

The Transient Voltage Instability Forms and Evolution Process in High-penetration Renewable Energy Power Systems

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KEY WORDS: high-penetration renewable energy; voltage instability patterns; static voltage stability; transient voltage stability; repeated fault ride-through instability; critical short circuit ratio

The fast response characteristics of renewable energy and other power electronic-interfaced equipment accelerate the dynamic evolution of system voltage, shifting the voltage stability problem from a purely load-side issue to a coupled source-load phenomenon. Consequently, both the modes and processes of voltage instability have undergone significant changes. Typical voltage-related behaviors for load inflow and renewable power export are illustrated in Fig. 1, while three representative voltage instability patterns at load and renewable integration points are shown in Fig. 2.

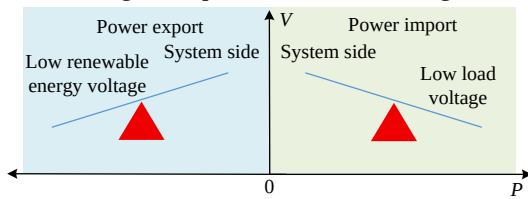


Fig. 1 Voltage issues of load inflow and renewable energy sources output

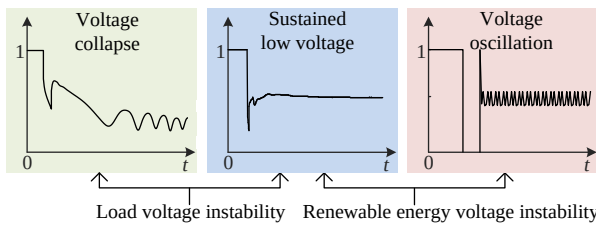


Fig. 2 Three types of transient voltage instability patterns at load and renewable energy integrated points

This study systematically reviews instability scenarios in high-penetration renewable energy systems and focuses on three newly emerging forms of instability at renewable access points: active power switching induced voltage oscillation, sustained low voltage during power reduction, and reactive power switching induced voltage oscillation. The overall classification of instability modes and scenarios for both load and renewable integration is summarized in Fig. 3.

Furthermore, when the Thevenin equivalent resistance is neglected, load and renewable access points share consistent static voltage instability mechanisms. With resistance considered, however, the sending and receiving ends exhibit distinct impacts on voltage stability, as illustrated by the P - V curves in Fig. 4.

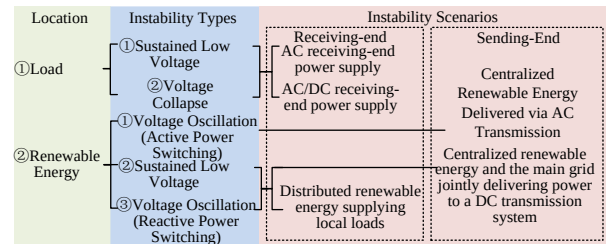


Fig. 3 Classification of voltage instability modes and scenarios for load and renewable energy sources

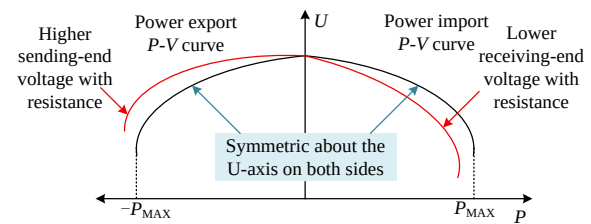


Fig. 4 P - V curve considering system-side resistance

Building on these insights, the paper summarizes new transient voltage instability mechanisms driven by renewable-energy control switching. The P - Q trajectories showing active-power oscillation and repeated LVRT transitions demonstrate that, during the recovery of active power toward its steady-state reference, the terminal voltage repeatedly crosses the LVRT threshold, inducing oscillations in both power and voltage. Different control strategies influence the oscillation speed and amplitude, as shown in Fig. 5.

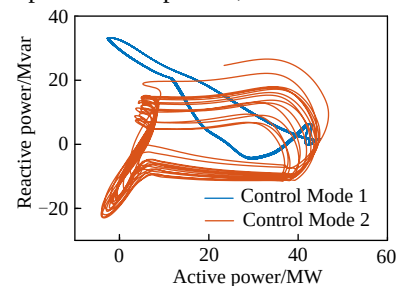


Fig. 5 P - Q plane trajectories during ARL instability under different control methods

Finally, an engineering-oriented quantitative assessment method for voltage instability is proposed. The results provide theoretical and practical support for understanding and managing voltage stability in emerging power systems with high renewable penetration.

Discussion on Necessary Constraints for Constructing Renewable Power Systems From the Small-disturbance System Strength Perspective

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KEY WORDS: eigen-subsystems; generalized short circuit ratio; strength constraints; global modes

The construction of renewable power systems is a pivotal step in achieving the energy transition. However, the large-scale integration of power electronic devices weakens system strength and substantially increases the complexity of dynamic characteristics. Thus, analyzing the necessary operation constraints of renewable power systems is necessary and challenging. Maintaining small-signal strength is the fundamental requirement for constructing the system. This study investigates the necessary constraints for constructing renewable power systems from the perspective of small-signal system strength, proposing mathematical constraints across three dimensions: voltage magnitude, angle, and frequency.

The proposed methodology is based on an eigen-subspace reduction technique applied to the original complex system. The eigen-subsystem of the original system, which focusing on key modes, can be obtained by:

$$\mathbf{L}_i = (\mathbf{Y}_i^H \mathbf{N} \mathbf{X}_i)^{-1} \mathbf{Y}_i^H \mathbf{J}_{\text{SYS}} \mathbf{X}_i = \mathbf{J}_{G,\text{eq}}(s) + \mathbf{J}_{\text{Neq}}(s) \quad (1)$$

By leveraging this method, low-order eigen-subsystems are derived to capture the key dynamic characteristics of the original system in three aforementioned dimensions as shown in Fig. 1. These eigen-subsystems effectively reflect the critical dynamic properties and serve as the foundation for analyzing system strength requirements.

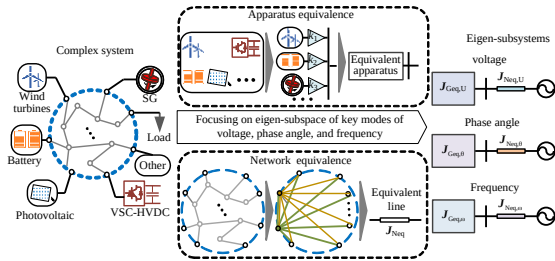


Fig. 1 Generation procedure of eigen-subsystem

Using these subsystems, the study introduces quantitative indicators for assessing system strength: the generalized short-circuit ratio for voltage (γ_{gSCR_U}), the generalized short-circuit ratio for angle ($\gamma_{\text{gSCR}_\theta}$), and the frequency dynamic deviation indicator (γ_{C_ω}). These metrics provide a robust framework for quantifying system strength and formulating the necessary

constraints. By ensuring compliance with these constraints, the system can achieve the required stability and disturbance rejection capabilities.

Specifically, the study establishes strength constraints critical by these three metrics, i.e., γ_{gSCR_U} , $\gamma_{\text{gSCR}_\theta}$, and γ_{C_ω} . These constraints are expressed as three inequalities, each delineating the dynamic performance boundaries for the voltage, angle, and frequency dimensions, as detailed in (2)–(4):

Voltage Strength Constraint:

$$\gamma_{\text{gSCR}_U} > \gamma_{C_{\text{gSCR}_U}} \quad (2)$$

Angle Strength Constraint:

$$\gamma_{\text{gSCR}_\theta} > \gamma_{C_{\text{gSCR}_\theta}} \quad (3)$$

Frequency Strength Constraint:

$$\gamma_{\omega} > \gamma_{C_\omega} \quad (4)$$

These inequalities represent the necessary conditions for achieving system stability under small disturbances.

To validate the proposed method and constraints, this paper conducts case studies based on a real-world renewable power system. The results are provided in Table 1. These cases demonstrate the effectiveness of the characteristic subsystems and the associated strength constraints in accurately representing and maintaining the dynamic stability of the system.

Table 1 Case validation results

Cases	Violated Constraints	Phenomena
Voltage	$\gamma_{\text{gSCR}_U} < \gamma_{C_{\text{gSCR}_U1}}$	Voltage Magnitude Monotonic Instability
	$\gamma_{\text{gSCR}_U} < \gamma_{C_{\text{gSCR}_U2}}$	Oscillatory Instability (Dominated by Voltage Amplitude Control Loop)
	$\gamma_{\text{gSCR}_U} < \gamma_{C_{\text{gSCR}_U3}}$	Voltage Fluctuation Exceeds Limit
Angle	$\gamma_{\text{gSCR}_\theta} < \gamma_{C_{\text{gSCR}_\theta}}$	Oscillatory Instability (Dominated by Synchronization Control Loop)
Frequency	$\gamma_{\omega} < \gamma_{C_\omega}$	Frequency Deviation Exceeds Limit

The findings highlight the importance of system strength as the foundation for maintaining robust dynamic performance. The study provides critical insights into the construction and operation of new power systems, outlining the necessary conditions for their stability. Furthermore, the research emphasizes the need for future studies to investigate additional dynamic modes and constraints to address the growing complexity as well as evolving demands of power systems.

Integrated Power Balancing Under the Unified National Electricity Market Environment

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KEY WORDS: power balance; power system dispatch; electricity market; security constrained unit commitment (SCUC); power supply's guarantee; new energy's consumption

It's necessary to combine basic integrated power balancing principles (IPB) with basic electricity market principles to establish cross- power balancing regional electricity market clearance mechanisms with integrated power balancing constraints, which are due to realize more benefits and efficiency with bulk power system's resources and abilities through market methods. At this point, the article focused on realizing IPB with principles of electricity market under unified national electricity market environment.

Firstly, integrated power balancing- security constrained unit commitment (IPB-SCUC) mechanism was proposed with mathematically combining basic IPB mechanisms and basic SCUC principles, of which ancillary benefit & cost calculation method and allocation scheme as well as differential contrast mechanism are also related, systematically constructing an improved IPB mechanism fit for unified national electricity market.

Fig. 1 shows the effectiveness of the proposed IPB-SCUC mode, which realizes better economy than conventional SCUC mode.

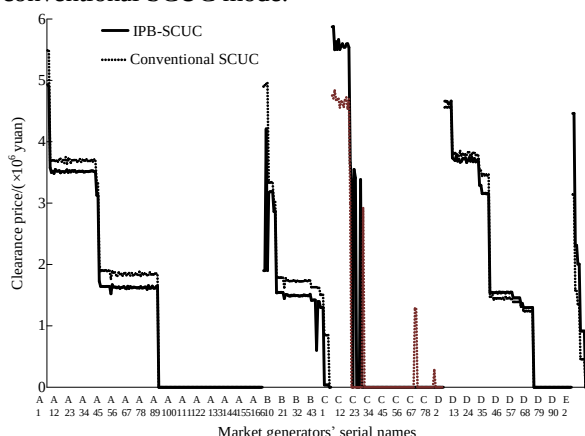


Fig. 1 Clearance results comparison of IPB-SCUC & conventional SCUC

With the proposed IPB mechanism power balancing zones' balancing boundaries are widely and deeply opened in order under the premise that power balancing zones are the basic units in power balancing procedure, realizing unified optimization and dispatching of power

balancing resources over the whole power system at market-oriented mode.

Secondly, by using the proposed IPB mechanism as the core engine, the universal methods of dispatching the entire system's resources under electricity market environment are proposed to systematically solve problems such as transmission channels' constraints, power supply gaps as well as new energy's consumption. With which the dispatching behavior's benefit & cost over IPB could be quantitatively estimated with value, realizing the unification of electricity current and value current. Lastly, all the theoretical analysis is verified by examples to be effective and meaningful.

Fig. 2 shows that the proposed Integrated Power Balancing mode would generate different influences on clearance results in different power balancing zones, compared with conventionally Independent Power Balancing mode. Therefore, all the IPB's influences on clearance results, costs & benefits of all power balancing zones would be precisely calculated in the paper to apply quadratic economy allocation and IPB-SCUC iteration, ensuring economical efficiency and fairness between power balancing zones.

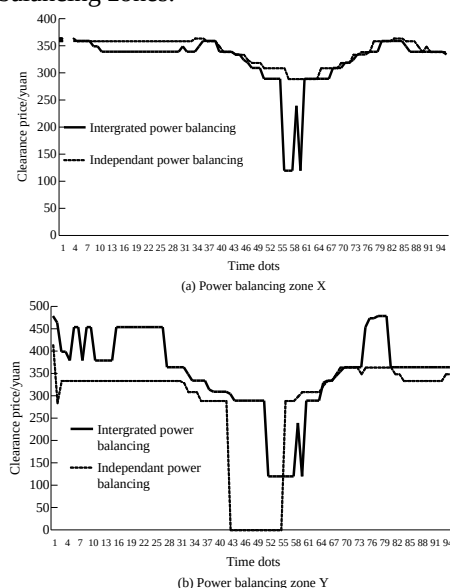


Fig. 2 Marginal Prices of different power balancing zones at different power balancing modes

AC Feasibility Restoration Algorithm of Power System Scheduling Model

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KEY WORDS: power flow restoration; AC feasibility; economic dispatch; secure and stable operation of power system

The integration of power electronic devices in modern grids presents challenges for maintaining reactive voltage stability, often causing dispatch solutions to deviate from AC power flow equations. To address this, this study proposes a general AC feasibility restoration algorithm that aligns dispatch solutions with AC power flow requirements and operational constraints. This algorithm enables both real-time operations while maintaining grid security and economic efficiency.

Fig. 1 illustrates the detailed procedure of the algorithm, which is composed of two models. The power flow restoration model (PFR) tackles situations where DC-based dispatch solutions lack reactive power information. It calculates optimal reactive power outputs and terminal voltages to ensure the solution conforms to AC power flow equations. By minimizing mismatches

between DC and AC branch active flows, the PFR restores feasibility efficiently. For large systems, a fast version of the model applies linear approximations to reduce computation time.

When dispatch solutions exceed operational constraints (e.g. nodal voltage or reactive power limits) the feasible solution restoration model (FSR) makes iterative adjustments. This model uses sensitivity matrices to optimize control variables like active and reactive power outputs, ensuring compliance with feasibility requirements. Iterations continue until the average feasibility violation rate (AFVR) falls below a predefined threshold, avoiding over-corrections while maintaining fast convergence.

