doubly-fed condenser (ESDFC); frequency trajectory; optimized control; rotor speed control; frequency response characteristic

With the large-scale integration of renewable energy sources like wind and solar, power systems face challenges such as reduced short-circuit capacity and insufficient rotational inertia, which is prone to transient voltage and frequency issues. Traditional synchronous condensers (SC) have low inertia and lack active speed regulation, making them ineffective in frequency support. The energy storage doubly-fed condenser (ESDFC), with its high inertia and wide slip variable-speed operation capability, offers significant advantages in frequency support. However, existing inertia control methods fail to account for the frequency modulation effects of other units and cannot balance steady-state constant-speed operation requirements. This paper proposes a rotor speed control strategy for ESDFC to optimize system frequency trajectory, aiming to meet both the maximum rate of change of frequency (RoCoF) constraint and minimize frequency deviation.

The paper derives an active power-frequency optimal control function for the synchronous condenser based on the frequency response model of grid-connected ESDFC. Through reverse-solving the designed frequency trajectory, the corresponding rotor speed control command is obtained via the swing equation, with its specific expression given as follows:

$$\omega_{r,ref} = \omega_{r0} + \frac{1}{2H_r\omega_r} \left(\alpha + \beta \frac{K_G T_G}{1 + T_G s} \right) \Delta f \quad (1)$$

where $\omega_{r,ref}$ is the rotor speed command value, ω_{r0} is the steady rotor speed value, ω_r is the current rotor speed value, H_r is the rotor mechanical inertia constant, α and β are the inertia coefficient and the compensation coefficient respectively, K_G and T_G are the magnification factor and the reheating time constant of synchronous machine governor, Δf is the grid frequency deviation.

The derived rotor speed control strategy comprises a rotor speed-frequency droop component and a first-order inertial component. The droop component provides equivalent inertia for the power grid, effectively suppressing the maximum RoCoF. Meanwhile, the

first-order inertial component compensates for the lag effect of synchronous machine governors, reducing frequency deviations. Under ideal conditions, this control architecture can achieve optimal control performance without frequency overshoot.

This paper discusses the calculation principles of key control parameters by considering both system operational requirements and speed limit constraints. The inertia coefficient α is prioritized for configuration based on frequency security constraints, followed by determining the compensation coefficient β according to the current speed margin, thereby preventing rotor speed limit violations during frequency support. Fig. 1 shows the rotor speed control block diagram of the ESDFC optimized for frequency trajectory control.

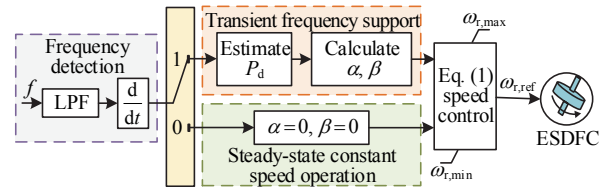


Fig. 1 Speed control block diagram for system frequency trajectory optimization

The simulation results demonstrate that the proposed speed control strategy enables ESDFC to simultaneously achieve three functionalities: steady-state fixed-speed operation, transient frequency support, and autonomous speed recovery. Compared with existing frequency support methods, the proposed strategy more fully utilizes the effective rotor energy storage of ESDFC, better satisfying both the maximum RoCoF constraint and the minimization requirement of maximum frequency deviation. Moreover, the proposed method features autonomous parameter adjustment according to different disturbance levels. When the stored energy is relatively low, it can still deliver satisfactory frequency support performance while ensuring the rotor speed remains within limits, demonstrating applicability to various disturbance types.

Research on Charging Scheduling for Electric Vehicle Clusters Based on Multi-agent Reinforcement Learning

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KEY WORDS: deep reinforcement learning; multi-agent; electric vehicle; charging scheduling; distributed architecture

The rapid growth of electric vehicles (EVs) is increasing the flexibility available to distribution networks, but uncoordinated charging can aggravate peak loads, voltage fluctuations, power losses, and local congestion. The scheduling problem becomes more difficult when photovoltaic (PV) generation, time-varying electricity prices, multiple distributed charging stations, heterogeneous user demands, and vehicle-to-grid operation are considered simultaneously.

To address these problems, this study proposes a multi-agent dynamic grouping value transformation algorithm, termed MADGVT, for coordinated charging and discharging of EV clusters. A regional distribution-network environment containing EV agents, charging-station agents, and distributed PV units is first modeled as a Markov game. The state space includes vehicle state of charge, arrival and departure times, charging demand, station-selection information, queue length, charging power, electricity price, node power flow, PV output, and node voltage. Reward functions are constructed to balance user charging demand, charging cost, travelling and waiting penalties, network power loss, load fluctuation, and voltage security. Multi-agent charging scheduling framework based on dynamic grouping is shown in Fig. 1.

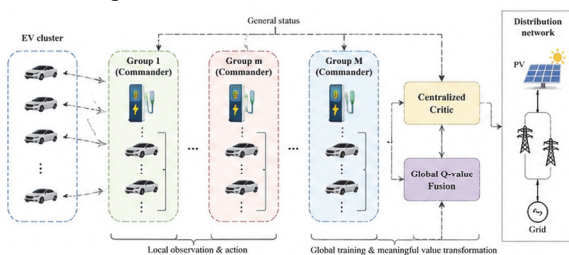


Fig. 1 Multi-agent charging scheduling framework based on dynamic grouping

MADGVT dynamically partitions EVs according to their selected charging stations and current operating states. Each charging station acts as the commander of its group, aggregates information from the follower EVs, and generates group-level decisions. A centralized group Critic evaluates the local decision quality, thereby decomposing the original large-scale problem into several lower-dimensional subproblems and reducing redundant

communication. Since different groups may exhibit cooperation, competition, and other non-monotonic interactions, a nonlinear mixing network is introduced to combine local Q-values. Two consistency losses align the mixed Q-value with a global Q-function at both suboptimal and optimal actions, enabling local value learning to support coherent global scheduling during centralized training while retaining distributed execution.

The proposed method is evaluated on an IEEE 33-bus distribution system containing six charging stations, three PV units, and 240 EVs, with a five-minute scheduling interval. Each station contains 20 chargers, the maximum charger power is 10 kW, and the station power limit is 150 kW. Compared with QMIX, NashQ, and MADDPG over 100 000 training episodes, MADGVT reaches stable performance after approximately 10 000 episodes and obtains the highest cumulative reward.

Day-ahead scheduling results show that MADGVT produces a smoother load curve, lower peak demand, smaller voltage fluctuation, and more balanced power allocation among charging stations than MADDPG and maximum-power charging.

While maintaining an average departure state of charge of 94.1%, MADGVT achieves the lowest charging cost, 0.857 yuan/kWh, compared with 0.868 yuan/kWh for MADDPG and 0.882 yuan/kWh for maximum-power charging. The learned policy also uses limited vehicle-to-grid discharging without reducing vehicle state of charge below the required target.

Robustness tests under sharply reduced and fluctuating PV output and randomly distributed EV arrivals keep all node voltages within the safe range. Further experiments on 141-bus and 300-bus systems with 480 and 960 EVs confirm that MADGVT preserves its reward and voltage-regulation advantages as the network scale increases.

These results demonstrate that dynamic grouping, commander-follower coordination, and globally consistent value transformation provide an effective and scalable solution for EV-cluster charging scheduling under complex, partially cooperative, competitive, and time-varying grid operating conditions.

Internal Condensation Flow Characteristics and Structural Optimization of S-CO₂ Centrifugal Compressors Under Near-critical Conditions

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(Department of Power Engineering, North China Electric Power University)

KEY WORDS: supercritical carbon dioxide(S-CO₂); centrifugal compressor; phase change condensation; structural optimization

Supercritical carbon dioxide (S-CO₂) Brayton cycle power generation systems have gained attention due to high cycle efficiency and compact structure. As a key component, the S-CO₂ centrifugal compressor operates near the critical point to utilize S-CO₂'s high compressibility. However, drastic changes in CO₂'s physical properties near the critical point may induce phase change condensation inside the compressor, leading to flow losses and blade erosion. Therefore, investigating the internal condensation characteristics of compressors has become one of the key focuses of current research.

Based on shear-stress transport (SST) $k-\omega$ turbulence model and an equilibrium phase change model, this paper analyzes the three-dimensional flow field inside a compressor, revealing the condensation mechanism of the S-CO₂ working fluid at the blade leading edge and tip clearance under near-critical point conditions. As shown in Fig. 1, an optimization-based flow control method utilizing blade leading-edge profile curvature is proposed. By replacing the circular arc profile with an elliptical curvature, the flow acceleration on the suction surface of the leading edge and the flow separation on the pressure surface are effectively mitigated, thereby resolving the condensation issue on the blade surface caused by intense shear and separation.

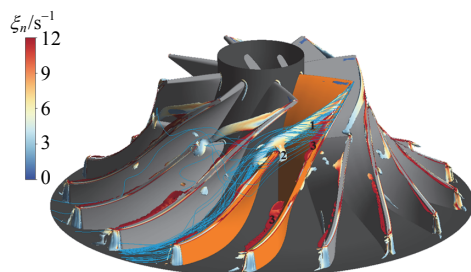


Fig. 1 The relationship between leading edge leakage flow and vortex structure

Furthermore, a tip flow regulation strategy based on the management of leakage flow and vortex structures is introduced in (Fig. 2). This approach suppresses the

formation and development of the leading-edge leakage vortex, effectively addressing the condensation problem in the tip clearance. Consequently, effective suppression of internal condensation and performance enhancement under near-critical point conditions are achieved.