Simulations are conducted on IEEE-30 and IEEE-118 systems, covering 8760 hours of operation. Results show that the algorithm restores AC feasibility effectively, with minimal cost increases: only 0.04% for the IEEE-30 system and 0.0006% for the IEEE-118 system in certain cases. In one scenario, 671 hours of constraint violations in the IEEE-118 system are resolved in a single iteration. The algorithm's average recovery time constitute only a minor fraction of the overall dispatch time, accounting for just 8%. Moreover, to demonstrate the convergence of the algorithm, AFVR variation curves are plotted based on scenarios recovered through multiple iterations, illustrating the algorithm's effectiveness in improving boundary violations.

This algorithm provides a robust tool for maintaining secure and economic grid operations, ensuring dispatch solutions meet both AC power flow equations and operational limits. Its ability to balance performance and efficiency makes it well-suited for modern power systems analysis.

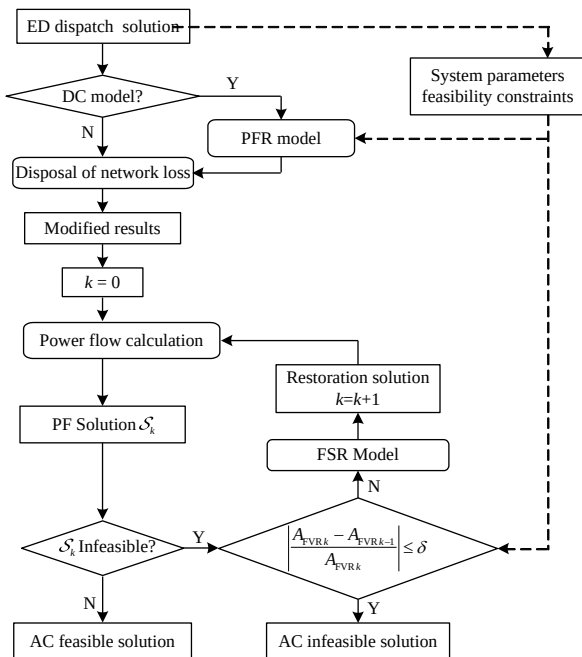


Fig. 1 AC feasibility restoration algorithm of ED dispatch solution

Reliability Assessment for SOP-based Flexible Interconnected Distribution Network Considering Post-fault Multi-stage Recovery

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KEY WORDS: soft open point; flexible interconnected distribution network; reliability assessment; mixed-integer linear programming; multi-stage recovery

Reliability assessment is essential for the planning and construction of flexible interconnected distribution network (FIDN) based on soft open point (SOP). This paper proposes a novel reliability assessment method for SOP-based FIDN considering post-fault multi-stage recovery. The proposed method is characterized by explicitly expressing the FIDN topology state through the decision variables of the optimization process, so as to establish a mixed-integer linear programming (MILP) model for FIDN reliability assessment.

Firstly, the multi-stage recovery process of FIDN is analyzed, and a FIDN reliability assessment framework with decoupled computation of multi-stage recovery process is proposed, as shown in Fig. 1. Secondly, a reliability assessment-oriented SOP equivalent model is established based on the external characteristics of SOP under normal operation and different faults, and a FIDN node-branch state correlation model is established to achieve network topology state explicitness. Then, the SOP fast transfer model under different strategies is established by considering the SOP capacity constraint and short-time overload capability. On this basis, a MILP model for FIDN reliability assessment is established by considering the multi-stage recovery process of SOP fast

transfer, fault point upstream recovery, tie switch switching transfer, and island operation.

Case studies are carried out on a modified 37-node system. The post-fault recovery processes are depicted in Fig. 2, and the results of the FIDN reliability assessment are shown in Table 1. It can be observed that the post-fault recovery process with multi-stage is more in line with the actual situation and can guide FIDN planning and construction in a more refined way. Specifically, the I_{SAIDI} and I_{EENS} solved under the consideration of post-fault multi-stage recovery are reduced by 6.595% and 7.029%, respectively, compared with the single-stage network reconstruction (SNR) method, which effectively improves the accuracy of FIDN reliability assessment.

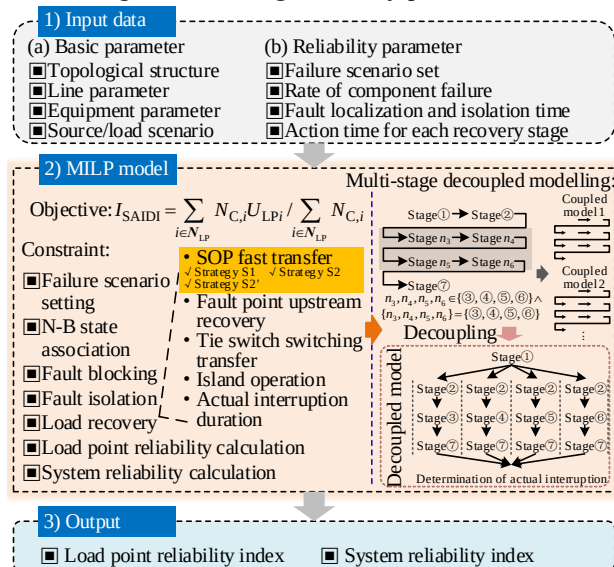


Fig. 1 Framework for FIDN reliability assessment

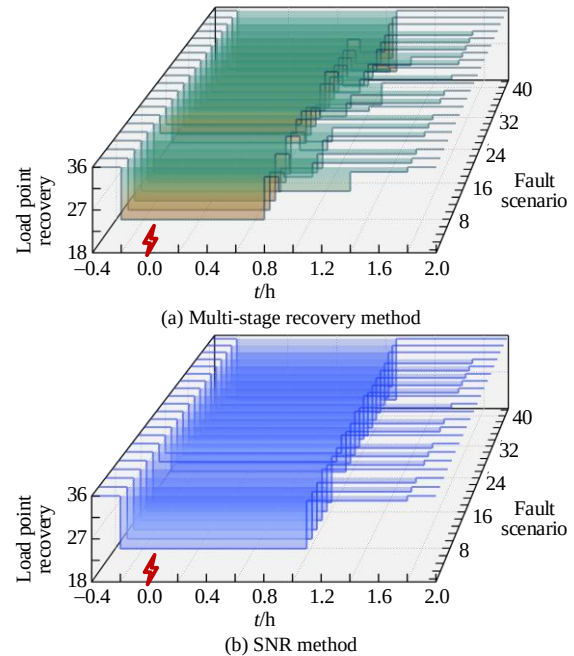


Fig. 2 Comparison of load recovery processes of the multi-stage recovery method with the SNR method

Table 1 Comparison of the results of the multi-stage recovery method with the SNR method

Method	$I_{SAIFI}/(\text{times/a})$	$I_{SAIDI}/(\text{h/a})$	$I_{SAIFI}/\%$	$I_{EENS}/((\text{MW}\cdot\text{h})/\text{a})$
Multi-stage recovery method	2.026	2.535	99.971	27.312
SNR method	2.026	2.714	99.969	29.377

Coal-electricity Price Interaction Mechanism Analysis Based on Mean-field Differential Game Equilibrium

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KEY WORDS: coal-electricity price interaction; coal-fired generation unit; differential game; mean-field game; equilibrium analysis

Under the construction of national-level market, coal-fired generation units are required to participate in the coal and electricity market. Massive coal-fired generation units will establish an interaction relationship between coal and electricity prices while influencing the markets operation. This paper investigates this interaction relationship from the perspective of non-cooperative game among massive coal-fired generation units.

The evolutionary dynamics of the coal storage $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ associated to a coal-fired generation unit is determined by coal procurement $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$, coal combustion $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ and coal inventory loss, as

$$ds_i(t) = u_i(t)dt - b_i(t)dt - \gamma_i S_i^{\max} dW_i(t) \quad (1)$$

where $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ represents the inventory loss coefficient, and $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ is an independent Winner process.

Given the trajectories of coal price $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ and electricity price $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$, the profit of a coal-fired generation company is

$$J_i = \mathbb{E}[\lambda(t)p_i(t) - C_i^S s_i(t) + \pi(t)u_i(t) + C^{\text{CO}_2} e_i(t) + \pi(T)s_i(T)] \quad (2)$$

where $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ and $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ represent the coal storage cost and carbon emission cost, respectively.

We use a supply function bidding model to depict the electricity market clearing, as

$$\lambda(t) = [D(t) - \sum_{k \in \mathcal{K}} P_k(t)]^+ / [\sum_{i \in \mathcal{I}} q_i(t)] \quad (3)$$

where $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ denotes the bidding parameter.

The coal transaction price is denoted by a Cournot model:

$$\pi(t) = \pi_0(t) + \max\{0, \alpha[\sum_{i \in \mathcal{I}} u_i(t) - \theta\Phi(t)]\} \quad (4)$$

where $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ denotes the coal floor price, $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ and $(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ are parameters of the Cournot model.

Then, since the coefficients of coal-fired generators

$(S_i^{\max}, P_i^{\max}, \eta_i, \varphi_i, \gamma_i)$ are in certain trend, the paper clusters the generators into 4 groups as Fig. 1.

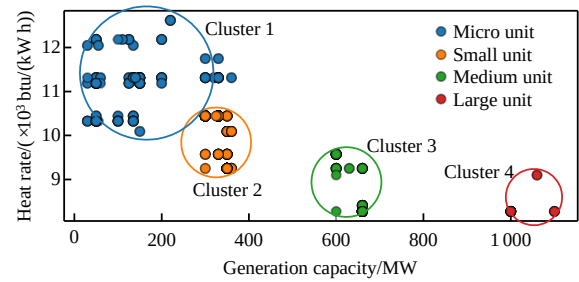


Fig. 1 Clusters of coal-fired generation units

The mean-field term for each group is defined as

$$\rho_{(l)}(s, t) = \frac{1}{N_{(l)}} \sum_{i \in \mathcal{G}(l)} \delta[s_{(l)}(t) = s] \quad (5)$$

Based on the mean-field game, this study investigates the 493 coal-fired generation units in Northwest of China. The coal storage evolution is presented in Fig. 2.

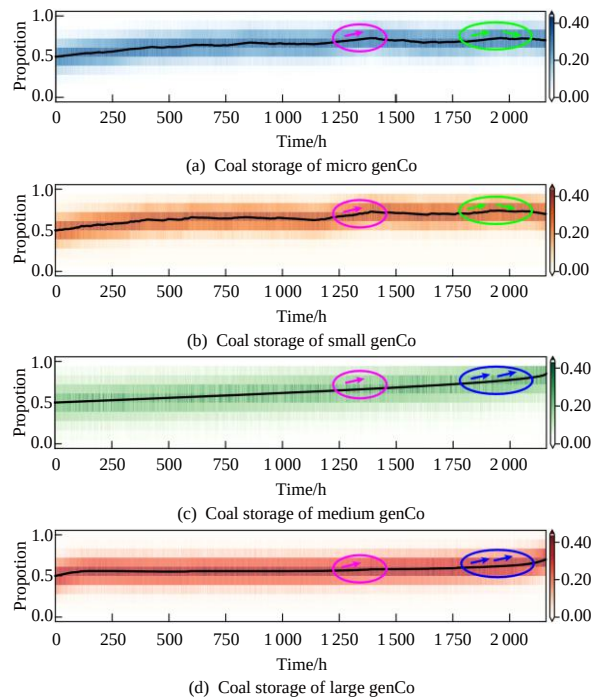


Fig. 2 Coal storage evolution

Finally, market regulation suggestions under steady coal supply and coal disruption cases are provided.

A Bi-level Optimization Model for Selecting $N-k$ Coordinated Fault Scenarios in Cyber-physical Power System Considering Cross-domain Cascading Failures

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KEY WORDS: cascading failures; cyber-physical power system; multi stage bi-level programming theory; observability; controllability

The classic $N-k$ security analysis method often selects the source fault accident set with the goal of maximizing harm, ignoring the synergistic amplification effect of cyber-physical interaction and the cross-domain cascading failures propagation process, thus resulting in a tendency to be conservative.

This paper focuses on characterizing the impact mechanisms of observability and controllability on the information side in cross-domain failure propagation.

This paper establishes a bi-level optimization model for $N-k$ contingency screening in a cyber-physical power system, considering cross-domain cascading failures. The upper layer aims to maximize load loss, while the lower layer aims to minimize load loss, enabling identification of high-risk collaborative fault scenarios and cross domain propagation paths in the cyber-physical power system, as shown in Fig. 1.

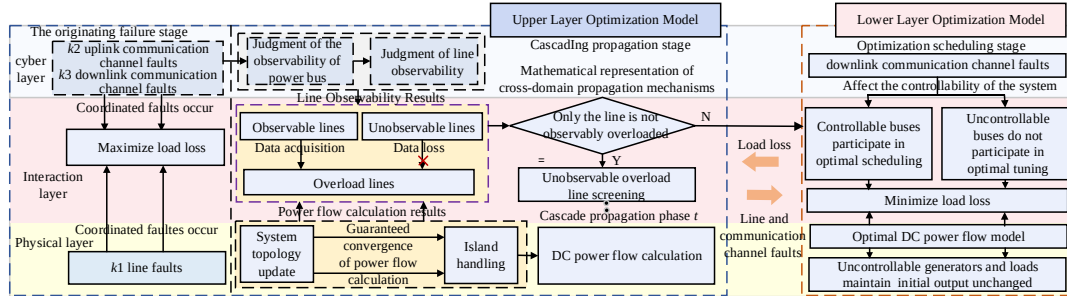


Fig. 1 Framework diagram of a bi-level optimization model for $N-k$ collaborative fault scenarios screening in cyber-physical power system considering cross domain cascading failures

The upper layer optimization model includes the initiating failure stage and the cascading propagation stage, while the lower optimization model includes the optimal scheduling stage.

1) In the initiating failure stage, k_1 power lines and k_2 uplink and k_3 downlink communication channels are randomly selected to trigger faults, simulating cyber-physical collaborative failures.

2) In the cascading propagation stage, line statuses are updated based on system observability and power flow calculations. Due to the changing topology and the emergence of islands, the model's feasibility region varies, increasing computational infeasibility. Thus, islands are processed and topology is updated to improve power flow calculation feasibility.

3) In the optimization scheduling stage, controllability of power buses is determined based on downlink communication faults. The dispatch center adjusts controllable generator and load outputs to minimize load loss, while uncontrollable generators and

loads maintain their initial outputs due to the inability to deliver control commands.

Fig. 2 shows that the model effectively identifies high-risk coordinated fault combinations and cross-domain fault propagation paths. With smaller communication faults, controllability dominates fault spread, so control backups should be prioritized; with larger failures, observability dominates, so measurement backups should be prioritized.