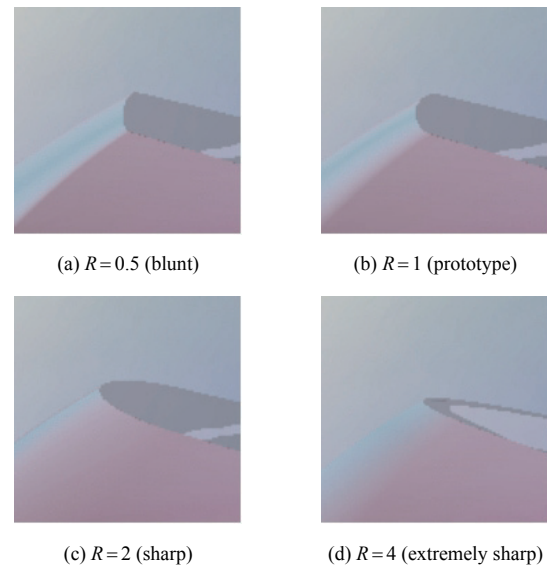


Fig. 2 3D images of different blade leading edge profiles

Compared to existing studies, this work systematically reveals the coupling mechanisms between internal condensation and the three-dimensional flow field in an S-CO₂ centrifugal compressor. Through entropy analysis and vortex identification, the intrinsic causal relationships between dynamic flow structures—such as flow separation at the blade leading edge and the development of tip leakage vortices—and the initiation and evolution of condensation are clarified. Notably, by integrating condensation control with blade optimization and axisymmetric endwall contouring, a novel design methodology based on leading-edge profile and endwall flow regulation is developed. This approach suppresses condensation at its source, rather than passively mitigating its effects, thereby bridging the research gap from phenomenological description to mechanism-based control.

Influence of Asymmetric Anode and Cathode Humidification Coupled Temperature on Water Transport and Performance of PEMFC

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KEY WORDS: fuel cell; proton exchange membrane; operating temperature; asymmetric humidification; numerical simulation; water management; renewable energy

Proton exchange membrane fuel cells (PEMFCs) are promising clean energy devices, but their performance strongly depends on effective water and thermal management, especially under varying temperatures and asymmetric humidification conditions. However, the interplay between proton transport and water management in such non-uniform environments remains unclear, presenting challenges for optimal fuel cell operation.

This paper combines experiments and simulations to investigate how working temperature and asymmetric anode/cathode humidification jointly affect proton transport and PEMFC performance. A proton transmembrane transport (PTT) model is developed, considering electro-osmotic drag, diffusion, and pressure-driven water flux across the membrane, and implemented in COMSOL Multiphysics. The model is

validated against polarization curve data from a custom-built PEMFC test setup.

Systematic tests at 50, 60, and 70°C with varying anode relative humidity (25%–100%, cathode fixed at 50%) show that the best cell performance and highest proton conductivity occur at 60°C and 75% anode RH. At higher temperatures, 100% anode humidification is required to mitigate membrane dehydration. Both simulation and experimental results reveal that cross-membrane water flux increases with current density and anode RH, but excessive temperature reduces overall water transport due to membrane drying. Local current density mapping demonstrates a “front-high/back-low” distribution under high current, reflecting efficient water transport at the inlet and mass transfer limitation at the outlet. The structure diagram of experimental hydrogen-air PEMFC system is shown in Fig. 1.

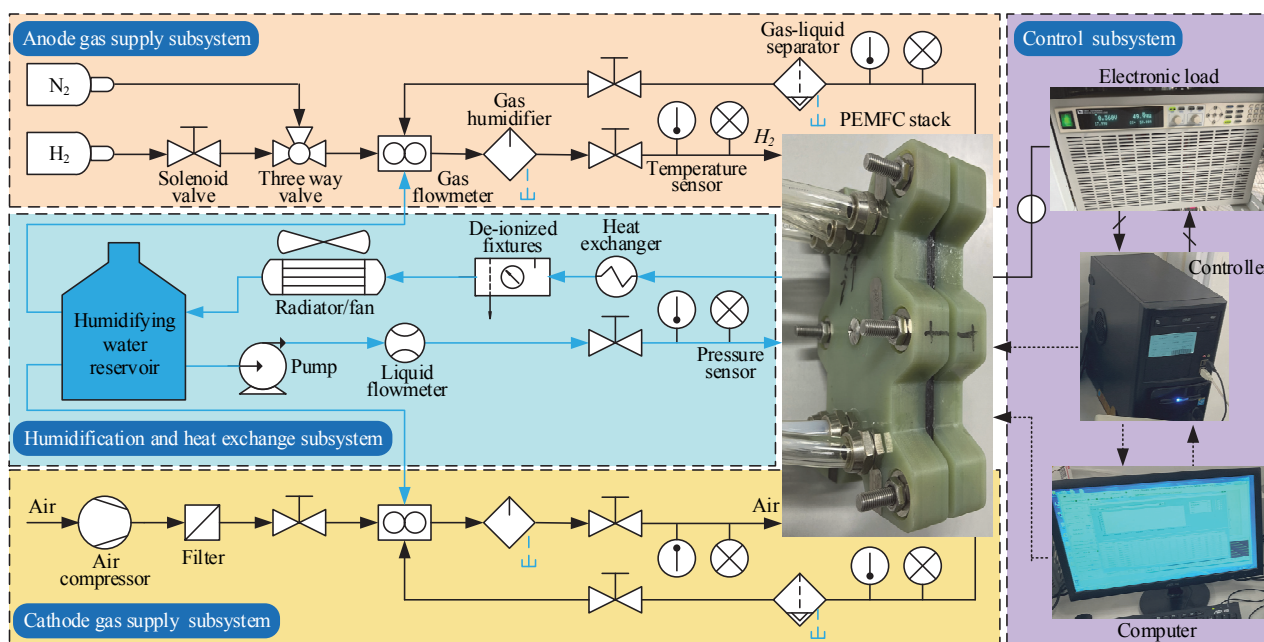


Fig. 1 Structure diagram of experimental hydrogen-air PEMFC system

The PTT model quantitatively captures the coupled effects of temperature and humidity on water management and cell performance, providing useful guidance for the design and operation of PEMFCs

under asymmetric humidification. These findings contribute to improved water management strategies and enhanced operational reliability for next-generation fuel cell applications.

Enhancing the High-temperature Energy Storage Performance of Polyetherimide by Chain Blocking

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KEY WORDS: polyetherimide; high temperature; energy storage performance; free volume; trap

The capacitor films are extensively utilized in power electronic devices and equipment due to their high power density, superior voltage resistance, and excellent long-term stability. With the rapid development of emerging sectors such as new energy vehicles, pulsed power systems, and aerospace applications, there is an increasing demand for enhanced high-temperature energy storage performance of capacitor films. In order to address the growing application requirements of film capacitors under extreme high-temperature conditions, it is imperative to develop novel high-temperature-resistant polymer dielectrics for energy storage.

This paper proposes utilizing functional groups Nadic anhydride (NA) for chain blocking to solve the problems of rapid growth in the high field conductivity, significant decrease in breakdown strength and energy storage density (U_e) of polyetherimide (PEI) at extremely high temperature. The effects of NA contents on the thermal stability, dielectric and energy storage properties of the N-PEI films are studied. Combining with the high field conductivity and depolarization

thermal stimulation current tests, the trap characteristics of N-PEI films are analyzed. In addition, the influence mechanism of NA on the electrical properties of N-PEI films is elucidated.

The results show that the appropriate content of NA blocking can ensure that N-PEI has a large molecular weight and reduces the free volume. As shown in Fig. 1, NA can introduce a large number of deeper traps which can effectively capture the free charges and shorten the hopping distance, thereby suppressing high temperature conductivity and improving the breakdown strength, which achieves the improvement in U_e and charge-discharge efficiency (η) at high temperature. When the content of NA is 5 mol%, the N05 film achieves a U_e of 6.8 J/cm³ at room temperature with an η of 95.8%. It is inspiring that the N05 film can still achieve an U_e of 4.39 J/cm³ ($\eta=90.9\%$) under 500 MV/m at 200°C, which is 109% higher than that of the traditional PEI (2.10 J/cm³). This article provides a new approach for the development of polymer dielectrics that are suitable for energy storage at high temperature.

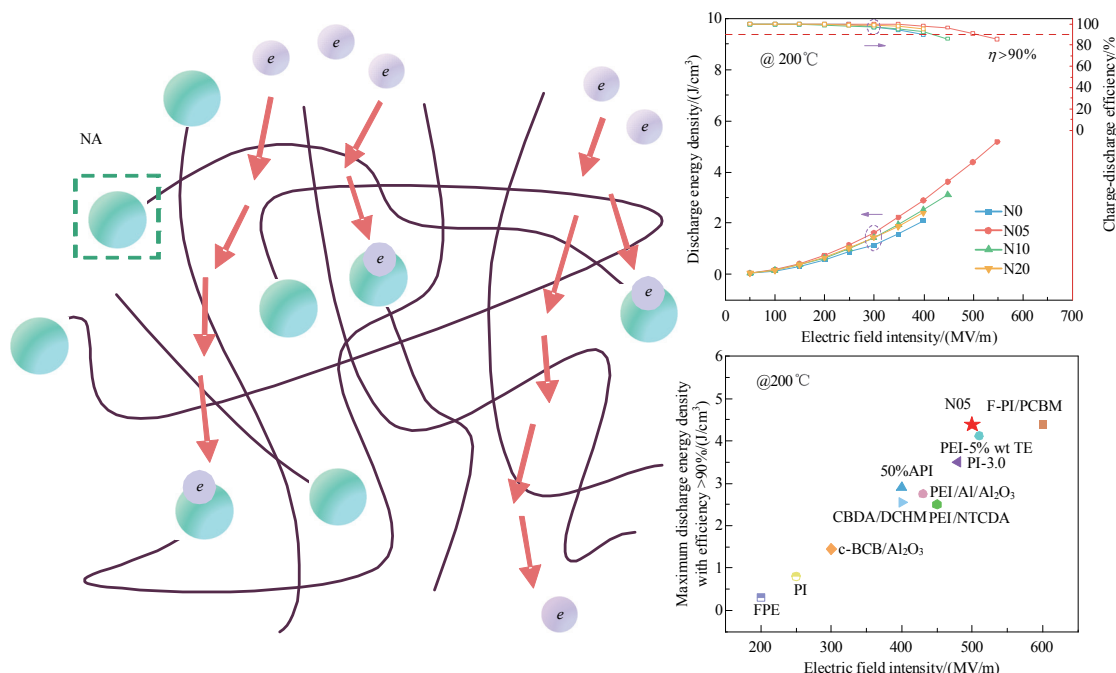


Fig. 1 Charge transport mechanism and energy storage performance of N-PEI

Frequency Stability Constrained Active Power & Energy Boundaries Calculation of Inverter Based Power Generation Resource Clusters

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(North China Electric Power University))

KEY WORDS: frequency stability; inverter-based power source; active power-energy demand boundary; frequency spatial distribution

The frequency control framework mimicking synchronous power source frequency regulation mechanisms fails to fully leverage the advantages of inverter-based resources (IBRs), such as flexible regulation and rapid response. From the perspective of the grid-connection point of IBR clusters, their frequency support capability for the main grid manifests as the post-disturbance active power-energy characteristic. This approach applies to diverse power source combinations and different grid-connection control modes (grid-following/grid-forming), offering a novel perspective for studying the main grid's frequency support requirements for IBR clusters.

This paper investigates the power system frequency stability requirements for the frequency regulation capability of IBRs represented by wind and solar power. It innovatively proposes the post-disturbance active power-energy time-domain curve as a key evaluation metric. Accounting for the spatial disparities in post-disturbance frequency distribution, a frequency-stability-constrained active power-energy requirement boundary calculation model is proposed. This model is suitable for scenarios involving multi-area systems, multiple disturbance types, and multi-interval boundary calculations. Furthermore, the boundary calculation under frequency stability constraints is equivalently transformed into a two-stage robust optimization problem. Subsequently, a solution algorithm based on Column and Constraint Generation (C&CG) is designed.

The frequency support effectiveness of IBR clusters

is assessed by post-disturbance frequency extremes. Under the premise of meeting frequency stability constraints, the active power-energy requirement curve imposes lower demands for frequency regulation reserve and incremental generation compared to the virtual inertia-primary frequency control architecture. This reduction helps enhance the willingness of renewable energy plants to participate in frequency support control. The proposed equivalent transformation method for the two-stage robust optimization problem of the IBR active power-energy requirement model, along with the adaptive difference step-size strategy, significantly improves computational efficiency. The efficiency gains become increasingly pronounced as the number of grid partitions (based on frequency characteristics), active power disturbances, and operational intervals grows. Improved system frequency response mode is shown in Fig. 1.

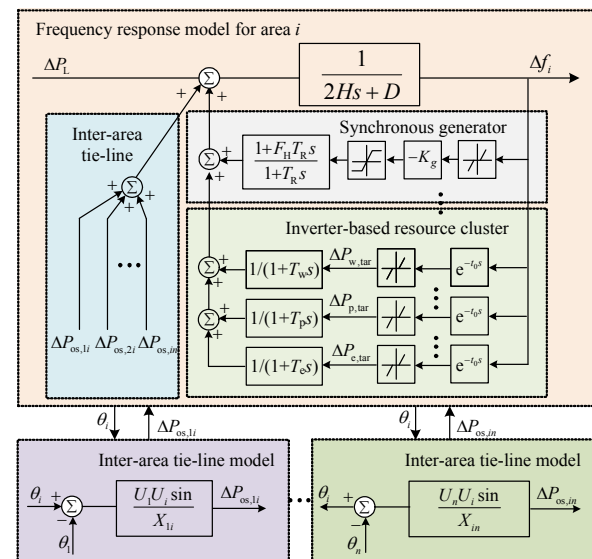


Fig. 1 Improved system frequency response model

Theory of Supply-demand Balance in Renewable-dominated Power Systems (Part III): Operational Decision-making Based on Decision-dependent Uncertainty

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KEY WORDS: renewable energy generation; high-penetration renewable power systems; supply-demand balance mechanism; decision-dependent uncertainty; power system operation

This paper is the third part of a series on supply-demand balance theory for renewable-dominated power systems. Part I established the fundamental understanding of decision-dependent uncertainty (DDU), while Part II investigated planning problems under DDU. Building upon these foundations, this paper focuses on operational decision-making under DDU.

Conventional operation methods typically model uncertainty as an exogenous factor independent of decisions, referred to as decision-independent uncertainty (DIU). However, in practices such as wind power reserve allocation and demand response, operational decisions can actively influence the magnitude and structure of uncertainty, resulting in DDU. Therefore, this paper aims to develop new theories and algorithms for supply-demand balancing, enabling secure and cost-effective operation of renewable-dominated power systems.

A key contribution of this paper is the discovery of the separability property of DDU sets. Specifically, DDU sets can be decomposed into an exogenous basic uncertainty support set and a decision-dependent coupling function. This decomposition provides a rigorous mathematical foundation for characterizing how operational decisions reshape uncertainty under DDU.

Building on the separability theory, this paper further establishes a new paradigm for supply-demand balancing. Under DIU, the dispatchable region must unidirectionally accommodate a fixed uncertainty set. In contrast, under DDU, the interaction becomes bidirectional: operational decisions can simultaneously regulate the dispatchable region and the uncertainty set. This shift uncovers the flexible adjustment potential embedded within DDUs.

Furthermore, this paper identifies the nonconvexity of the robust feasible region induced by DDU, and further reveals that such nonconvexity leads to the failure of conventional cutting-plane methods due to loss of synchronization. To address this issue, this paper proposes a generic cutting-plane framework under DDU. By exploiting the separability of DDU sets, the proposed framework constructs separability-based worst-case scenario mappings and reformulates decision-dependent cuts. Consequently, existing methods, including Benders' decomposition and column-and-constraint generation, can be extended to obtain optimal solutions while guaranteeing robust feasibility. Case studies demonstrate that exploiting DDU can improve system flexibility, security, and operational economy in renewable-dominated power systems.

Sub/Super-synchronous Oscillation Suppression Method for Direct-driven Wind Farm Based on Variable Operating Condition Equivalent Model and Optimal Emergency Power Control

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(School of Electrical Engineering, Southeast University)

KEY WORDS: sub/super-synchronous oscillation; oscillation suppression; equivalent model; emergency power control

The dynamic interaction between various power electronic devices and power grids in modern power systems can lead to serious sub/super-synchronous oscillation issues. Due to the insufficient real-time performance of controller parameter/structure modification, current oscillation suppression methods mostly employ direct wind farm tripping strategy, which exacerbate grid impacts and exhibit poor economy. Therefore, a sub/super-synchronous oscillation suppression method for direct-driven wind farm based on variable operating condition equivalent model and optimal emergency power control is proposed.

The framework of the proposed sub/super-synchronous oscillation suppression strategy is shown in Fig. 1. Firstly, an equivalent mathematical model is established by characterizing direct-driven wind farm admittance under multiple operating conditions as functions of operational variables. Then, the oscillation suppression problem is formulated as a multi-objective optimization problem that simultaneously considers economic efficiency and suppression effectiveness. Finally, an emergency power control (EPC) strategy is proposed for sub/super-synchronous oscillation suppression.

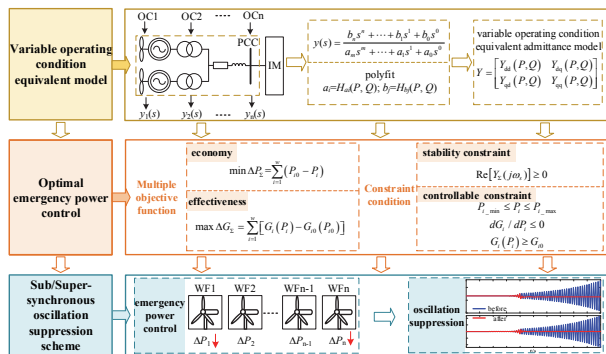


Fig. 1 The framework of the proposed sub/super-synchronous oscillation suppression strategy

The multi-objective function (M-OF) is established as follows:

$$\text{OF1: } \min \Delta P_{\Sigma} = \sum_{i=1}^W (P_{i0} - P_i)$$

The total active power reduction ΔP_{Σ} of wind farms is the least.

$$\text{OF2: } \max \Delta G_{\Sigma} = \sum_{i=1}^W [G_i(P_i) - G_{i0}(P_{i0})]$$

The increase of the real part of the system's aggregated admittance ΔG_{Σ} at the oscillation frequency ω_s is the most.

A four-machine grid-connected system was built in Matlab/Simulink for comparative verification. Fig. 2 shows the time-domain waveforms of active and reactive power with different methods. After the emergency power control of each wind farm is carried out according to the proposed method, the system oscillation transitions from amplitude oscillation to stable state, thereby achieving effective oscillation suppression.

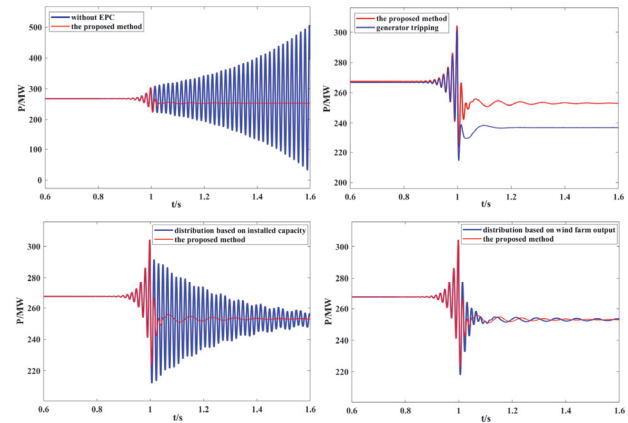


Fig. 2 Time-domain waveforms of active and reactive power with different methods

Besides, the proposed method is compared with generator tripping schemes and commonly used emergency power control methods. The results indicate that generator tripping causes the most power loss, whereas the proposed method results in the least. Moreover, the proposed method can rapidly suppress oscillation while minimizing system power, demonstrating superior effectiveness and economy.

Thermal Propagation Path-constrained Inversion Localization Methodology for Cascading Thermal Runaway Failures in LiFePO₄ Energy Storage Batteries

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KEY WORDS: lithium-ion battery storage; battery thermal runaway; battery mechanism-data modeling; thermal runaway propagation characteristics; fault inversion localization

To mitigate the thermal runaway cascade failure risks in densely arranged battery modules within modern energy storage systems, this study extracts critical parameters through experimental thermal abuse tests, analyzes the evolution from single-cell triggering to cascade propagation, and proposes a path-constrained

fault inversion localization framework, as shown in Fig. 1. Focusing on 280 A·h LiFePO₄ cells, modules, and clusters as research objects, this paper designs thermal abuse experiments to capture key node parameters, systematically revealing cell-level thermal runaway thresholds and evolution mechanisms.