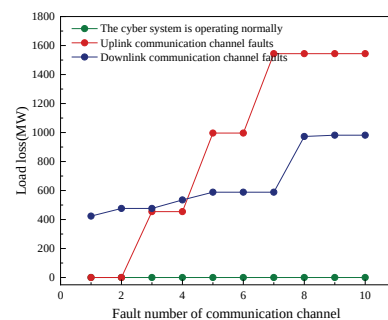


Fig. 2 $N-1$ scenario of 500 kV system in a province

Extended Locational Marginal Price: A Linear Relaxation Pricing Method Based on Convex Hull of Unit Commitment and Its Applications in Electricity Spot Market

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KEY WORDS: Electricity spot market; Locational marginal pricing; non-convex pricing; convex hull of unit commitment; uplift costs

Market clearing begins with security-constrained unit commitment problems, which include non-convex costs such as start-up/shut-down and non-load costs. In fact, non-convex costs are always excluded in locational marginal prices, making it challenging for units to obey scheduling instructions issued by the independent system operators according to these existing locational marginal prices, against “incentive compatibility”. Therefore, to motivate these units to execute scheduling instructions, it is necessary to compensate not only the opportunity cost but also the financial transmission rights costs and other financial attributes, denoted by uplift costs. However, the uplift costs fail to participate in pricing with competitive market incentives, which may pay different fees for the same service, eventually leading to discrimination.

To bring non-convex costs into locational marginal prices, reduce uplift costs, and thereby improve market fairness, this paper proposes a linear relaxation pricing method based on the convex hull of unit commitment, whose details are demonstrated in the following figure.

As Fig. 1 shows, this paper investigates the convex hull of single-unit unit commitment and then proposes its

convex hull model. Based on this convex hull model, this paper then provides a linear relaxation model for unit commitment and further introduces its corresponding linear relaxation pricing model, eventually generating the extended locational marginal price. Non-convex costs are incorporated into this extended locational marginal price, thus achieving the reduction of uplift costs.

Numerical experiments are conducted on modified IEEE-30 and Polish-2383 systems; the proposed method (denoted by P3) is compared with the traditional locational marginal prices (denoted by P1 and P2).

As shown in Table 1, the proposed pricing method will take non-convex costs into account, and its extended locational marginal price can significantly reduce the uplift cost as above expects, eventually improving market fairness. As shown in Table 2, this proposed pricing method performs well in applications as no huge computational burden is necessary when providing the extended locational marginal price to reduce uplift costs.

Table 1 “Uplift costs” under different pricing methods

Method	IEEE-30		Polish-2383	
	Uplift costs/\$	Percentage/%	Uplift costs/\$	Percentage/%
P1	353 252	100.00	1.284×10^7	100.00
P2	50 292	14.24	6.424×10^5	5.00
P3	40 216	11.38	5.051×10^5	3.93

Table 2 Efficiency of different pricing methods

Method	Scale	Nonzeros*	Comput. time*/s	Rate
P1	223 658×31 008	45 037 180	6.139	1.000
P2	254 343×54 264	45 219 904	99.398	16.191
P3	308 459×762 186	48 063 962	33.319	5.427

*“Nonzeros” represents the nonzero element of the coefficient matrix; Clearing time is not counted in computational time.

Moreover, limited by the objective existence of the duality gap, any locational marginal price will inevitably generate uplift costs. Therefore, after minimizing uplift costs as much as possible, it will also be necessary to investigate how to allocate uplift costs in the future.

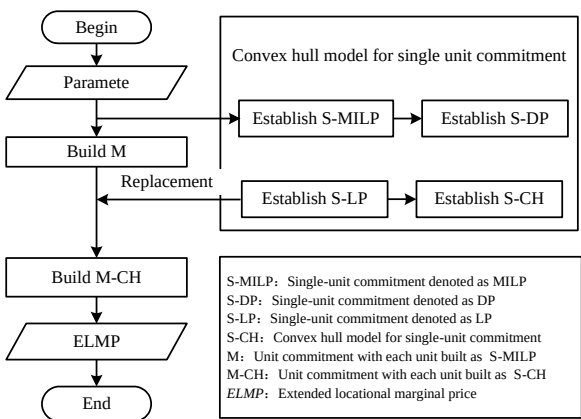


Fig. 1 Schematic diagram of A linear relaxation pricing method based on the convex hull of unit commitment

A Coordinated Trading Mechanism for Electricity-carbon Markets with Composite Regulation of Carbon Emission Rights

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KEY WORDS: carbon allowance; composite regulation; electricity and carbon markets; dynamic carbon price; coordinated trading

To support the "Dual Carbon" goals and promote the construction of a new power system, China is accelerating the improvement of its carbon trading market mechanisms. Under the background of deep integration between electricity and carbon markets, there is an urgent need to establish an institutional guarantee system through the optimal design of carbon market mechanisms, as well as develop refined decision-making models for coordinated trading of power generators in the electricity-carbon markets to achieve synergistic optimization of environmental and economic benefits. Based on an in-depth analysis of the dynamic interaction feedback relationship between electricity and carbon markets, this paper innovatively proposes a coordinated electricity-carbon market trading decision model considering composite regulation of carbon emission rights. The overall framework of the proposed model is shown in Fig. 1.

The carbon market, which uses carbon emission rights as trading targets to control carbon emissions, consists of a primary market for carbon allowance allocation and a secondary market for carbon allowance trading. To address issues such as excessive carbon allowance allocation caused by the current fully free allocation mechanism, this paper introduces a paid allocation method and designs a related paid auction mechanism. By setting trigger conditions to strengthen the linkage between primary and secondary carbon markets, a composite regulation mechanism between markets is formed. This mechanism balances the supply-demand relationship between the two-level carbon markets, solving the problem of insufficient market liquidity caused by unbalanced carbon allowance allocation in traditional carbon markets. Furthermore, through in-depth analysis of the dynamic interaction between electricity and carbon markets, a decision-making framework for electricity-carbon markets under composite regulation is proposed, which provides

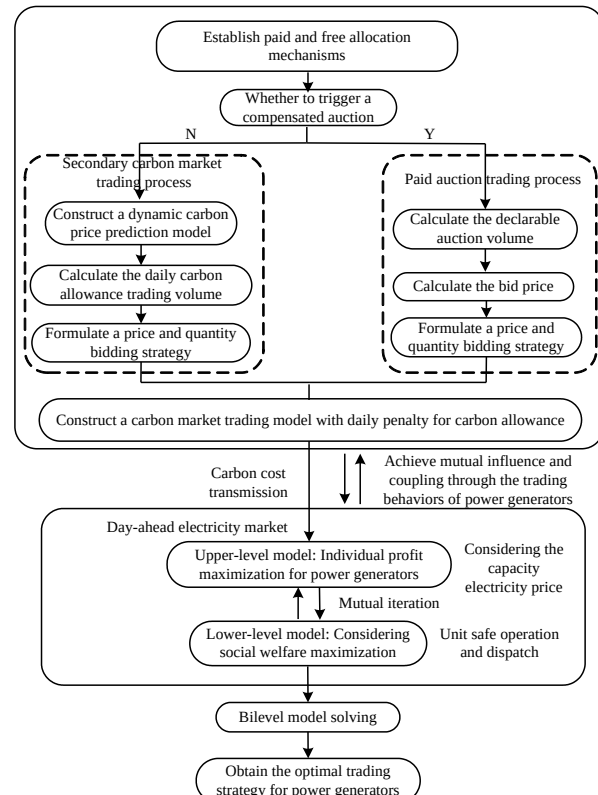


Fig. 1 Framework of coordinated electricity and carbon market trading decision model with composite regulation

theoretical support for power generators to formulate comprehensive trading strategies.

To address challenges such as uncertain dynamic demand and information constraints in carbon markets, this paper establishes a dynamic carbon price prediction model and a daily carbon allowance adjustment allocation model based on supply-demand relationships. By integrating capacity electricity prices and carbon cost transmission relationships, a bi-level optimization model for the electricity market is constructed. Through iterative algorithm solving, optimal trading strategies for electricity-carbon markets are obtained. This model not only improves relevant carbon market mechanisms but also provides refined modeling for power generators' trading in electricity-carbon markets, achieving optimized coordination of electricity-carbon markets.

Research on Coordinated Optimization of Multiple Frequency Regulation Resources Considering Frequency Stability of Inter-regional HVDC Interconnected Systems

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KEY WORDS: inter-regional HVDC interconnected systems; coordination of multiple frequency regulation resources; HVDC frequency regulation; frequency dynamics

The widespread application of ultra-high voltage direct current technology is driving the transition of power systems towards a mode of regional grid interconnection. As synchronous generators in power systems are gradually replaced by power electronic equipment such as new energy sources and large-scale HVDC systems, the power systems face increased frequency security risks. Fully utilizing the frequency support capabilities of various frequency regulation resources has become an effective approach. Within a region, flexible coordination between conventional units and new energy units should be considered; between regions, utilizing HVDC systems can achieve flexible frequency support.

To this end, this paper establishes a frequency response model for an inter-regional HVDC interconnected system, as shown in Fig. 1. This model considers the impact of HVDC, new energy units, and conventional units on frequency dynamics, and describes the relationship between power disturbances and frequency deviations in different regions.

Unlike single-area frequency regulation, the frequency

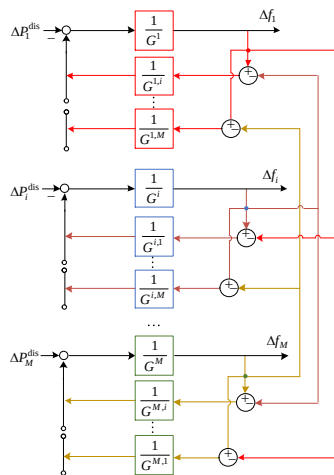


Fig. 1 Frequency response model of inter-regional HVDC interconnected systems

dynamics between multiple regions considering DC frequency regulation exhibit a coupling relationship. The frequency dynamics across the regions are shown in Fig. 2 when a disturbance occurs in area D2. Fig. 2 reflects the mutual influence of frequency dynamics between multiple regions under DC participation. The frequency drop in each region differs, which is determined by the response capabilities of the frequency regulation resources within each region and the strength of the connected DC regulation capability. When disturbances occur in different regions, the maximum frequency deviations in each region are shown in Table 1.

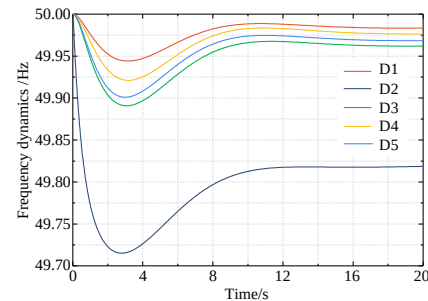


Fig. 2 Frequency dynamics of each area after a disturbance in area D2

Table 1 Maximum frequency deviation in each area after a disturbance in different areas

Disturbed area	f_1/Hz	f_2/Hz	f_3/Hz	f_4/Hz	f_5/Hz
D1	0.430 4	0.114 5	0.043 25	0.031 1	0.039 2
D2	0.056 0	0.284 8	0.109 3	0.079 0	0.099 0
D3	0.013 4	0.069 1	0.315 6	0.067 9	0.023 8
D4	0.020 3	0.105 0	0.142 8	0.408 7	0.036 0
D5	0.015 7	0.081 1	0.030 8	0.022 2	0.389 4

Furthermore, this paper further analyzes the impact of frequency security constraints, HVDC regulation, and the regulation of renewable energy units. The numerical results demonstrate the effectiveness of the proposed method and highlight the advantages of coordinating multiple frequency regulation resources in a HVDC interconnected system.

Parameter Identification for Power Grid Line Based on Dynamic Spatiotemporal Adaptive Graph Neural Network

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KEY WORDS: power grid line parameter identification; spatiotemporal information integration; maximum information coefficient; bayesian optimization; graph convolutional networks; temporal convolutional networks; dynamic spatiotemporal adaptation module

The accuracy of transmission line parameters is crucial for reliable electrical grid analysis and computation. Factors such as climate, geography, and operational conditions cause dynamic changes in line parameters, while inaccuracies due to human error or outdated databases can compromise grid calculations. This paper introduces a method using a dynamic spatio-temporal adaptive graph neural network for identifying line parameters, aiming to significantly enhance accuracy and robustness in complex environments.

This paper proposes a method for identifying power grid line parameters that leverages spatio-temporal information to enhance prediction accuracy and utility. The method's framework, outlined in Fig. 1, progresses

through five primary steps:

1) Data sample generation: by utilizing the Pandapower tool, sectional load flow data with Gaussian noise is generated to simulate measurement data, alongside real-time line parameters for subsequent analysis.

2) Feature selection: measurement features are evaluated for their correlation with line parameters by using maximum information coefficient (MIC), with the most relevant features organized into datasets XD.

3) Graph data construction: structural and measurement feature data are integrated to form spatio-temporal graph datasets $G_D=(V_D, E, A)$ across historical data.

4) Bayesian optimization: hyperparameters such as input feature dimensions and time window lengths are optimized by using a probabilistic surrogate model guided by the expected improvement (EI) acquisition function.

5) Model application: the optimized model is applied to a test set, and its capability for accurate and robust line parameter identification in simulated power grid environments can be assessed.

To verify the efficacy of the proposed method, this paper conducts extensive simulations within the IEEE 39-bus system under various complex grid scenarios, such as noise interference, data loss, and topology changes. The method displays exceptional identification precision and robustness. Enhanced by the dynamic spatiotemporal adaptive module (DSTAM), the model excels in capturing the unique spatio-temporal dynamics of each line, maintaining high accuracy even with significant data gaps or sampling deficiencies. The proposed parameter identification model also demonstrates superior adaptability and generalization across rapidly changing grid topologies.