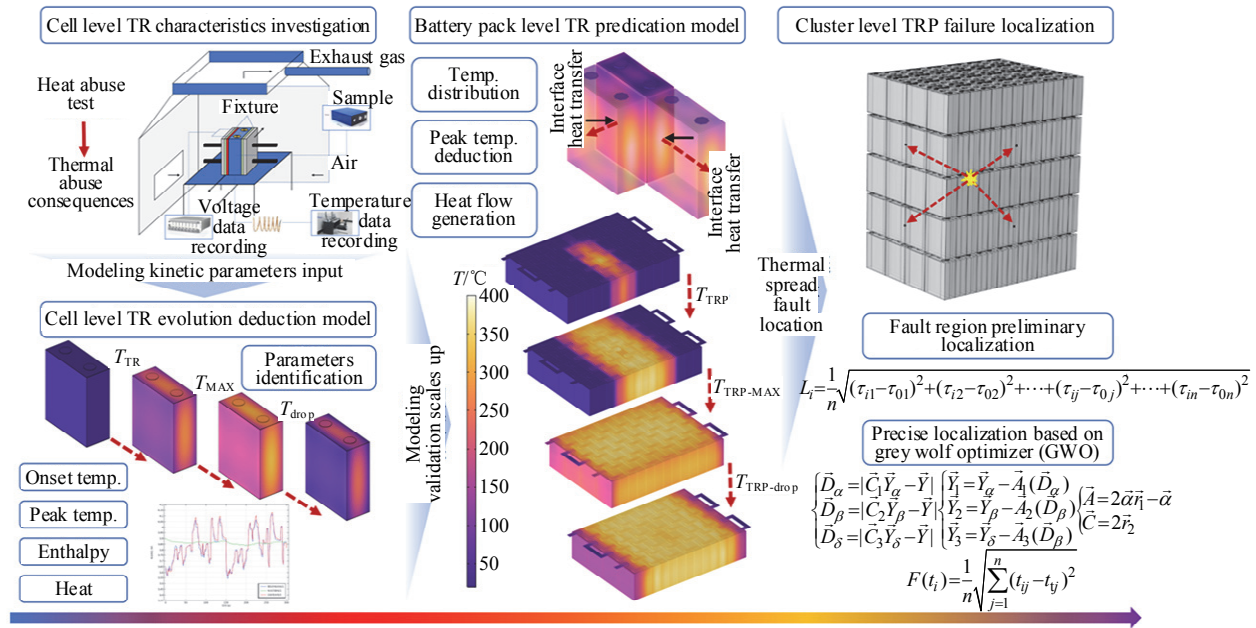


Fig. 1 Framework diagram of thermal runaway propagation modeling and fault localization for energy storage batteries

Guided by empirical safety failure data, this paper develops a validated 3D multiphysics coupling model incorporating the Forgetting Factor Recursive Least Squares (FFRLS) method to establish time-variant mappings between SOC and thermal runaway parameters. This SOC-adaptive model accurately predicts thermal propagation paths and energy release characteristics at varying SOC levels.

A hybrid Genetic Algorithm-Grey Wolf Optimizer (GA-GWO) enhanced Time Difference of Arrival (TDOA) framework that integrates thermal energy flow evolution with fault inversion optimization is proposed, enabling precise cluster-level fault localization in complex operating scenarios with demonstrated localization accuracy. This methodology establishes a

rigorous scientific foundation for safety-critical design in grid-scale energy storage deployments. The accuracy of fault location is in exhibition by Fig. 2.

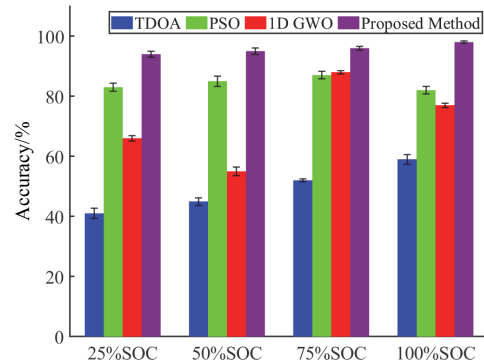


Fig. 2 Accuracy comparison of fault location methods

Differential Load Analysis of Multiple Components for Floating Wind Turbines Based on Integrated Wind-wave-current Simulation Under Typhoon Scenarios

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KEY WORDS: floating wind turbine; wind-wave-current coupling; typhoon; load predication

Floating wind turbines are often located in deep offshore areas and are frequently subjected to typhoon impacts, exhibiting complex motion states and significant wind-wave-current coupling under typhoon conditions, rendering their load analysis highly challenging. To address this, this paper proposes a differentiated multi-component load analysis method for floating wind turbines based on integrated wind-wave-current simulation under typhoon scenarios.

Aiming at the challenges in accurately simulating wind-wave-current interactions due to rapid and intense energy exchange during typhoon development, a refined coupled numerical modeling approach integrating finite volume coastal ocean model (FVCOM), simulated wave model (SWAN), and forecasting model (WRF) is developed FVCOM/SWAVE-WRF (FSW). The method

employs a fourth-order Runge-Kutta scheme to solve the wave action equations, decomposing wave state updates into four intermediate time steps to mitigate numerical dissipation and enhance stability.

Given the complex dynamic responses and heterogeneous load distributions of floating wind turbine components under varying environmental conditions, this study develops a multi-component load prediction framework based on wind-wave-current coupled simulation data, to explicitly account for the differentiated influences of environmental loads. The model incorporates a multi-scale multi-attention channel convolution module (MMACM) to explicitly capture the varying impact levels of different environmental factors on structural loads, with the detailed architecture illustrated in Fig. 1.

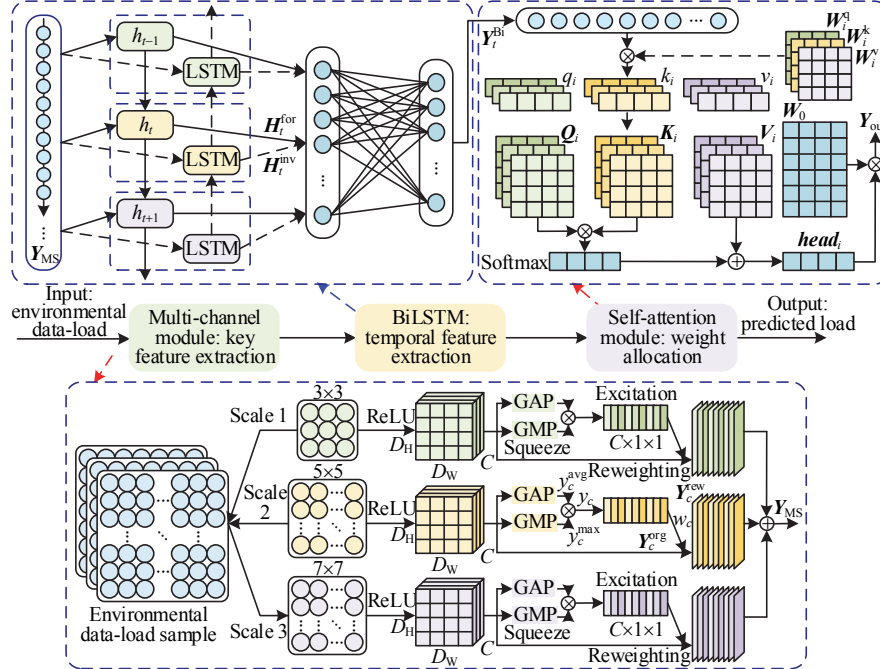


Fig. 1 MMACM-BiLSTM load prediction module

Building upon the Paris model, this study formulates a load transmission mechanism based on predicted load values that quantifies how external environmental loads propagate to critical internal components. The derived analytical framework enables a coupled reliability assessment of both external and internal subsystems of floating wind turbines under combined environmental loading conditions.

The results demonstrate that the proposed

integrated FSW modeling framework accurately captures typhoon evolution dynamics. The MMACM-BiLSTM model reveals that aerodynamic forces predominantly affect loads on blades, towers, and main shafts, while hydrodynamic forces mainly influence mooring system loads. Additionally, corrosion severity significantly accelerates component degradation, and wind speed exhibits pronounced impacts on structural reliability across all components.

Coupled Aerodynamic-hydrodynamic-mooring Dynamics Analysis of Large-scale Floating Vertical Axis Wind Turbines Based on Spar Platforms

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2. School of Engineering, University of Liverpool; 3. Shanghai Publishing and Printing College)

KEY WORDS: floating vertical axis wind turbines (VAWT); Spar; aero-hydro-mooring coupling; computational fluid dynamics (CFD); dynamic response

The increasing size of floating wind turbines and their ongoing deployment into deeper waters are leading to challenges such as surging structural loads and rising operation and maintenance costs. However, vertical-axis wind turbines (VAWTs) demonstrate significant potential for offshore wind applications due to their low center of gravity, relatively simple mechanical structure, insensitivity to wind direction changes, and lower maintenance costs.

This study focuses on a large-scale Spar-based VAWT, establishing a full-scale numerical model of the floating VAWT system. Using computational fluid dynamics (CFD) methods with volume of fluid (VOF) and dynamic fluid-body interaction (DFBI) models to simulate its six-degree-of-freedom (6-DOF) motion under combined wind-wave loads, this paper investigates the coupled aerodynamic-hydrodynamic-mooring dynamic characteristics of the floating VAWT under environmental excitations.

The results demonstrate that the floating VAWT exhibits pronounced fluctuations in its power coefficient curve with continuously varying amplitudes, reaching a peak value of 1.2. This phenomenon is attributed to the 6-DOF platform motions induced by wave loads, which

significantly alter the rotor's instantaneous apparent wind speed, consequently causing variations in the torque output, as illustrated in Fig. 1.