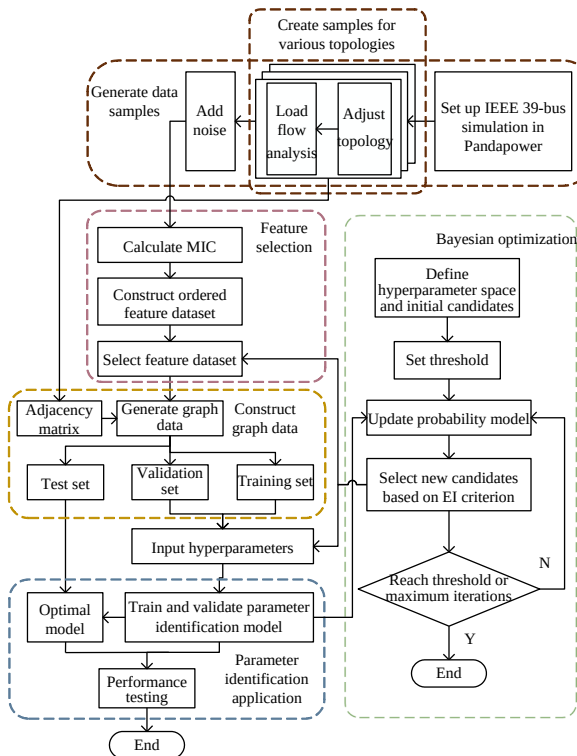


Fig. 1 Overall framework and process of the parameter identification method

Development and Challenges of Intelligent Operation and Maintenance of Integrated Energy Systems Based on Digital Twin

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KEY WORDS: integrated energy system; mechanism-driven; data-driven; digital twin; heterogeneous energy

With the progress of energy technology, the expansion of market demand, the continuous support of national policies, as well as integrated energy systems have been applied to many fields such as power, heat, transportation, building, industry, etc., and are rapidly developing towards intelligence and greening. Traditional integrated energy system operation and maintenance is usually based on automated control systems and manual experience regulation, making it difficult to meet the integrated energy system's new operation and maintenance requirements. In the future, technology and markets will drive the development of decarbonized, decentralized, and digital energy systems. Therefore, there is an urgent need to adopt more advanced and intelligent means to realize intelligent operation and maintenance of integrated energy systems, so as to more accurately and timely grasp the system's operating status, optimization potential, and abnormal fault conditions, as well as to promote the digital transformation and sustainable development of the energy industry.

Because of the digital twin technology's depth of interactivity, virtual-real synchronization, high simulation precision, real-time, and other characteristics, in the many integrated energy intelligent operation and maintenance technology route, digital twin technology can deeply integrate the energy and power system, achieving the simulation and analysis of all elements, all components, all working conditions as well as the whole process of integrated energy system, which injects a new impetus for the simulation of the integrated energy system and the optimization of the operation. However, the structure of the integrated energy system is more complex, with a wide variety of equipment, and there are still many challenges to realizing the digital twin intelligent operation and maintenance of the integrated energy system. Therefore, in this paper, for the park-

level integrated energy system arranged on the load side, this paper firstly analyzes the digital twin operation and maintenance demand for the integrated energy system as a whole, and proposes the intelligent operation and maintenance architecture of the integrated energy system under the support of the digital twin in the example of an industrial park, as shown in Fig. 1.

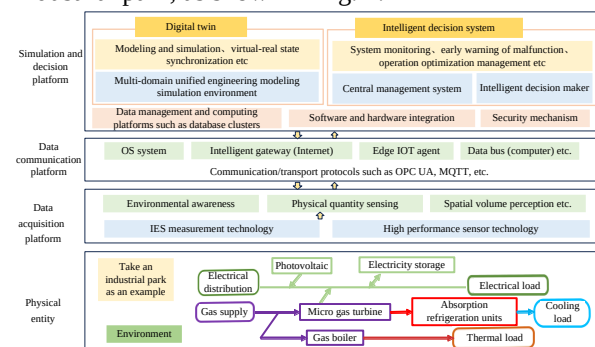


Fig. 1 Schematic diagram of intelligent operation and maintenance architecture of integrated energy system based on digital twins

In this architecture, the integrated modeling-optimization-verification simulation platform is taken as the core foundation, and the intelligent decision-making platform matching the business requirements of system monitoring, optimized operation, and fault early warning is constructed based on the real-time interaction between the entities and the models, which ultimately supports the development of the integrated energy intelligent operation and maintenance and other businesses. Secondly, it further introduces the current research status of integrated energy system modeling based on dual-driven physical mechanism and operation data, as well as the research progress of heterogeneous energy system topology identification technology and solution method. Subsequently, it describes the research progress of online simulation, operation optimization, and fault analysis of integrated energy system. Finally, it summarizes the development and challenges of the digital twin-based integrated energy system.

Integrated Energy System Analysis——From Numerical to Analytical (III): Hybrid Timescale Economic Dispatch

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KEY WORDS: integrated energy system; multi-timescale; numerical method; analytical method; hybrid timescale dispatch

Multi-timescale property is an important feature of integrated energy systems (IES) to coordinate heterogeneous resources and enhance operational flexibility. However, traditional numerical methods for economic dispatch mainly represent this property by discretization and neglect the asynchronous features among different subsystems, making the dispatching accuracy and efficiency limited by spatial-temporal resolutions. To be specific, electric power propagates at the speed of light, and the timescale under steady-state conditions is seconds to minutes. Thermal power and gas flow propagate at the fluid flow rate, and their timescale is generally tens of minutes to hours, showing obvious delay characteristics. Given a dispatch command, the fast dynamic characteristics of the power system allow its electric state to reach stability quickly. Thus, its dispatch interval τ_e is short and the adjustment is more frequent, as shown in Fig. 1(a), where P is the active power. Relatively speaking, due to the slow dynamics of gas and thermal power flow, the gas and thermal states usually

enter a new adjustment process before they are stable after one adjustment, and the states continuously change within the dispatch intervals. Thus, the dispatch interval τ_g and τ_h of the gas and heating systems are relatively long, as shown in Fig. 1(b) and (c), where q and T are the gas mass flow rate and water temperature, respectively.

The physical characteristics shown in Fig. 1 bring two difficulties to the economic dispatch of IES. First, the dispatch commands of each subsystem may be asynchronous. In the process of joint dispatch, it is generally necessary to estimate the state distribution of a single subsystem to provide operating boundary information for other subsystems. For example, when three subsystems are coupled through the gas turbine (GT) and CHP unit, it is necessary to estimate the gas states at 08:10 based on the commands at 08:00 and 08:20, and estimate the thermal states at 08:10 based on the commands at 08:00 and 08:15, so as to provide the necessary boundary information for the operation of the power system. Second, since the electric state can be quickly stabilized, the power system generally performs dispatching at the time of the dispatch command. However, due to the slow dynamics of gas and thermal power flows, decision-making based only on the state distribution at the time of the dispatch command is difficult to reflect the state variations (temperature, gas mass flow) within the dispatch interval, which further affects the accuracy of the decision.

To handle these problems, this paper develops two economic dispatch models based on the previously-proposed analytical method. The first type of model considers the instantaneous balance of multi-energy flow coupling and directly uses analytical methods for analysis. The second model considers the energy balance within the dispatch interval and transforms the instantaneously analytical expression into the average-value formulations. Simulations verify the superiority of the proposed methods in efficiency and accuracy over traditional discretization-based methods.

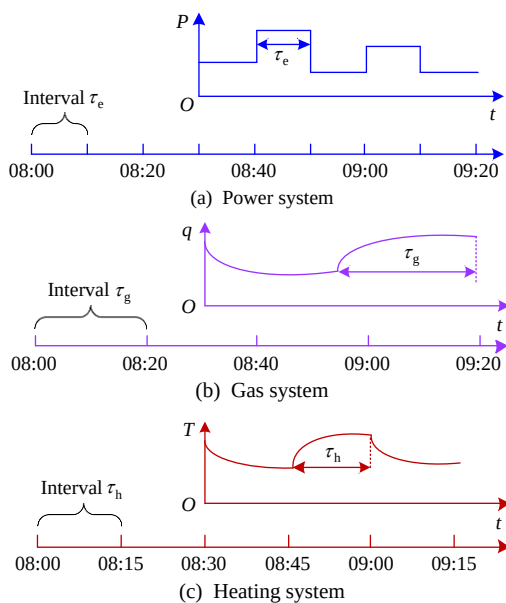


Fig. 1 Hybrid timescale economic dispatch of electricity, gas and heating integrated energy system

Energy Optimization Management of Edge Data Centers Considering Computing Power-electrothermal Coupling

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KEY WORDS: edge data center; renewable energy; task migration; computing power-electrothermal coupling; Lyapunov optimization

Data center marginal deployment is one of the effective ways to solve the difficulty in meeting the computing power needs of users. Multi-system cooperative optimal scheduling is the key technology to realize long-term stable and efficient operation of edge data center.

In this paper, a multi-system optimization strategy for edge data center based on computing power and electrothermal coupling is proposed. Task migration policies can be used to implement computing power

migration on hosts to avoid overtemperature and task congestion on some hosts. The online control algorithm based on Lyapunov can ensure the long-term stable operation of edge data centers without the prior knowledge of the system. The proposed generalized Benders algorithm can decouple the problem, solve the difficult problem of mixed integer programming in high dimensional state space, and realize its fast and accurate solution. System model is shown in Fig. 1.

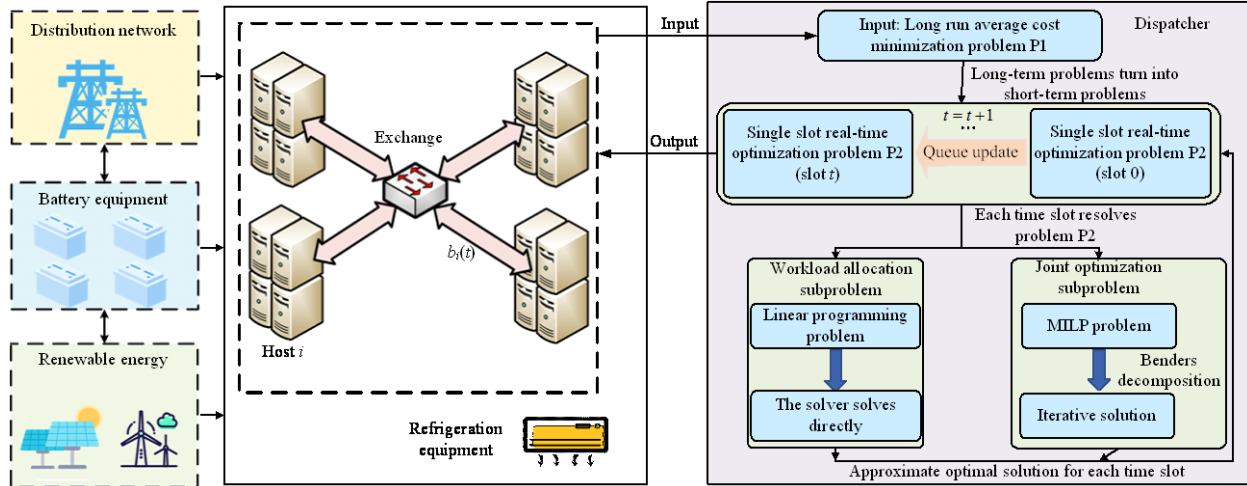


Fig. 1 System model

In order to solve the problems such as the high operating cost of edge data centers and the substantial increase in carbon emissions, a multi-system joint optimization model is designed with the total operating cost of the system as the target, and the objective function is as follows:

$$\begin{cases} \Psi[a(t), b(t), \beta_{ik}(t), D(t), P_{co}(t)] = \sum_{t=1}^T [V(t) + C(t)] \\ \text{s.t.}, (2), (4) - (9), (10), (12), (18), (20), (22), \forall i, t \end{cases} \quad (1)$$

Where, $a_i(t)$ and $b_i(t)$ respectively represent the total amount of workload received and processed by each time slot of host i . $\beta_{ik}(t)$ is the task transfer variable; $D(t)$

represents the amount of charge and discharge of the battery in each time slot t ; $P_{co}(t)$ indicates the power consumption of air conditioners in the data center during the t period. $C(t)$ is the battery loss cost.

Compared with the operation strategy without considering the computing power-electrothermal coupling characteristics, the strategy proposed in this paper can make full use of the adjustable potential of the computing power, realize the reasonable allocation of host tasks, avoid host task blocking and hot spots caused by excessive temperature, reduce the operating cost by 25%, and achieve rapid convergence compared with other algorithms.

Low-carbon Economic Dispatch of Integrated Energy Systems Considering “Coal-fired+” Coupling Power Generation and Flexible Resource Reserves

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KEY WORDS: integrated energy system; flexible resources; biomass co-combustion carbon capture power plant; reserve capacity; stochastic optimization

Under the goal of “dual carbon”, the task of clean and low-carbon transformation of integrated energy system (IES) is arduous. On the one hand, the traditional thermal power unit power generation technology has high pollution problems, and it is urgent to promote coal consumption substitution and transformation and upgrading. On the other hand, under the high proportion of wind power integration, its randomness and volatility make the system less flexible, and the phenomenon of power abandonment is serious. At the same time, due to the uncertainty of wind power, the system needs to reserve more reserve capacity to ensure the safe and stable operation of the system. In this regard, a low-carbon economic dispatch method of integrated energy system considering “coal-fired+” coupling power generation and flexible resource reserve is proposed to jointly optimize the energy, reserve and energy regulation of other energy systems, reduce system carbon emissions and improve flexibility.

In this paper, “coal-fired+” coupling power generation and carbon capture utilization and storage technology will transform thermal power units into biomass co-combustion carbon capture power plant (BCCPP) to achieve low-carbon flexible transformation. At the same time, considering the impact of wind power uncertainty on the system, this paper considers the coupling relationship between electricity, heat, gas and hydrogen in the integrated energy system, establishes a flexible resource reserve model for multi-energy systems, and proposes a two-stage stochastic optimization scheduling method considering multiple flexible resource reserves. The influence of wind power uncertainty is balanced by the reserve of flexible resources.

The IES two-stage stochastic optimization scheduling framework is shown in Fig. 1. The decision-making of the model in the first stage is applicable to all

methods in the second stage. In the second stage, based on the decision-making of the first stage, the adjustment strategy to deal with the uncertainty of wind power is formulated. In the second stage, the power balance in each wind power scenario is guaranteed by the adjustment of flexible resources. Reserve deployment represents the actual reserve capacity value provided by flexible resources, and other energy systems meet the flexibility requirements of different systems through the energy regulation of flexible resources based on the energy coupling relationship. The two stages are coupled with each other through reserve capacity, reserve deployment, output of flexible resources and energy regulation.