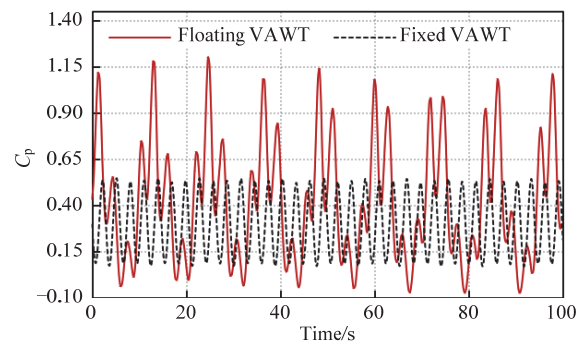


Fig. 1 Comparison of power coefficients between fixed and floating VAWTs

Further analysis comparing the aerodynamic characteristics of floating and fixed VAWTs reveals that the floating VAWT exhibits a larger wake region with distinct “wavy” patterns forming at the upper wake boundary, along with faster wake recovery. This phenomenon reflects how wave-induced platform motions introduce additional disturbances to enhance turbulent mixing, thereby accelerating wake recovery. Fig. 2 presents the velocity field distribution characteristics at the $Y=0$ cross-section.

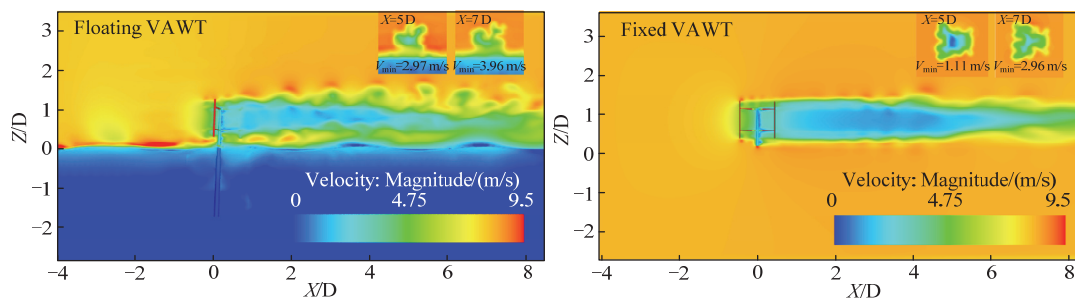


Fig. 2 Velocity field distribution characteristics of floating and fixed VAWTs in $Y=0$ cross section

This study comparatively studies the aerodynamic differences between floating and fixed VAWTs, with further examination of the hydrodynamic response of

floating VAWTs. The findings are expected to provide valuable references for understanding the motion characteristics of floating VAWT.

Synchronous-like Mechanism Analysis and Inertia Evaluation of Offshore Wind Farms Integrated HVDC System

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KEY WORDS: offshore wind farms; VSC-HVDC; inertial response; inertia evaluation

Recently, the voltage source converter-high voltage direct current (VSC-HVDC) has become critical for integrating large-scale offshore wind power, making the equivalent inertia assessment of offshore wind farms integrated HVDC system (OWF-HVDC) vital for coastal grid frequency stability. Existing studies, based on an energy equivalence perspective, are limited as they overlook the coupling relationship and transient support power transfer mechanisms among multiple internal devices. To address this issue, this paper proposes a method for accurately assessing the inertia of OWF-HVDC based on the internal voltage equivalence perspective.

The system's inertia support is based on typical inertia control without relying on communications. The VSC-HVDC provides immediate DC capacitor support and transmits the receiving-end frequency disturbance to the sending-end, activating the OWF's $d\omega/dt$ control.

As shown in Fig. 1, after a receiving-end frequency disturbance, the inertia support physical process of the OWF-HVDC is similar to that of a synchronous machine, which this paper refers to as synchronous-like mechanism. The inertia support physical process of the OWF-HVDC includes the following two stages:

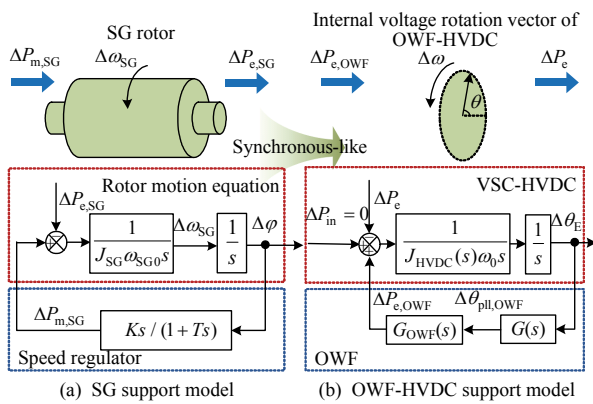


Fig. 1 Synchronous-like mechanism of OWF-HVDC

1) Similar to a synchronous machine using rotor kinetic energy to support the grid frequency during the inertia response stage, the VSC-HVDC modulates its DC voltage control command, thereby enabling the DC

capacitor to release or absorb energy to damp grid frequency fluctuations.

2) Similar to a synchronous machine changing the mechanical power output of the prime mover according to the rotor speed change during the primary frequency regulation stage, the OWF changes its speed command according to the sensed sending-end frequency change to provide inertia support.

Based on the aforementioned synchronous-like mechanism and the support model of the OWF-HVDC shown in Fig. 1(b), a synchronous-like model of OWF-HVDC is established from the perspective of internal voltage equivalence, enabling accurate assessment of the system's partitioned and total inertia.

Fig. 2 shows the equivalent inertia time/frequency domain curve obtained from the inertia assessment results. The OWF-HVDC firstly utilizes the rapid inertia response of the VSC-HVDC to avoid a steep initial frequency drop; secondly, the OWF demonstrates stronger inertia support capabilities, providing more active power support.

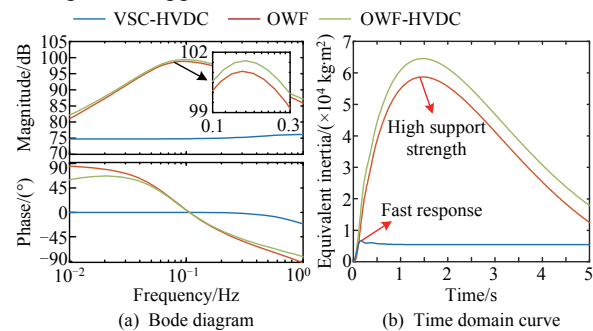


Fig. 2 Time-frequency domain characterization of equivalent inertia of OWF-HVDC

Finally, an analysis of the equivalent time/frequency domain curves clarifies the influence of $d\omega/dt$ control parameters, DC capacitor inertia control parameters, and speed control loop parameters on the equivalent inertia. This analysis guides the design of a PSO-based tuning method for optimally balancing support strength and response speed.

Control Techniques for Enhancing Transient Overload Capability of High-Voltage Transformerless Battery Energy Storage System

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KEY WORDS: high-voltage transformer-less; battery energy; grid forming; grid transient support; short-term overload

Grid-forming high-voltage transformerless energy storage is a critical equipment for supporting the steady-state power balance and transient active support of new power systems. To achieve transient support, a certain overcurrent capability is required. However, the current practice of over-sizing devices leads to increased system costs. This paper leverages the modular topology and control flexibility of high-voltage transformerless energy storage systems to propose a dynamic topology reconfiguration method for enhancing overload capability. Furthermore, an electro-thermal coupling model for the devices is established, and an online junction temperature estimation method is introduced. By implementing closed-loop control of the junction temperature, the thermal stress margin of the power devices is fully exploited, leading to the development of methods for maximizing and regulating the overcurrent capability of grid-forming equipment. Based on the above research, the short-term overload capability of high-voltage transformerless energy storage equipment is economically enhanced.

In addition to the system's built-in bypass switch B, two additional switches S_1 and S_2 are installed in the submodule to enable system topology reconfiguration. Switch S_1 remains in the normally closed state, while S_2 operates in the normally open state. Building upon the original full-bridge submodule, two additional contactors or bidirectional thyristors are configured to complement the submodule's existing bypass unit. By designing appropriate switching logic and transition timing, the submodule can operate in either full-bridge or half-bridge mode. In half-bridge mode, the parallel connection of dual thyristors doubles the current-carrying capacity compared to full-bridge mode.

Following a transient fault, the grid-connected high-voltage direct-coupled system autonomously responds to support the power grid, as shown in Fig. 1. Hysteresis control is introduced to switch the topology between full-bridge and half-bridge modes based on junction temperature and grid connection point voltage, thereby avoiding repeated triggering of the topology reconstruction logic.

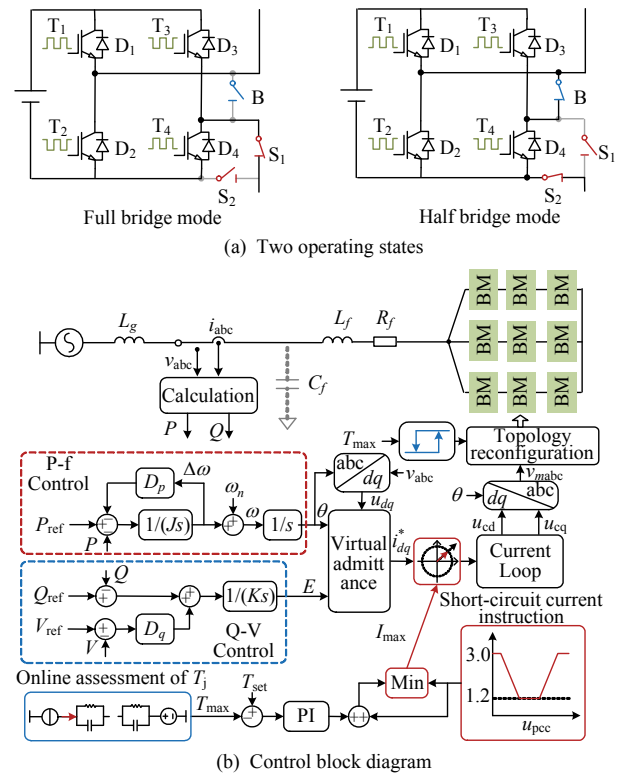


Fig. 1 Grid forming control strategies of high voltage transformerless BESS

Following an actual transient fault in the power grid, the rapid rise in transient current causes a corresponding rapid increase in junction temperature. Topology reconfiguration must account for the process time required for switch operation and logical reliable switching. Therefore, during this process, the magnitude of transient current must be limited based on junction temperature. Concurrently, this section introduces a junction temperature closed-loop control to fully utilize the device's junction temperature margin, thereby further enhancing the equipment's overload capability. The difference between the online-evaluated junction temperature T_{max} and the junction temperature setpoint T_{set} is processed through a proportional-integral controller to generate a current limit value. This value is then combined with the short-circuit current command and subjected to a minimum value logic operation to produce the final transient current limit value.