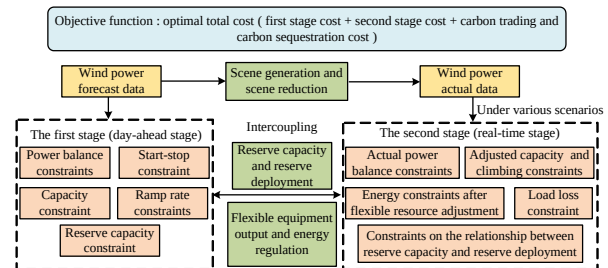


Fig. 1 IES scheduling architecture considering flexible resources reserve

Compared with the traditional scheduling method, the introduction of BCCPP can promote the low-carbon transformation of thermal power units from the perspectives of carbon substitution and carbon removal. Its carbon emission is 7.23% lower than that of traditional thermal power units, and the total system cost is 0.78% lower, which can promote the low-carbon operation of thermal power units. At the same time, IES optimizes the system reserve capacity through two-stage stochastic optimization and coordination of multiple flexible resources to promote wind power consumption and reduce the system cost. The upper and lower reserve capacities are increased by 17.91% and 206.28% respectively, which improves the system flexibility.

Multi-timescale Transient Stability Issues and Research Status of Renewable Energy Grid-connected Systems During Grid Faults

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KEY WORDS: multi-timescales; the renewable energy grid-connected system; sequential response and switching; transient stabilization mechanism; cross-timescale interactions

The development of renewable energy sources is an important approach to achieving the aim of “carbon peak and carbon neutrality”. In contrast to the conventional synchronous generator, the renewable energy generation equipment emerges multi-timescale transient response characteristics during grid faults, which profoundly impacts the transient behavior and stability of renewable energy power systems.

In recent years, the multi-timescale transient stability issues have been studied by many scholars and researchers. The existing reviews mainly focus on the transient modeling, analytical and control methods summary, without distinguishing the transient instability issues under different timescales, failing to reveal the multi-timescale instability phenomenon. To cope with this issue, this paper firstly proposes the multi-timescale transient stabilization framework and summarizes the current research of transient instability mechanism.

Firstly, the generic multi-timescale control block of DFIG-based wind turbine connected to grid has been introduced, then the transient instability phenomenon of DFIG-based WT is analyzed and compared with the synchronous generator. Secondly, the sequential response and switching process of renewable energy grid-connected system is analyzed during various grid faults, as shown in Fig. 1.

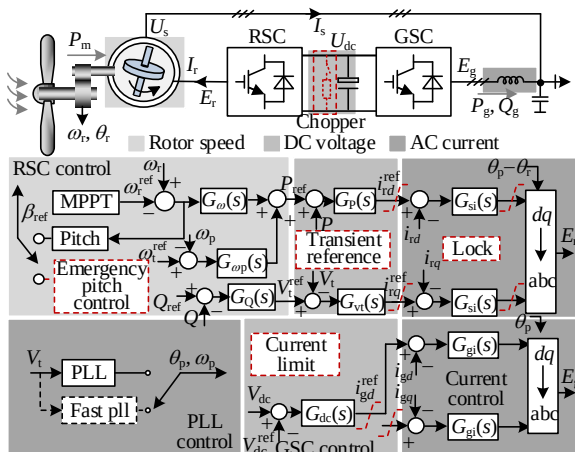


Fig. 1 Sequential response/switch action of DFIG-based WT

The main architectures of transient stabilization mechanism research are summarized from three levels of transient stabilization mechanisms, i.e., AC current timescale, DC voltage timescale and rotor speed timescale, as shown in Fig. 2.

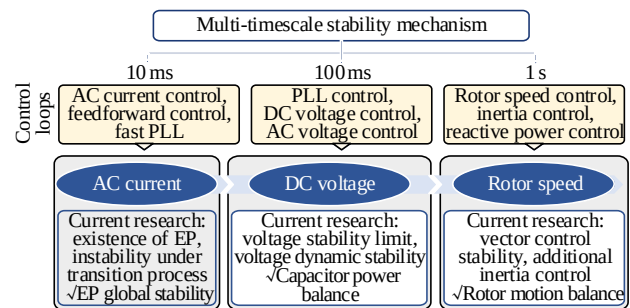


Fig. 2 Multi-timescale transient stable mechanism of renewable energy power system

Based on the Fig. 2, an overview of the existing studies is carried out in three timescales, and the main stabilization mechanisms in each timescale are condensed. It is pointed out that, 1) In AC current timescale, the transient instability issues are decomposed into the existence of equilibrium points and transition process of equilibrium points. 2) In DC voltage timescale, the static voltage stability limit is mainly determined by the power balance equation, and the dynamic voltage amplitude motion is driven by the unbalanced power. 3) In rotor speed timescale, the transient instability is divided into two categories, i.e., vector control and additional inertia control. In addition, the multi-timescale transient stabilization control of renewable energy grid-connected system are summarized and compared.

Finally, the future research directions are prospected in terms of cross-timescale interaction mechanism, multi-scale nonlinear switching dynamics modeling, quantitative analysis of cross-timescales coupling system, and control theory under complicated perturbations.

Clustered P2H Model and Its Application in Power System Operation Simulation

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KEY WORDS: power-to-hydrogen(P2H); multi-state; integer variables; clustered model; large-scale

As an effective method to mitigate the issue of electricity curtailment caused by the uncertainty of wind and solar power, Power-to-Hydrogen (P2H) technology plays a crucial role in power systems. Given the limited capacity of P2H devices, industrial-scale P2H plants typically consist of numerous P2H devices and supporting equipment, which involve a multitude of variables. Furthermore, P2H devices must account for multiple state transitions during operation, encompassing complex constraints. Consequently, the numerous variables and constraints in the model of P2H plants significantly increase the difficulty of solving the optimization operation problems associated with power systems that contain large-scale P2H devices.

This paper proposes a clustered modeling method for the multi-state P2H device, which utilizes integer variables. The approach simplifies the complex variables and constraints associated with the P2H plant model, thereby enhancing computational efficiency. The working state and switching process of the P2H device are illustrated in Fig. 1.

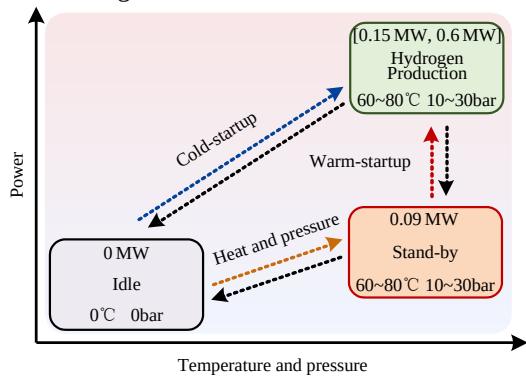


Fig. 1 Diagram of relationship between the working state and switching process of the P2H device

Considering the operational characteristics of P2H plants, the method groups P2H devices with the same or similar parameters into a single category. Each category of devices includes three states: idle, hydrogen production, and stand-by, represented by three integer variables a , b , and c respectively (all integer variables can take values of $0, 1, 2, \dots, N_m$, where N_m is the total

number of devices in that category).

$$a_{m,t}, b_{m,t}, c_{m,t} \in \{0, 1, \dots, N_m\} \quad (1)$$

Considering the state switching time t_m , list the state switching logic constraints using a as an example.

$$\begin{cases} a_{m,t} - a_{m,t-1} = a_{m,t}^{\text{st}} - a_{m,t-t_m}^{\text{sd}} \\ a_{m,t}^{\text{st}} \leq N_m - a_{m,t-1} \\ a_{m,t}^{\text{sd}} \leq a_{m,t-1} \\ a_{m,0} = a_{m,\text{init}} \end{cases} \quad (2)$$

where $a_{m,t}^{\text{st}}$ is the number of devices that startup action in state a during period t , $a_{m,t}^{\text{sd}}$ is the number of devices that stop action in state a , $a_{m,0}$ is the starting variable for a , and $a_{m,\text{init}}$ is the initial number of state a .

To accurately describe the switching process between different states of the P2H device, six additional integer variables are introduced:

$$N_{ab-m,t}, N_{ac-m,t}, N_{ba-m,t}, N_{bc-m,t}, N_{ca-m,t}, N_{cb-m,t} \in \{0, 1, \dots, N_m\} \quad (3)$$

Then this paper establishes an optimization operation simulation model for hydrogen-containing power systems, with the goal of minimizing the comprehensive operating costs of the power system, including thermal power units, P2H plants, and renewable energy units.

The improved IEEE-RTS79 calculation results demonstrate that the P2H clustered method (PCM) offers significant accuracy advantages over the traditional simple amplification method (SAM). The results are given as Table 1. As the scale of the P2H devices increases, the system cost deviation remains below 0.2%, while the solution time is substantially reduced. This method offers an efficient solution tool for simulating renewable energy systems with large-scale P2H devices.

Table 1 Comparison of solutions to different methods

index	Precise model	PCM	SAM
$f_{\text{totalcost}}/\$$	718 084.2	718 834.2	718 139.7
$\Delta\text{cost}/\%$		1.04	0.08
$t_{\text{solution}}/\text{s}$	3 339.61	88.22	63.33
α_{ac}		37.86	52.73
$\Delta\text{P2H}/\%$		2.16	0.37
$\Delta U_c/\%$		6.30	1.46

Multi-photovoltaic Two-stage Fault Ride-through Coordinated Control Strategy

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KEYWORDS: distribution network; multiple photovoltaics source; fault ride-through; coordinated control; consensus algorithm

Limited by the single control objective and control means, traditional LVRT strategies used for asymmetric faults in multi-photovoltaic(PV) power systems may suffer from voltage and current violation, frequency stability issues, and lack of coordination. Therefore, this paper proposes a fault ride-through coordination strategy for multiple PV sources based on a consistency algorithm.

First, in the initial stage following a fault, the remaining capacity of the PV inverter is prioritized for reactive power support, preserving the active power output capability of the PV source. At the same time, a consistency iterative update method is activated to update the reactive current deviation and operational status information as shown in Equations (1)、(2), coordinating the positive sequence active and reactive currents.

$$I_{q,need} = I_{q,ref}^+ - I_q^+ \quad (1)$$

$$M = \begin{cases} 1, & I_{q,max}^+ \geq 0.8 \\ 0, & I_{q,max}^+ < 0.8 \end{cases} \quad (2)$$

Second, in the second stage, based on the relationship between the voltage at the PV grid connection point and the current output from the PV system during an asymmetrical fault, a method to reduce the maximum phase voltage is proposed. Subsequently, the factors affecting the current magnitude are analyzed. Provided that the positive-sequence active current remains unchanged and current-limiting requirements are met, the positive- and negative-sequence reactive currents of the PV output are coordinated and updated. The overall process of the two-stage fault ride-through coordination control strategy in multiple PV sources is shown in Fig. 1.

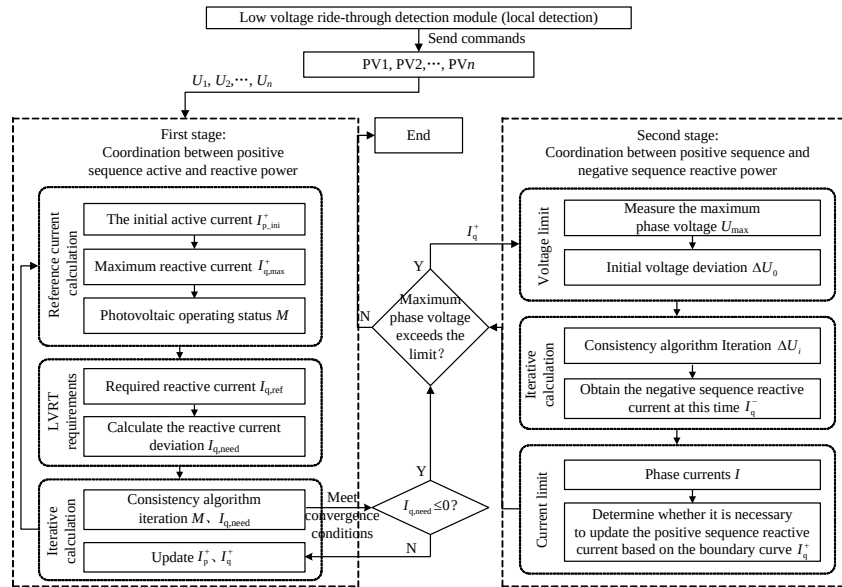


Fig. 1 Flow chart of two-stage fault ride-through coordination control strategy

Finally, a 10 kV grid-connected simulation system with photovoltaic (PV) sources is established by utilizing Matlab/Simulink. Simulation tests under different fault scenarios are conducted to validate the proposed two-stage fault ride-through method. The test results show that this approach can provide voltage support while reducing the risk of PV disconnection due to frequency instability, preventing voltage and current

limits from being exceeded, as well as achieving coordinated operation among multiple PV sources.

Compared to other LVRT strategies, the proposed approach provides stronger voltage and frequency support, fully coordinates multiple PV sources within the system, and accelerates the adjustment of electrical quantities during the fault ride-through process.

Differential Protection Scheme for Distribution Lines Considering the Role of Photovoltaic Grid-connected Control With Integrated Multiple Harmonic Information

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KEY WORDS: distribution network faults; grid-connected photovoltaic systems; fundamental and second and third harmonic fault components; differential current protection

Under the “dual carbon” strategy, photovoltaic (PV) power generation has garnered significant attention. PV systems interface with the AC power grid through power converters. In the event of a power grid fault, the output current of PV systems, influenced by the control characteristics of the converters, can impact the relay protection of the interconnected grid, which leads to the conventional current protection being inadequate for the protection requirements of PV systems once they are integrated into the distribution network. Research into novel protection principles suitable for active distribution networks will facilitate the widespread integration of PV power supplies and provide vital theoretical support for achieving the dual carbon targets.

To address the aforementioned issues, this paper initially investigates the impact of PV positive sequence PQ grid-connected control, low-voltage ride-through control, and converter output current limiting control on the output current of PV power sources during various operational stages. Analytical expressions for the fundamental wave and the second and third harmonic components of the PV output current under control influence are deduced. The concept of paralleling output from multiple frequency-band current sources is introduced to construct an equivalent model that accurately reflects the output characteristics of photovoltaic systems.

Subsequently, based on the aforementioned model, the voltage, current, and power output characteristics of PV systems are analyzed for different fault types and locations. A novel differential protection scheme is proposed, following a quantitative mathematical analysis of the positive sequence fault component current fundamental wave and the second and third harmonic electrical information at the differential protection detection point post-fault in the distribution system. This scheme utilizes various fault component information generated under grid-connected control to resolve issues of protection failure caused by the controlled characteristics of PV output.

Finally, Matlab is employed to construct a PV grid-connected system model, thereby validating the effectiveness of the proposed scheme.

Based on the above analysis, the design criteria are derived as follows:

$$\text{Judgment 1: } 0^\circ \leq \arg(\Delta \dot{I}_{m1}) - \arg(\Delta \dot{I}_{n1}) \leq 125^\circ \quad (1)$$

$$\text{Judgment 2: } \Delta I_{n1,3} + \Delta I_{n1,2} \geq 0.6\% \quad (2)$$

$$\text{Judgment 3: } \mu = \Delta I_{m1} + \Delta I_{n1} \geq \mu_{\text{set}} I_N \quad (3)$$

where $\Delta \dot{I}_{m1}$ and $\Delta \dot{I}_{n1}$ are the fundamental frequency fault component currents at the measurement points on the system side and the PV side; $\Delta I_{n1,3}$ and $\Delta I_{n1,2}$ are the contents of the 3rd harmonic component currents and the 2nd harmonic component currents at the measurement points on the PV side. The overall flow of protection is shown in Fig. 1.

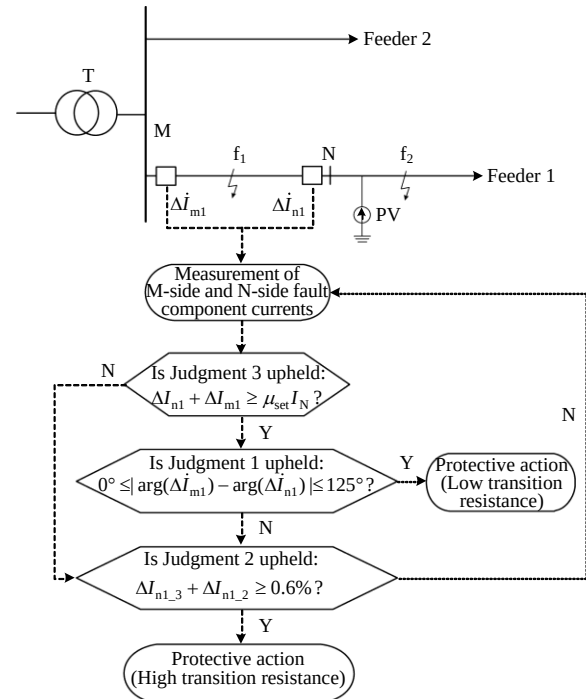


Fig. 1 Protection overall flow chart

In Fig. 1, M and N are the electrical quantity measurement points on the system side and PV side of the protected area section.

Online Insulation Identification of Transmission Cable in Offshore Wind Farm Based on Harmonic Current Amplification

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KEY WORDS: offshore wind farm; transmission power cable; insulation identification; harmonic current; harmonic amplification

Offshore wind farms are usually connected to the power grid via long high-voltage transmission cables, and it is of great significance to identify the insulation condition of the cables accurately to ensure the safety of the grid. Existing methods for insulation identification using signals such as partial discharges and DC leakage currents are limited by the weakness of the measurement signals, which makes it difficult to apply in practice.

This paper proposes a novel method to identify the insulation condition of cables in offshore wind farms online based on the correlation between the amplification factor of the harmonic currents and the insulation condition. It has been found that there are always amplification factors of harmonic current below the 25th order, which are very sensitive to the insulation condition, in the range of nominal cross-sections and lengths of cables in offshore wind farms. Given this perspective, the

correlation function between the harmonic current amplification factor and the insulation parameter of the cable is constructed, then a set of overdetermined equations is established based on the harmonic measurement data at different moments, and finally, the insulation parameter is solved by using the Levenberg-Marquardt algorithm.

The harmonic current amplification factor at resonance frequency is sensitive to the cable insulation parameter and can be determined based on (1).

$$j\cot(100\pi hl\sqrt{L_f C_f}) \approx Z_s \sqrt{C_f / L_f} \quad (1)$$

where, L_0 and C_0 are the inductance and capacitance per unit length, respectively; h is the order of harmonic current, l is the length of the cable, and Z_s is the equivalent harmonic impedance of the power grid. The schematic diagram of insulation condition identification is shown in Fig. 1.

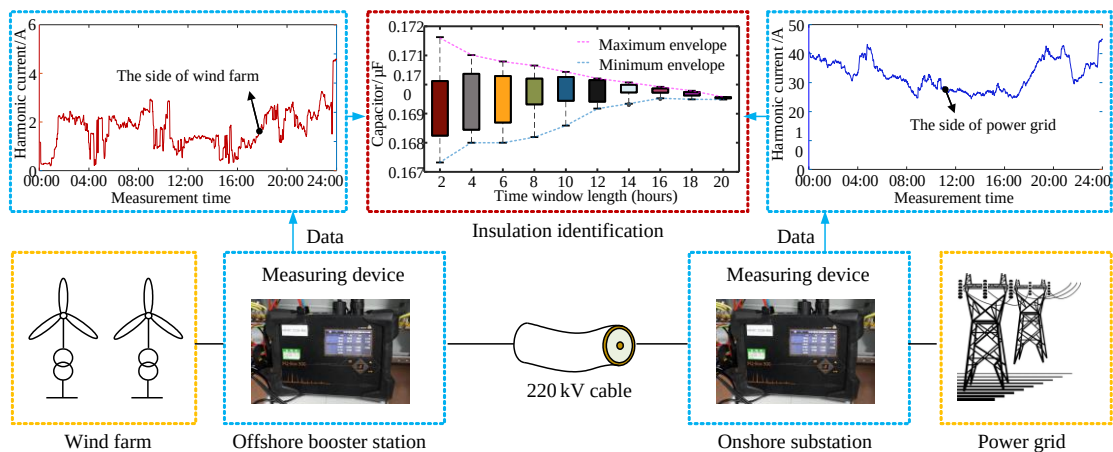


Fig. 1 Online insulation identification of transmission cable in offshore wind farm based on harmonic current measurements

The proposed method can achieve insulation identification based only on the data provided by the harmonic measurement devices already in offshore wind farms. Compared with the existing methods, there is no need to add new measurement devices, and the required data are easy to obtain online, which makes it

practical. In addition, for the first time, the cable insulation condition is identified based on harmonic data from two operating offshore wind farms, and the results are very consistent with the actual condition of the wind farms, which proves the effectiveness of the proposed method.

Optimization on Vibration Mode of Large-scale Straw Vibrating Grate Boilers

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KEY WORDS: straw; vibrating grate boiler; vibration mode; steam production efficiency; pollutants

Vibration mode of straw vibrating grate boilers has a comprehensive effect on the solid-phase combustion in the fuel bed and the homogeneous combustion in the freeboard, as well as on pollutant emissions. Its optimization is an effective way to improve combustion efficiency and reduce pollutant emissions of the boilers.

In this study, a 130 t/h vibrating grate boiler is studied, which utilizes a typical fuel, wheat straw. Based on the developed MTPP grate combustion model, this paper carries out numerical simulation to comprehensively study the effect of the vibration process on the combustion in both the fuel bed and the freeboard, exploring scientific vibration patterns.

The results indicate that the fuel bed of a straw vibrating grate boiler generally adopts a bottom-ignited layer combustion mode, as shown in Fig. 1. The length of the front zone for ignition preparation is closely related to the residence time of the fuel on the grate, while the rear zone for flame propagation is not directly related to it.

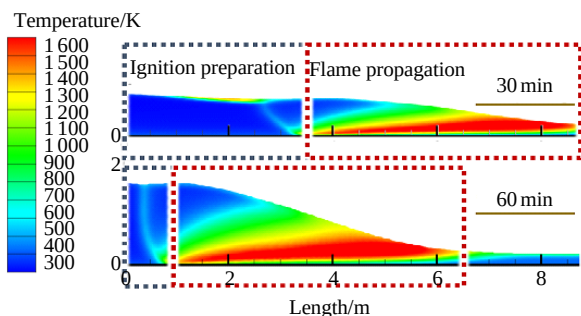


Fig. 1 Bed combustion with different residence times

With the time requirement for ignition fulfilled, vibration with a short interval and a high frequency can strengthen the crushing of coke block and improve the burnout of bed. Additionally, increasing the frequency of vibration motor can further enhance the crushing of coke block. While shortening the ramp-up, sustain, and ramp-down time periods of the vibration can reduce bed movement distance, providing a wider range for these adjustments.

The optimization in vibration mode can effectively alleviate the concentrated pyrolysis, reducing the emissions of CO and NO_x. It also weakens the concentrated combustion in the fuel bed, and promotes

the mixing of bed particles, preventing localized high temperature and inhibiting the release of inorganic sulfur.

After applying the adjustment in vibration in the real boiler, the burnout of both the fuel bed and gases in freeboard is significantly improved, which leads to a higher steam production efficiency and a lower fuel consumption, as shown in Fig. 2.

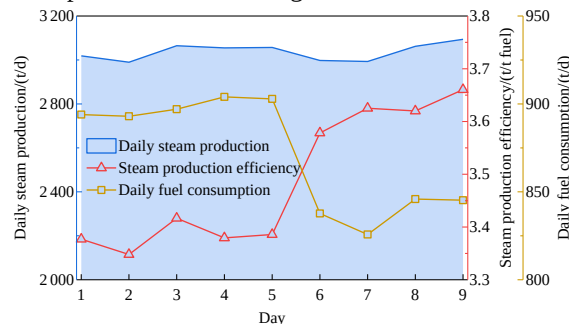


Fig. 2 Daily steam production, daily fuel consumption and steam production efficiency during the adjustment

Moreover, with a stable emission level (after flue gas cleaning process) of NO_x and SO₂, the consumption of their reagents for pollution control is also greatly reduced, as shown in Fig.3. In conclusion, the adjustment considerably increases the profits of power generation and heat supply from straw combustion.

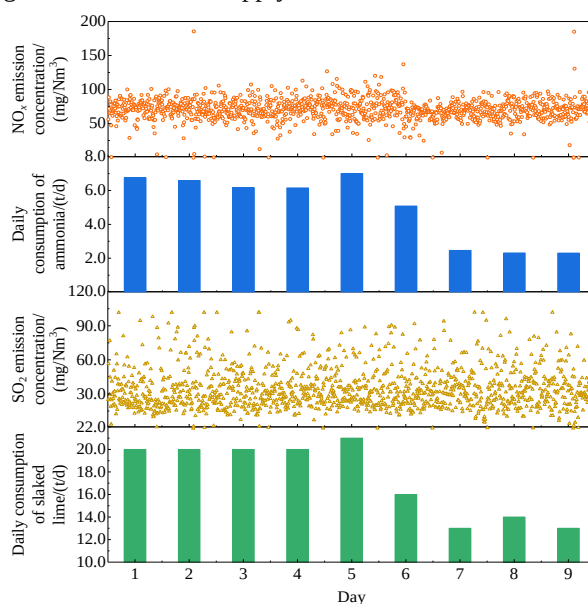


Fig. 3 Emission concentration of NO_x and SO₂, and the consumption of their reagents during the adjustment

Design and Performance Analysis of S-CO₂ Solar-coal Complementary Power Generating System With Thermal Energy Storage Unit

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KEY WORDS: S-CO₂ cycle; Brayton cycle; tower solar energy; solar-coal complementary; coal consumption rate

Currently, there is relatively little research on the S-CO₂ solar-coal complementary power generating (SCCPG) systems. And the integration location of solar energy is single and the integration ratio is low, which

has failed to achieve high-quality utilization of solar energy. Therefore, this paper proposes three S-CO₂ SCCPG systems with thermal energy storage units (shown in Fig. 1).

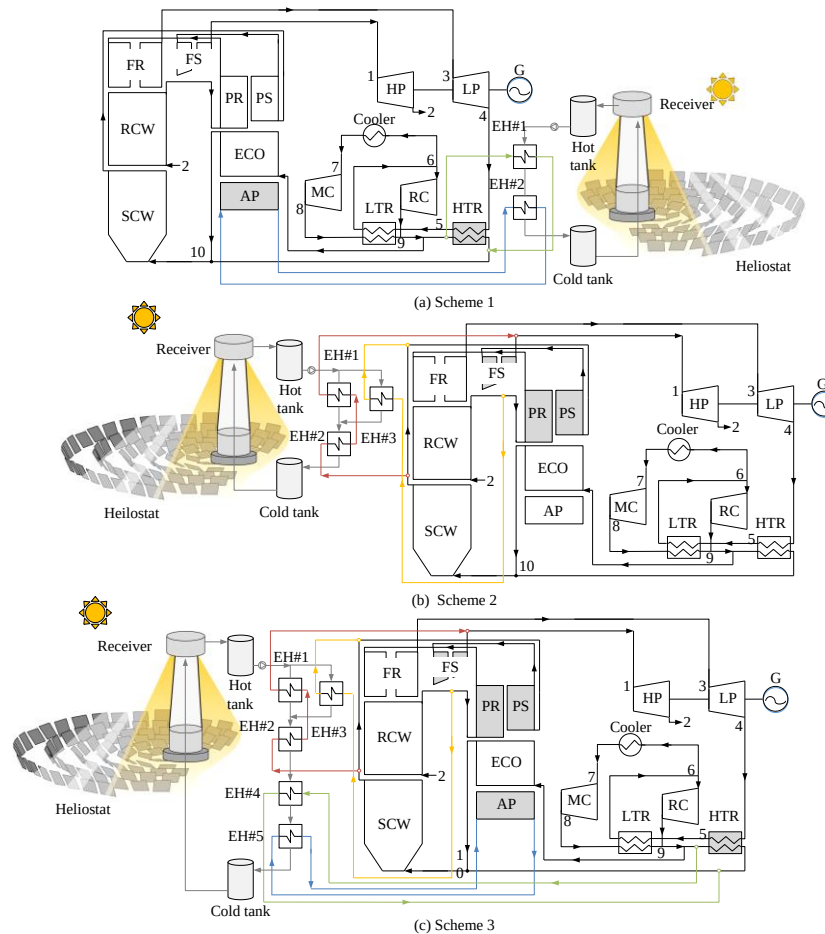


Fig. 1 Three S-CO₂ SCCPG systems with thermal storage units

In scheme 1, the working fluid and cold air of the boiler inlet are heated by solar energy to replace the heat loads of the high-temperature recuperator and air preheater; In scheme 2, solar energy is used to heat the superheated and reheated working fluid, replacing the heat loads of the primary reheater, primary superheater, and final superheater; Due to the fact that the thermal storage fluid still has the ability to continue heating low-grade working fluid after exchanging heat with high-grade working fluid, based on the scheme 2, solar energy is used to continue heating the working fluid and cold air of the boiler inlet in scheme 3.