Analysis and Calculation of External Electrical Characteristics for Controllable Turned-off Current Source Converters Under Electromechanical Transient Conditions

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KEY WORDS: current source converter can be turned off; controllable commutation; external characteristic analysis; power support

The active turn-off capability of the turn-off current source converter during commutation allows for flexible firing angle adjustment in transients, leading to better transient active and reactive power performance.

For forced commutation, the traditional commutation angle m is no longer applicable. The commutation angle μ can be divided into two stages: the natural commutation angle μ_1 and the forced commutation angle μ_2 , as shown in Fig. 1.

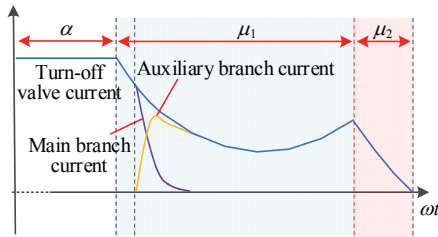


Fig. 1 Commutation process of CLCC

μ_1 can be actively controlled, μ_2 is determined by various factors such as MOV voltage and μ_1 , CLCC does not experience commutation failure. The on-bridge current is always equal to I_d when the commutation is completed. Therefore, the expression for the forced commutation angle μ_2 can be derived.

$$I_d = \frac{\sqrt{2}U_2}{2X_L} [\cos \alpha - \cos(\alpha + \mu_1 + \mu_2)] + \frac{U_{ar}}{2X_L} \mu_2 \quad (1)$$

The solution process of Equ. (1) requires iterative calculations, Direct application is rather complicated. The forced commutation process is influenced by various factors such as MOV voltage and μ_1 , μ_2 is very small in practical engineering and can be simplified by using an approximate linearization method. At this point, μ_2 can be expressed as:

$$\mu_2 = \frac{2X_L I_d + \sqrt{2}U_2 [\cos(\alpha + \mu_1) - \cos \alpha]}{\sqrt{2}U_2 (\pi - \alpha - \mu_1) + U_{ar}} \quad (2)$$

By performing FFT analysis on the voltage and current of the converter, the expressions for active power and reactive power can be obtained as follows:

$$\begin{cases} P = -\frac{3U_2^2}{2\pi X_L} \sin(2\alpha + \mu_1 + \mu_2) \sin(\mu_1 + \mu_2) - \\ \quad \frac{3\sqrt{2}U_2 U_{ar}}{\pi X_L} \cos(\alpha + \mu_1 + \frac{\mu_2}{2}) \sin \frac{\mu_2}{2} \\ Q = \frac{3U_2^2}{2\pi X_L} [\cos(2\alpha + \mu_1 + \mu_2) \sin(\mu_1 + \mu_2) - \\ \quad (\mu_1 + \mu_2)] - \frac{3\sqrt{2}U_2 U_{ar}}{\pi X_L} \sin(\alpha + \mu_1 + \frac{\mu_2}{2}) \sin \frac{\mu_2}{2} \end{cases} \quad (3)$$

During the natural commutation process, the actual natural commutation angle μ'_1 is related to the trigger angle α . It can be divided into three working conditions. The relationship between the actual natural commutation angle and the trigger angle is as shown in the following equation:

$$\mu'_1 = \begin{cases} \mu_1, & \alpha \leq \pi - \frac{\mu_1}{2} \\ 2(\pi - \alpha), & \pi - \frac{\mu_1}{2} < \alpha < \pi \\ 0, & \alpha \geq \pi \end{cases} \quad (4)$$

The power characteristic curve of the controllable current source converter is shown in Fig. 2.

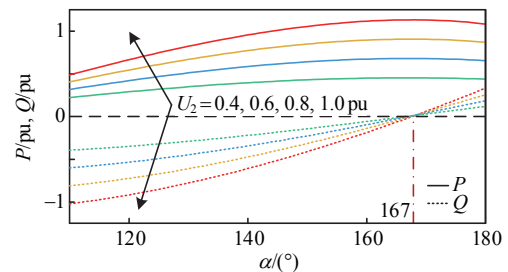


Fig. 2 Power characteristic

The reactive power injected by the converter into the system increases as the trigger angle increases. Since there is no problem of commutation failure, when an AC system fault is detected, the converter can consider increasing trigger angle to provide support for the receiving grid.

Review and Analysis of the Operation Mechanisms of Magnetic Coupling Wireless Power Transfer Technology

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KEY WORDS: wireless power transfer; magnetic coupling; parity-time symmetry; analysis of operation mechanisms

Magnetic coupling wireless power transfer provides an effective solution for the safe and reliable power supply of electrical equipment in unmanned environments such as deep space, deep sea and deep earth. With the development of technology, a variety of novel operation mechanisms have been proposed, and there are problems such as conceptual confusion, principal differences and characteristic differences, which lead to the lack of corresponding guidelines for system design and the selection of operating mechanisms. In this paper, we analyze the “traditional ZPA mechanism”, “MIT resonance mechanism”,

“complex eigenstate mechanism”, “OA-based PT symmetry mechanism” and “inverter-based PT symmetry mechanism” in terms of physical principles, parameter criteria, realization methods and corresponding energy efficiency characteristics, which provide theoretical guidance for the selection of the actual system operation mechanism shown as Table 1. On this basis, the current research progress of PT symmetric wireless power transfer systems is summarized, and the key scientific and technological problems and development trends that need to be solved at present are further discussed.

Table 1 Comparative analysis of different operating mechanisms

Response type	Operating mechanism	Regulation parameters	Energy efficiency characteristics	System complexity
Forced response	Traditional ZPA	Given ω_0 , first adjust C_2 to ensure maximum efficiency, then adjust C_1 to ensure power	Achievement of local power optimization and shorter transmission distances	Simple circuit structure, no need to add detection and control loop
	MIT resonance	First match C_i to ensure that each RLC circuit ω_0 is consistent, and then adjust the power supply frequency $\omega = \omega_0$	Suitable for medium-range distance transmission	Relatively simple circuit structure, no need to add control loops
	Complex eigenstate	Without any parameter requirements, the power supply frequency is equal to the resonant frequency of the system ω_t	Maximum power output, able to strike a good balance between efficiency	Complex determination of operating frequency, dependent on mutual sensing
	Inverter-based PT symmetry	Detecting the primary voltage and current and adjusting the power supply frequency to make them in phase	Constant and efficient energy transfer independent of mutual inductance ($k > k_c$)	Relatively complex circuit structure, need to increase the detection, control and other circuits
Free response	OA-based PT symmetry	No need for any detection and control circuit, no need to adjust any parameter, with self-tuning	High positional robustness ($k > k_c$) but low output power	Relatively simple circuit structure, no need for any control circuits

This paper firstly focuses on system modeling and response analysis, categorizing the various existing operating mechanisms of MC-WPT systems in accordance with response types and revealing their essential differences from innovative perspectives. Then it analyzes the operating mechanism of the negative resistive excitation system, namely the OA-based PT symmetry mechanism, and elaborates its mapping relationship from both circuit and quantum viewpoints. Secondly, it summarizes the operating mechanisms of another category of independent source excitation system, covering the conventional ZPA mechanism, MIT

resonance mechanism, complex eigenstate mechanism and inverter-based PT symmetry mechanism; these mechanisms are comparatively analyzed from the dimensions of system response, parameter design and operation theory. On the basis of the above analyses, the paper further carries out a systematic discussion on the research hotspots of PT symmetry mechanisms that possess strong positional robustness and high-efficiency transmission performance. Finally, it provides an extended prospect of the crucial scientific and technical challenges to be addressed as well as the future development trend of this field.

The Fault Identification Method for PMSG Driven by the Integration of Multi-dimensional Transformer Algorithm and Electromagnetic Transient Modeling

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KEY WORDS: offshore wind power; permanent magnet synchronous generator (PMSG); modeling and simulation; fault identification; multi-dimensional Transformer

As the core power generation component in wind power systems, the Permanent Magnet Synchronous Generator (PMSG) — once faulty — can significantly impact the entire system. Therefore, timely diagnosis and identification of its faults hold substantial engineering practice value for system operation and maintenance. However, internal fault identification methods still face challenges such as scarcity and imbalance of actual fault data, complexity of internal signal processing, as well as insufficient extraction of deep-level fault features.

Based on the PSCAD/EMTDC platform, this paper constructs electromagnetic transient equivalent models of PMSG covering five typical internal fault types, using flux linkage as the core state variable. These models are integrated into wind turbine units for multi-operating condition simulations, thereby establishing a balanced dataset. Subsequently, a multi-dimensional Transformer encoder is proposed, employing parallel time-frequency feature extraction and gating mechanisms for fault classification. Fig. 1 illustrates the schematic diagram of the PMSG internal structure and fault principles.