The calculation results indicate that the coal consumption for power generation can be reduced by integrating solar energy, thus achieving energy conservation and emission reduction. Under the design condition, compared with coal-fired power generating (CPG) system, the CO₂ emission rates of schemes 1, 2, and 3 decrease by 14.87, 43.62 h, and 29.20 g/(kW·h). Among the three schemes, scheme 2 has the lowest coal consumption rate and CO₂ emission rate, and the overall performance of the system is the best. Therefore, tower solar energy is more suitable for replacing the high-temperature range of CPG system.

CO₂ Emission Prediction of Coal-fired Power Plants With Principal Component Analysis and Neural Network

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(Shanghai University of Electric Power)

KEY WORDS: principal component analysis; back propagation neural network; CO₂ emissions; correlation analysis; data dimensionality reduction

Coal-fired power plants are one of the main sources of CO₂ emissions. Establishing a CO₂ emission prediction model for coal-fired power plants can support energy planning and effectively control carbon emissions.

There are many prediction models for CO₂ emissions, but there is few discussions on the selection process of input variables in these models. Based on machine learning, this paper further introduces data analysis methods such as correlation analysis, describes in detail the screening process of input variables, and establishes a prediction model combining principal component analysis and backpropagation neural network (PCA-BP). The flowchart of the prediction model is shown in Fig. 1.

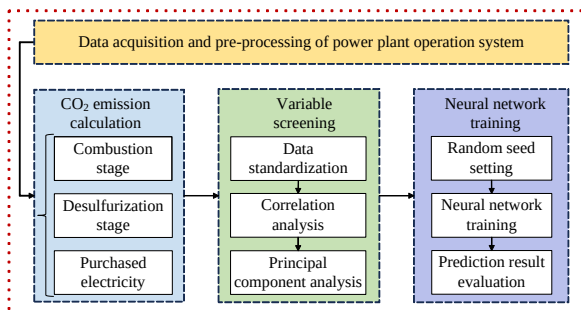


Fig. 1 Flowchart of PCA-BP CO₂ emission prediction model

The data on CO₂ emissions is not only an important basis for evaluating CO₂ emissions but also essential information for constructing predictive models. Taking a coal-fired power generation unit with an installed capacity of 660 MW as an example, this paper uses the emission factor method to calculate the CO₂ emissions from the boiler combustion system (E_1) and the desulfurization system (E_2). The formulas are as follows:

$$E_1 = F_C N_{CV} C_C O_F \times \frac{44}{12} \quad (1)$$

Where F_C represents the coal consumption (t), N_{CV} represents the average lower heating value of coal (TJ/t), C_C represents the carbon content per unit heating value of coal (tCO₂/TJ), O_F represents the carbon oxidation rate of coal (%), and 44/12 represents the ratio of the molecular weight of carbon dioxide to carbon.

$$E_2 = C_{AL} E_F \quad (2)$$

Where C_{AL} represents the consumption of carbonates in the desulfurizer (t) and E_F represents the emission factor of carbonates in the desulfurizer (tCO₂/t).

To reduce the number of input variables for the predictive model, this paper calculates the correlation coefficients between variables. Redundant variables with weak correlations to the target variable, CO₂ emissions, are removed. Based on the correlation analysis, variables are further screened according to the principles of principal component analysis (PCA), effectively achieving data dimensionality reduction.

The simulation results show that the model can effectively predict CO₂ emissions from coal-fired power plants. Compared to other models, the PCA-BP neural network prediction model has a simple structure and wide range of applicability. During the training process, it can automatically adjust the neural network weights based on errors to achieve accurate predictions.

Energy Efficiency Calculation of Deep Coupling System Between Solar Energy and Ultra Supercritical Coal-fired Power Units

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KEY WORDS: solar power; photothermal system; coal-fired power generation; coupling system; flour milling system

In order to improve the efficiency of solar power generation and reduce power generation costs, this article proposes a deep coupling mode between solar energy and coal-fired units, which uses a solar thermal system to heat the unit feedwater from the outlet of the high-pressure heater, vaporizes the feedwater, and then enters the boiler superheater for further heating before entering the high-pressure cylinder of the steam turbine. The exhaust steam from the high-pressure cylinder of the steam turbine first enters the solar thermal system for heating, and then enters the boiler reheater for further heating before entering the intermediate pressure cylinder of the steam turbine. By adopting this coupling mode, the boiler can eliminate the economizer and water-cooled wall, and necessary technical modifications can be made to the powder production system, including the use of hot flue gas powder production, the addition of smoke powder heaters, and the elimination of the boiler's primary air system.

Taking a 670 MW ultra supercritical coal-fired power unit as a case study, the energy efficiency and economy of the system after deep coupling with solar energy are calculated and analyzed. The results show that the power generation efficiency of solar thermal power could reach 47.31% after coupling with coal-fired power units. Due to the coupling of solar energy systems, the coal consumption of coal-fired units decreases significantly with the increase of the proportion of solar thermal energy, as shown in Fig. 1.

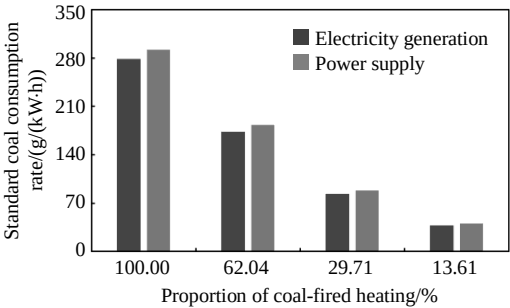


Fig. 1 Coal consumption and coal heat proportion of the unit

Through the economic calculation of the coupled solar thermal system of coal-fired units, the results show that when using coal saving calculation, it takes more than 10 a at a standard coal price of 800 yuan/t. If the standard coal price rises to 1200 yuan/t, the investment payback period will be less than 7 a, as shown in Fig. 2. If solar energy is used for grid connected electricity calculation, the investment payback period of the coupling system will be 4.74 a when the grid connected electricity price of the solar thermal part is 0.5 yuan/(kW·h), and 7.89 a when the electricity price is reduced to 0.3 yuan/(kW·h), as shown in Fig. 3. This coupling system is economically more competitive compared to a simple solar thermal power station.

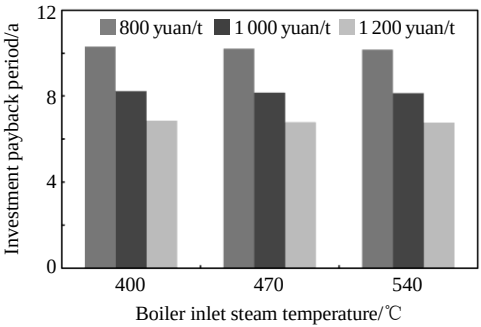


Fig. 2 Investment payback period of coupled solar thermal system (based on coal consumption savings)

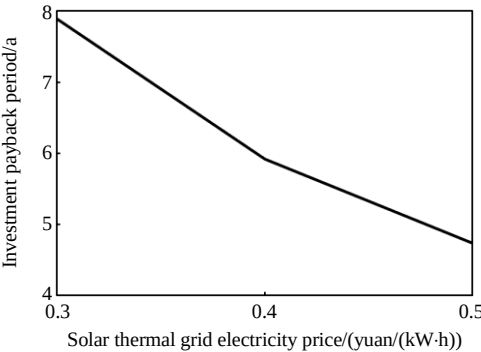


Fig. 3 Investment payback period of coupled solar thermal system (based on internet revenue)

Railway Virtual Power Plant and Its Carbon Emission Reduction Strategy

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KEY WORDS: railway traction power supply system; flexible interconnection of different phases; railway virtual power plant; carbon emission reduction regulation; capacity design

The relatively poor power quality, low capacity utilization and high electricity costs in the traction power supply systems of the existing electrified railways become the main pain points for the railway industry. Meanwhile, the demand for virtual power plants by the utility grid is growing. However, the electrified railways not only have a large scale but also closely overlap with the grid in spatial distribution, but they fail to form a good complement to the power system.

This paper proposes a railway virtual power plant concept based on the flexible interconnection technology for different phases in a traction power supply system, a carbon emission reduction regulation strategy, and a capacity design approach for the railway virtual power plant that considers the optimal economic benefits. A railway virtual power plant includes a friendly railway system, an information network system and a resource aggregation and trading system. The friendly railway system and the resource aggregation and trading system jointly achieve the information flow interaction with the bulk power system and the power (carbon) market through the information network system. The resource aggregation and trading system aggregates distributed power resources (trains, renewable energy sources, energy storage systems and so on) within the friendly railway system, coordinates the active participation of the railway traction power supply system in power or carbon market transactions, and ensures the friendly interaction between the electrified railway and the bulk power system. The primary structure is shown in Fig. 1.

To achieve better carbon emission reduction effects through the regulation of electrified railway, railway virtual power plant optimizes the net load of the traction power supply system in the 3-phase grid, and the decrement of active power demands may further lead to a decrease in overall network losses within the utility grid, equivalently reducing the carbon emissions from traditional power plants. The process of carbon emission reduction brought by railway virtual power plant is depicted in Fig. 2.

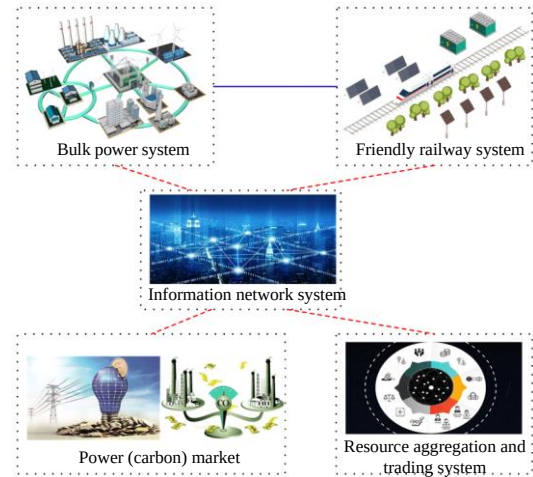


Fig. 1 Primary structure of railway VPP

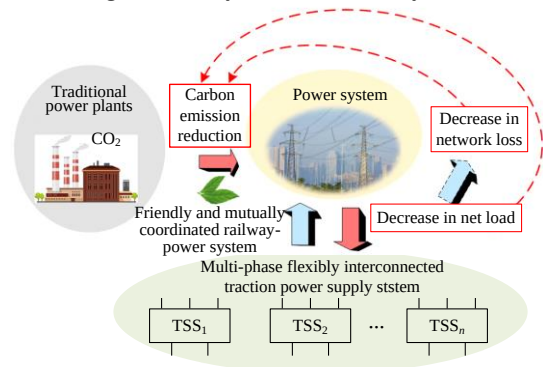


Fig. 2 Carbon emission reduction brought by railway virtual power plant

The capacity design objective function of the railway virtual power plant participating in the carbon market is

$$\min F = (C_{\text{INS}} + C_{\text{MAI}}) / (R_E + R_{\text{CER}}) \quad (1)$$

where, C_{INS} and C_{MAI} are the total installation cost and the operation and maintenance costs during the project life cycle of the new facilities, respectively; R_E is the saved electricity cost; R_{CER} is the revenue from the carbon emission reduction subsidies; F is the capacity configuration performance.

Compared to the traditional scheme, the results show that the proposed method can significantly reduce the electricity cost paid by the railway and bring appreciable carbon market subsidies and satisfactory power qualities at the point of common coupling.

Intelligent Design of Power Electronics: Technical Roadmap Overview and Frontier Exploration

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KEY WORDS: power electronics; artificial intelligence (AI); deep supervised learning; deep reinforcement learning; large language models; intelligent agents in power electronics

Power electronics (PE) technology has been widely applied in various fields. As PE designs involve a lot of knowledge and design constraints, satisfactory PE designs and products require a lot of time, money and effort. Given the rapid development of artificial intelligence (AI) technology, combining AI with PE design to achieve “Intelligent Design of PE” becomes a topic of great concern in both the academic and industrial fields.

This paper provides a comprehensive review of the intelligent design of PE. The analyses cover multiple perspectives such as time, technology, and development trends:

1) The application of traditional AI in PE design is reviewed, and its strengths and weaknesses are analyzed;

2) The application of deep supervised learning (DSL) in PE design is discussed, and the main limitation to its application in PE design is pointed out;

3) The integration methods of deep reinforcement learning (DRL) with PE design are analyzed, and several design cases are analyzed and discussed;

4) The feasibility of combining large language models (LLM) with PE design is proposed, and several cutting-edge exploration examples are given to demonstrate the “PE Agent” concept, and the challenges and solutions are also presented;

5) Finally, the combination methods of AI design tools and traditional design tools are summarized.

Based on the discussions, a development roadmap for intelligent design of PE is formed, as Fig. 1 shows:

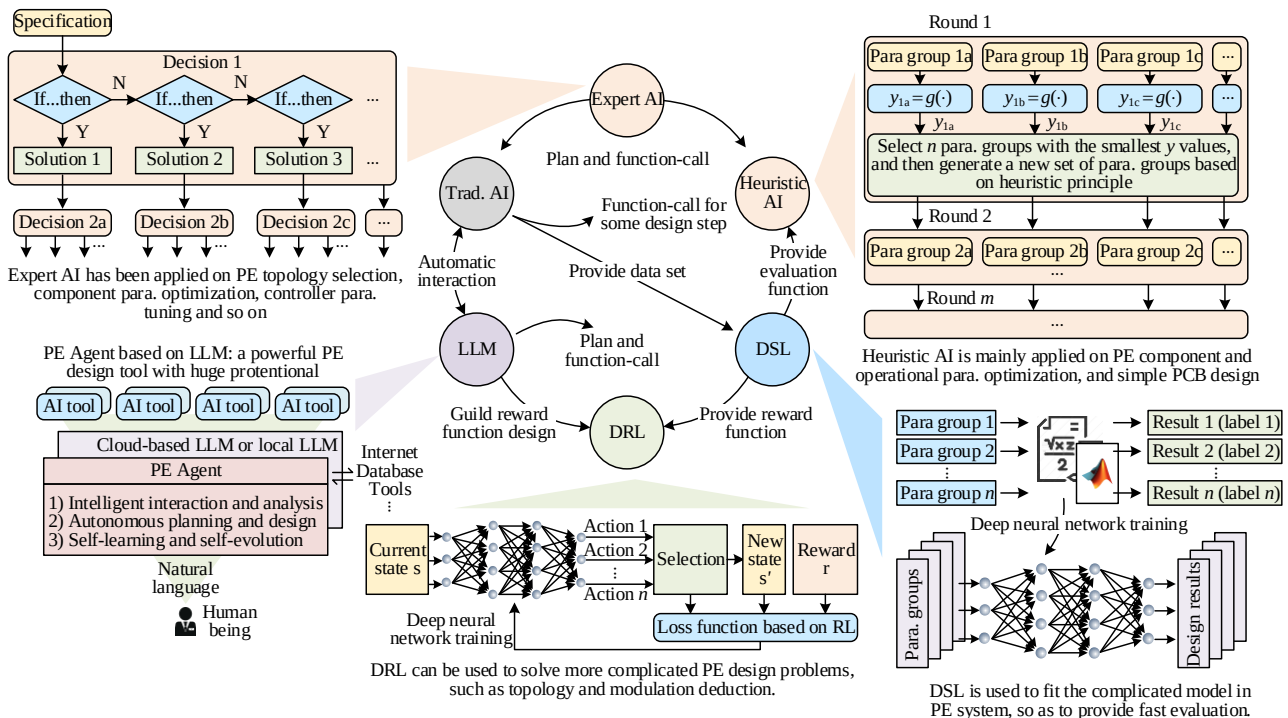


Fig. 1 Technical Roadmap Overview and Frontier Exploration of Intelligent Design of PE

1) Traditional AI, DSL and DRL provide different approaches to solving specific design tasks in PE, and relevant research findings are being enriched.