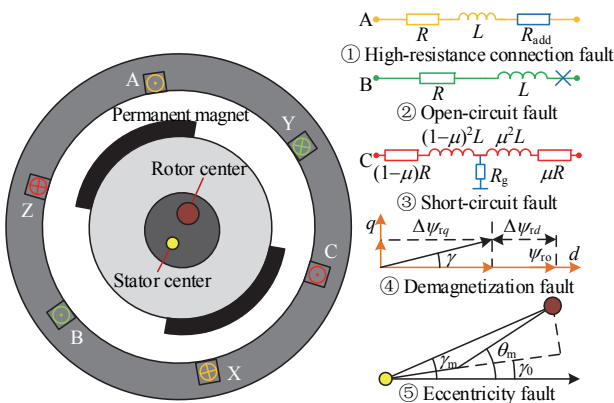


Fig.1 PMSG internal structure and fault mechanism diagram

Through comparison with traditional models, the performance of the proposed method is quantitatively analyzed using five evaluation metrics. The resulting confusion matrix is shown in Fig. 2. This method

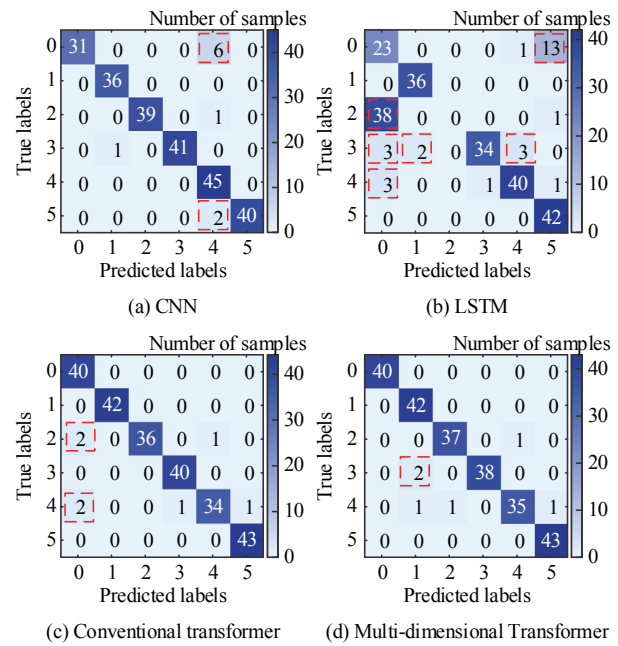


Fig. 2 Confusion matrices of different models

achieves 99.8% identification accuracy, demonstrating favorable identification performance.

Table 1 presents the hyperparameter settings in the multi-dimensional Transformer model.

Table 1 Performance comparison of different models on test set

Hyperparameter	Value/type
Model dimension	512
Self-attention head dimension	8
Number of attention heads	8
Hidden layer dimension	1 024
Number of encoder layers N	8
Number of epochs epoch	100
Batch size	32
Optimizer	Adagrad
Learning rate scheduler	CosineAnnealingLR

In summary, this PMSG internal fault identification framework can rapidly analyze internal faults based on external characteristic signals, while exhibiting high accuracy and convergence speed.

Control Strategy of a Dual-drive Parallel System for the Intelligent Working Platform of High-voltage Transmission Crossing Frames

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KEY WORDS: crossing frame intelligent working platform; dual-drive parallel system; decoupling control; adaptive backstepping control (AdBC)

This paper takes the dual-drive parallel system of an crossing frame intelligent working platform as the research object and proposes an adaptive backstepping cross-coupled control strategy. The strategy eliminates mechanical coupling effects between the dual-drive systems through decoupling control. Based on backstepping design and a parameter adaptation

mechanism, it enables real-time estimation of uncertain parameters caused by variations in load mass and position, thereby improving control accuracy and system adaptability. By introducing a cross-coupling control structure, the dynamic coordination between the dual-drive systems is enhanced, and synchronization error is reduced. The principle is shown in Fig. 1.

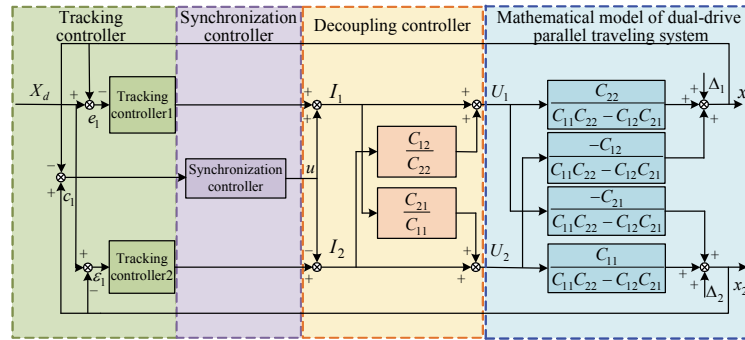


Fig. 1 Control schematic diagram

The established coupled mathematical model of the dual-drive parallel system is given as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = C^{-1} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} + \begin{bmatrix} \Delta_1 \\ \Delta_2 \end{bmatrix} = \frac{1}{C_{11}C_{22} - C_{12}C_{21}} \begin{bmatrix} C_{22} & -C_{12} \\ -C_{21} & C_{11} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} + \begin{bmatrix} \Delta_1 \\ \Delta_2 \end{bmatrix} \quad (1)$$

The decoupled model of the dual-drive parallel system is given as follows:

$$\ddot{x}_1 = \frac{1}{ML_b^2 + J + J_1 r_1^2 L^2 / K} (-f_1 L^2 \dot{x}_1 + \frac{L^2}{K} I_1 - K_\beta x_1) + \Delta_{a1} \quad (2)$$

The control law of the controller designed based on adaptive backstepping control is as follows:

$$I_1 = e_1 + \left(\int_0^t \ddot{x}_d e_2 + k_1 \dot{e}_2 \right) (\ddot{x}_d + k_1 \dot{e}_1) + \left(\int_0^t y_2 e_2 \right) y_2 + \left(\int_0^t y_1 e_2 \right) y_1 - \left(\int_0^t -e_2 \right) + k_2 e_2 \quad (3)$$

Experimental verification is conducted on the crossing frame intelligent working platform, and the response curves of position error and synchronization error are shown in Figs. 2, 3, and 4.

The experimental results show that the maximum tracking errors of traveling system A and traveling system B are 1.779×10^{-4} m, the root mean square values

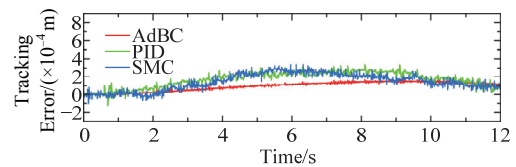


Fig. 2 Tracking error of x_1

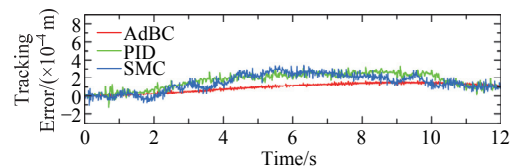


Fig. 3 Tracking error of x_2

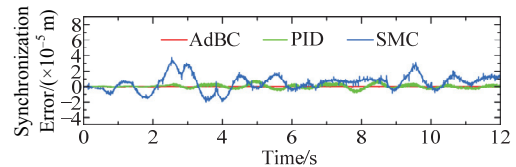


Fig. 4 Synchronization error

are 1.058×10^{-4} m, the maximum synchronization error is 7.275×10^{-7} m, and the root mean square value is 1.173×10^{-7} m. The experimental results show that the control strategy can significantly reduce the tracking errors and synchronization errors.

Data-driven Control of PMSM via Model-free Adaptive Sliding Mode Based on Improved EKF

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KEY WORDS: permanent magnet synchronous motor; model free adaptive sliding mode control; improved kalman filter algorithm; pseudo partial derivative; data driven

In high-end applications, permanent magnet synchronous motors must meet stringent performance requirements for control. However, harsh environments, complex conditions, and nonlinear parameter variations often cause model mismatch, affecting speed response.

This paper proposes a model-free adaptive sliding mode control method based on an improved Kalman prediction and update pseudo-partial derivative algorithm. It aims to eliminate the dependence on physical parameters while improving the accuracy of data-driven models. The strategy comprises prediction update and sliding mode components. The former considers the time-varying nature of the PPD, establishes a data-driven model, and employs an improved extended Kalman Filter (IEKF) for real-time prediction and update, thereby accurately describing the motion state of the PMSM system. The latter integrates a variable-speed power reaching law with a global fast integral terminal sliding mode surface to constrain the system's motion state.

To thoroughly evaluate the control signal's tracking error and convergence rate, this paper designs the control law as follows:

$$\Delta i_q^*(k) = \frac{\alpha T_s^2 |s(k)|^\gamma \operatorname{sgn}[s(k)]}{c_3 \hat{\phi}_c(k|k)} - \frac{\left[\frac{1}{T_s} - \delta - \gamma |s(k)| \right] T_s^2 s(k)}{c_3 \hat{\phi}_c(k|k)} + \frac{c_1 T_s e(k) + c_2 T_s E(k)}{c_3 \hat{\phi}_c(k|k)} \quad (1)$$

where $\hat{\phi}_c(k|k)$ denotes the PPD value after the prediction update of the IEKF; δ and γ constitute the variable-speed term of the sliding mode reaching law, while α and χ form the power term of the sliding mode reaching law; $E(k)$ represents the integral terminal error term of the sliding mode function; c_1 , c_2 , c_3 denote the coefficients of the sliding mode function; T_s represents the sampling period. The schematic diagram is shown in Fig. 1.

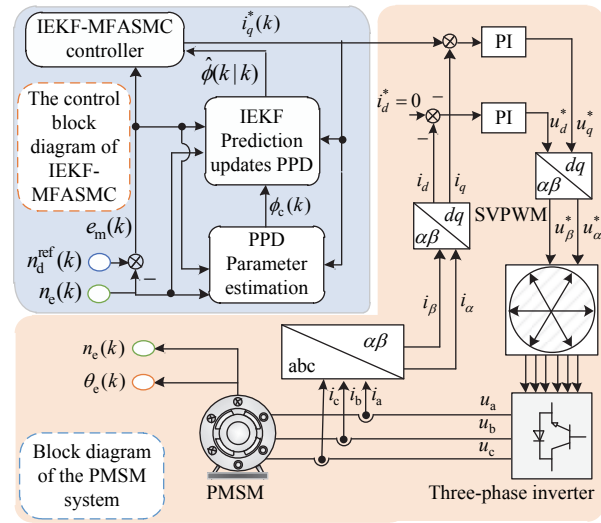


Fig. 1 System structure of the proposed method

The proposed method has been validated through stability analysis, simulation, and experimental validation, which confirm its effectiveness. The following conclusions can be drawn:

1) The proposed data-driven control method is independent of an accurate parametric model of the motor, yet can still comprehensively capture its nonlinear dynamic characteristics, adjusting parameters accordingly.

2) This paper presents an IEKF-based algorithm for predicting and updating PPD. By introducing Q and R to adjust the initial PPD value and leveraging the real-time state reconstruction capability of IEKF, the method reduces the system's reliance on accurate PPD compensation. This breakthrough addresses the limitation of CFDL-based MFAC, which depends heavily on estimating time-varying PPD.

3) Combining the advantages of MFAC and discrete integral sliding mode control, a fast integral terminal sliding surface with a variable-speed power reaching law is designed. This structure maintains global convergence speed while effectively suppressing chattering.

Breaking Characteristics of Series Arc Asynchronous Coordination for Self-triggered Low-voltage Hybrid DC Circuit Breakers

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KEY WORDS: low-voltage DC system; hybrid circuit breaker; arc; short circuit breaking

System voltage levels in photovoltaic power stations, energy storage, and data centers have rapidly reached the 1500 V upper limit stipulated by the IEC standard. For 1500 V and higher DC breaking requirements, challenges remain in achieving large capacity with miniaturization, and combining low cost with high reliability.

A series arc asynchronous coordination topology is proposed for self-triggered low-voltage hybrid DC circuit breakers. This topology contains breaking units A and B formed by the series connection of multiple poles in a molded case circuit breaker (MCCB), with an electronic module connected in parallel with unit B. The core design concept is to utilize the arc in unit A and the electronic module to work together to distribute the high voltage stress during breaking. Fig. 1 shows the topology and short circuit breaking working process using the two-pole design as an example. Stage I: During normal operation and the initial stage of rising short circuit current, the current flows successively through the two metal contacts. Stage II: The contacts of units A and B open to generate arcs, limiting the short circuit current to the level of the tail current. Stage III: The IGBTs conduct, and the arc of unit B drives the current to commute to the branch where unit A and the IGBTs are located, and the arc of unit B extinguishes. Stage IV: The IGBTs are turned off, and the overvoltage exceeds the varistor voltage of metal oxide varistors (MOVs). The short circuit current flows through the branch where unit A and the MOVs are located, and gradually decreases under the combined action of the MOV clamping voltage and the arc voltage of unit A. Stage V: The arc in unit A is extinguished, with the unit serving as an electrical isolation barrier. This topology can increase the total breaking voltage, reduce the arc erosion of the mechanical contacts, and lower the requirements for both IGBT rated voltage and MOV selection.

Fig. 2(a) and (b) show the two-pole breaking effects at 750 and 1000 V respectively, and (c) shows the three-pole breaking effect of 1500 V (with unit A consisting of two poles in series). Compared with MCCB

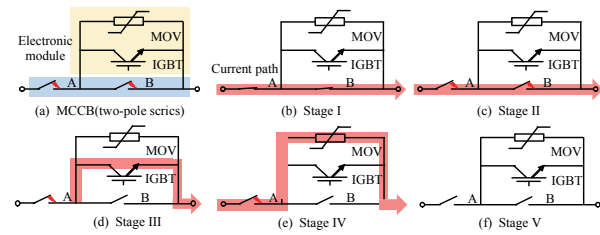


Fig. 1 Topology and working process of series arc asynchronous coordination topology

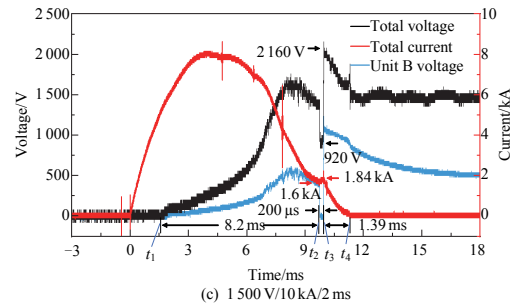
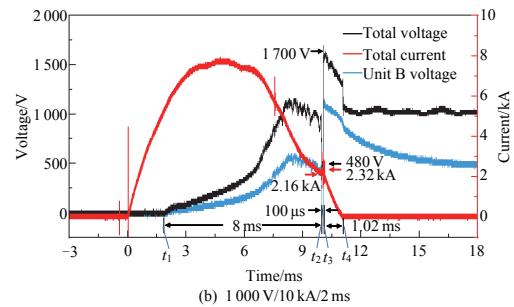
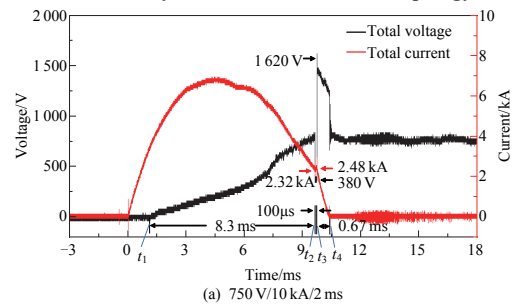


Fig. 2 Breaking test waveforms of series arc asynchronous coordination topology

and the existing self-triggered hybrid topology, which can only break at voltage levels of 750 V and below, the voltage level and short circuit capacity of the proposed topology have both doubled, while the cost and volume have not significantly increased.

Molecular Dynamics Simulation of the Effect of Coupling-modified Nanosilica on the Properties of Silicone Rubber

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KEY WORDS: silicone rubber; coupling modification; nano-SiO₂; molecular dynamics simulation; thermodynamic properties; electrical performance

Methyl vinyl silicone rubber (MVSR) is widely used as an external insulation material in power systems due to its excellent insulation properties, resistance to high and low temperatures, and lightweight characteristics. However, during prolonged operation, silicone rubber undergoes irreversible thermal aging and electrical aging influenced by various factors, leading to material degradation and ultimately diminished performance metrics.

Currently, incorporating nano-silica has become an effective method to enhance silicone rubber performance. However, nano-silica readily aggregates, diminishing its reinforcing effect on silicone rubber. Modifying nano-silica with coupling agents can suppress self-aggregation, thereby further improving the overall properties of silicone rubber.

This study employs molecular dynamics (MD) simulations to construct models of silica surfaces grafted with silane coupling agent (KH-550) at grafting ratios of 5%, 10%, 15%, and 20%. The simulations analyze changes in glass transition temperature (T_g), thermal conductivity (λ), elastic modulus (E), relative permittivity (ϵ_r). Changes in microstructure,

thermodynamic properties, and electrical performance before and after modification are analyzed via mean square displacement (MSD), free volume (FFV), and radial distribution function (RDF) studies.

Results indicate that nano-SiO₂ doping effectively enhances silicone rubber properties, while coupling modification further improves performance. However, different grafting rates exhibit varying degrees of enhancement. The effect of coupling-modified grafting ratio on silicone rubber properties exhibits nonlinearity with an optimal value. The composite with a 10% grafting ratio demonstrates the most significant improvements: a 61% increase in glass transition temperature (T_g), a 75% enhancement in thermal conductivity, a 50% rise in Young's modulus, and a 32% reduction in relative permittivity at 300 K. Microstructural analysis indicates that this grafting ratio exhibits stronger bonding interactions, reduced free volume, and lower mean square displacement (MSD). Stronger bonding interactions enhance the order of the silicone rubber, while reduced free volume effectively restricts molecular chain motion, ultimately improving both thermal conductivity and mechanical properties.

Operating Time Dispersion of Circuit Breakers With Spring Mechanisms Based on Multi-field Coupling Simulation

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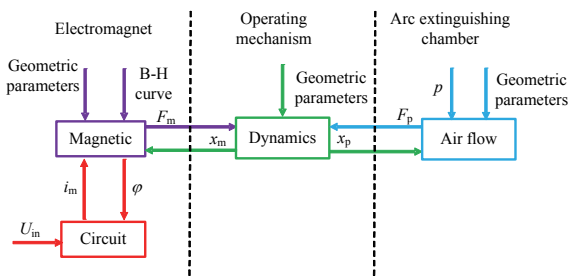
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KEY WORDS: high-voltage circuit breakers; spring mechanisms; operating time dispersion; coupling simulation; influence factors

The dispersion of the operating time of circuit breakers has a direct impact on the accuracy of phase selection control. It is difficult for the existing research on the dispersion of the operating time of circuit breaker mechanisms to quantitatively analyze the complete factors and the degree of influence that affect the operating time of spring mechanisms due to the lack of a complete and accurate coupled simulation model. In response to this deficiency, starting from the geometric model of the mechanism, this paper establishes a coupled simulation model of the electromagnet magnetic field - the dynamics of the operating mechanism - the gas flow field of the arc extinguishing chamber to explore the operating time dispersion mechanism of high-voltage circuit breakers with spring-equipped mechanisms.

To study the factors influencing the opening and closing time in the entire operating chain of the circuit breaker, this paper respectively establishes the electromagnet model, the operating mechanism model and the arc extinguishing chamber model, and realizes the coupling among the models. The coupling method of the model is shown in Fig. 1.



i_m -Coil current; ϕ -magnetic flux; U_m -control voltage; F_m -electromagnetic force output; p -pressure; x_m -displacement of the iron core; x_p -displacement of the moving contact; F_p -Load force.

Fig. 1 Schematic diagram of the coupling mode of the simulation model

Among them, both the electromagnet model and the arc extinguishing chamber model are established based on the COMSOL finite element simulation, the operating

mechanism model is established based on the ADAMS multi-body dynamics simulation, and Simulink is used as the data interaction platform to achieve the coupling between the models. In addition, a mechanical characteristic test platform is built based on the ZF27-363 spring-mechanism circuit breaker. The experimental results show that the contact stroke, speed, opening and closing coil current, and breaking signal during the operation of the circuit breaker are basically consistent with the simulation results. Moreover, the time error of each opening and closing stage is within $\pm 5\%$.

Based on the coupling model, the factors affecting the operating time in the actual operation of the circuit breaker are analyzed. The main influencing factors studied are: the control voltage of the electromagnet, the force of the opening and closing spring, the air pressure of the arc extinguishing chamber, and the friction coefficient of the transmission rotating parts. The opening and closing time influence index is defined to quantitatively evaluate the influence degree of each influencing factor on the operating time. Except for the friction coefficient, the closing spring force has the greatest influence index on the closing time (0.497), and the air pressure has the smallest influence index (0.047). The influence index of the opening spring force on the opening time is the greatest (0.441), and that of the air pressure is the smallest (0.063). Among the rotating parts, the friction coefficient of the camshaft has the greatest influence index on the closing time (1.201), and the friction coefficient of the rocker arm transmission shaft has the greatest influence index on the opening time (0.616). Meanwhile, the opening and closing times are respectively divided into three segments, and the influences of each influencing factor on the time of each segment are analyzed. The sources of the deviations of the opening and closing times in various situations are determined.