2) Intelligent agents based on LLM will play a key role in the next stage of intelligent design of PE. It will not only achieve comprehensive intelligence in the

entire design process, but also realize “self-learning” and “self-evolution” through design.

3) By fully integrating traditional design tools with AI design tools, more innovations in methods and tools can be provided, further expanding the connotation of intelligent design.

Improved Synchronized SVPWM Strategy for High-power Three-level ANPC Traction Inverter

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KEY WORDS: high power; three-level active neutral point clamped inverter (3L-ANPC); low carrier ratio (C_r); synchronized space vector pulse width modulation (SVPWM); spectral analysis; smooth switching

In optimizing the harmonic performance of the output voltage, synchronized space vector pulse width modulation (SVPWM) can be adopted in the low carrier ratio condition of a high power traction inverter. Under the integer multiple carrier ratio of three, to achieve synchronization, phase voltage symmetry, and avoid two-level jump (TLJ), this paper proposes sector division methods and sampling point setting methods, as shown in Fig. 1 and Fig. 2, respectively. Based on this, any pulse number in the half-period can be realized, and it can be shifted to the single-pulse overmodulation region.

□ N-type small vector starting region □ P-type small vector starting region

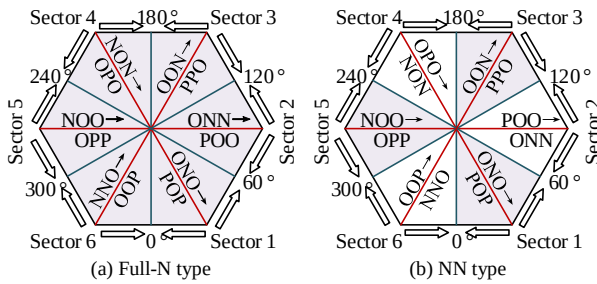


Fig. 1 Synchronized modulation sector division method under an odd and even multiple C_r of three

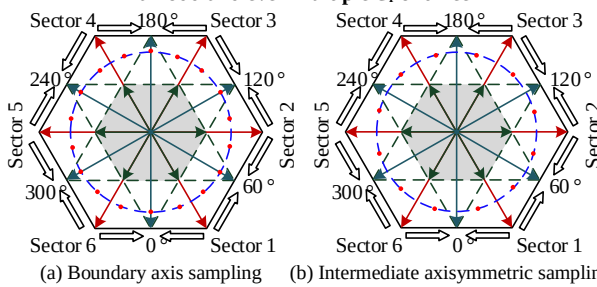


Fig. 2 Setting method for QWS sampling points when $C_r=9$ and 6

To analyze the harmonic characteristics of the proposed ISSVM, based on the double Fourier transform, this paper proposes a phase voltage spectrum analysis method for the 3L converter under SVPWM. The relationship between phase voltage symmetry and harmonics can be fundamentally proven. When SVM_Cr12_1 is used, the baseband harmonic expression is (1).

$$A_{0n} + jB_{0n} |_{n \geq 1} = \{jMu_{dc} / [4\pi(n^2 - 1)]\} [2 - 4\sqrt{3} \cdot \cos(n\pi/6)] [\sin(n\pi/6) - \sin(n\pi/2) + \sin(5n\pi/6)] \quad (1)$$

For the switching between two ISSVMs with the same C_r and two different C_r , the execution of the switch

sequence and the variation of the triangular carrier after switching are analyzed, as shown in Fig. 3. For the proposed ISSVM, smooth switching without TLJ and obvious current fluctuation can be achieved by phase compensation and switching in a specific angle region.

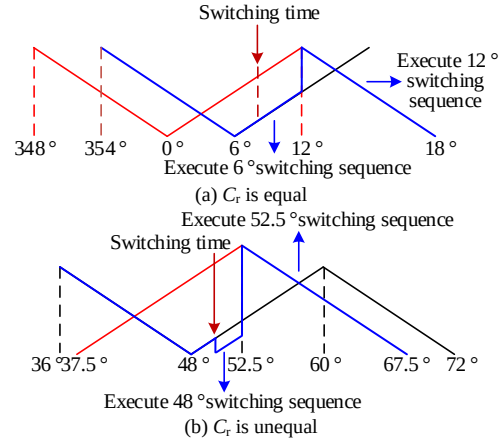
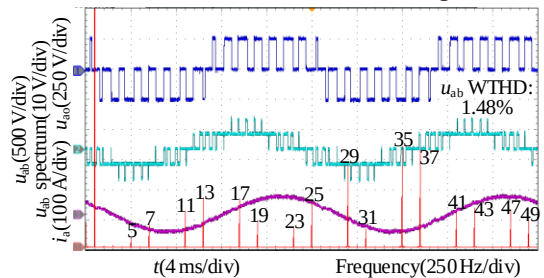
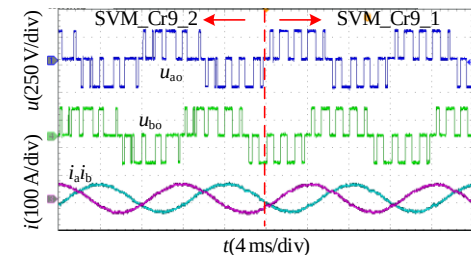


Fig. 3 The execution of the switch sequence and the variation of the triangular carrier after switching

The experimental results show that the proposed synchronized SVPWM strategy can satisfy the TPS, HWS, and QWS. Smooth switching between the two modulation strategies without TLJ and obvious current fluctuation can be realized, as shown in Fig. 4.



(a) SVM_Cr12_1 phase voltage, line voltage, and FFT results



(b) Switching from SVM_Cr9_2 to SVM_Cr9_1 phase voltage and current

Fig. 4 Experimental results

Dual-load Three-level Rectifier Power Decoupling Control and Capacitance-voltage Fluctuation Suppression

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KEY WORDS: dual-load rectifier; zero-sequence voltage injection; the relationship of power distribution; power decoupling; suppression for capacitor-voltage-fluctuation

In recent years, Three-level neutral point clamped rectifier has been widely used in various fields. With the rise of the Photovoltaic-storage-charge-triad Micro-Grid system, the independent and stable control of the voltage of the upper and lower DC sides as well as the power of the upper and lower loads of the three-level rectifier has become more and more critical.

This paper proposes a general control method for dual-load T-type three-level rectifier is proposed. Firstly, based on the CBPWM modulation method, the relationship between DC zero-sequence voltage injection and power distribution of the upper and lower DC sides of the dual-load T-type three-level rectifier is analyzed, and the power decoupling control method is given. Secondly, this paper analyzes and plots the limits of the average-power-ratios of the upper and lower DC sides under different modulation regimes, and calculates the instantaneous component of the zero-sequence voltage according to the control target of constant instantaneous

power of the upper and lower DC sides to suppress the voltage fluctuation of the capacitance on the DC side.

The most crucial process in this paper is to solve the following two modulation-voltages $u_{Z,dc}$ and $u_{Z,ac}$. When $k_{Z,dc} \in [-0.6, 0.6]$, it has high linearity with k_{up} , and $u_{Z,dc}$ can be determined by fitting the following formula:

$$u_{Z,dc} = (k_{up} - 0.5)U_m / 0.6 \quad (1)$$

The $u_{Z,ac}$ can be calculated by the following formula:

$$u_{Z,ac} = \begin{cases} \bar{P}_{up} / i_{MAX}^* - u_{MAX} - u_{Z,dc} \\ \bar{P}_{low} / i_{MIN}^* - u_{MIN} - u_{Z,dc} \end{cases} \quad (2)$$

where $u_{Z,dc}$ is the DC zero-sequence voltage, $u_{Z,ac}$ is the zero-sequence voltage instantaneous component, k_{up} is the power distribution coefficient of the upper load, $\bar{P}$ is the average power of each load, i is the current of the grid, u is the output voltage of the IGBT. The specific control and implementation method is shown in Fig. 1.

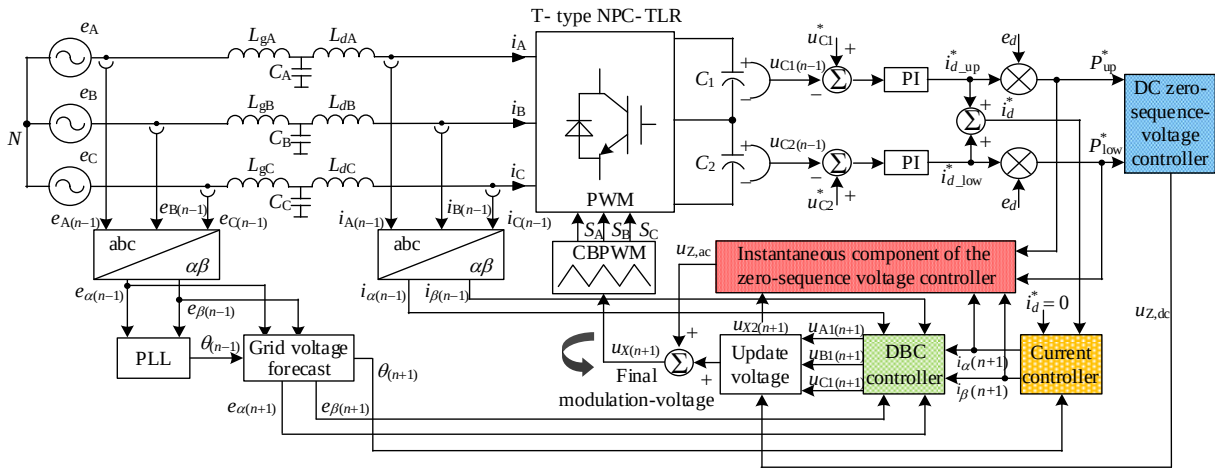


Fig. 1 Control block diagram of Dual-load T-type three-level-rectifier

Compared to traditional method, the proposed method is based on the injection of zero-sequence voltage which simplifies the complicated calculation caused by the synthesis of voltage vectors in the case of asymmetric operation of the upper and lower DC sides. It can deal with the two operational conditions of the

voltage asymmetry as well as the power asymmetry of the upper and lower load, and can effectively suppress the DC capacitor voltage fluctuation. In addition, the feasibility and effectiveness of the proposed method are verified by steady-state and dynamic experiments in this paper.

Zero-sequence Current Suppression Method for Twelve-phase Open-winding Induction Motor

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2. National Key Laboratory for Electromagnetic Energy (Naval University of Engineering))

KEY WORDS: twelve-phase induction motor; open winding; polyphase park transform; zero sequence current; closed-loop control; quasi-proportional resonant

The twelve-phase open-winding motor system has the advantages of good redundancy and small torque ripple. It is the first choice for large-capacity propulsion of ships. However, the open-winding motor system has the problem that the zero-sequence current is difficult to suppress. The research object of this paper is a twelve-phase diode-clamped three-level inverter driving a twelve-phase open-winding induction motor, as shown in Fig. 1.

Considering that the zero-sequence current of four channels is the alternating current of $\pi/4$ phase difference, this paper introduces the generalized Park transformation of multiphase AC system to realize the closed-loop control

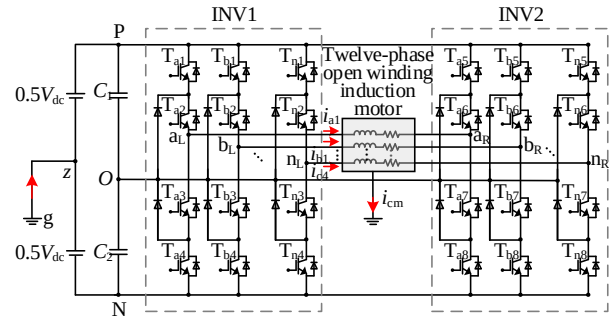


Fig. 1 The main circuit of twelve-phase open-winding induction motor and its matching H-bridge inverter

of zero-sequence current. The eight-phase Park transformation matrix, as shown in formula (1).

$$C(\theta)_8 = \frac{1}{2} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{\pi}{4}) & \cos(\theta - \frac{\pi}{2}) & \cos(\theta - \frac{3\pi}{4}) & \cos(\theta - \pi) & \cos(\theta - \frac{5\pi}{4}) & \cos(\theta - \frac{3\pi}{2}) & \cos(\theta - \frac{7\pi}{4}) \\ -\sin \theta & -\sin(\theta - \frac{\pi}{4}) & -\sin(\theta - \frac{\pi}{2}) & -\sin(\theta - \frac{3\pi}{4}) & -\sin(\theta - \pi) & -\sin(\theta - \frac{5\pi}{4}) & -\sin(\theta - \frac{3\pi}{2}) & -\sin(\theta - \frac{7\pi}{4}) \\ \cos \theta & \cos(\theta - \frac{\pi}{2}) & \cos(\theta - \pi) & \cos(\theta - \frac{3\pi}{2}) & \cos \theta & \cos(\theta - \frac{\pi}{2}) & \cos(\theta - \pi) & \cos(\theta - \frac{3\pi}{2}) \\ -\sin \theta & -\sin(\theta - \frac{\pi}{2}) & -\sin(\theta - \pi) & -\sin(\theta - \frac{3\pi}{2}) & -\sin \theta & -\sin(\theta - \frac{\pi}{2}) & -\sin(\theta - \pi) & -\sin(\theta - \frac{3\pi}{2}) \\ \cos \theta & \cos(\theta - \frac{3\pi}{4}) & \cos(\theta - \frac{3\pi}{2}) & \cos(\theta - \frac{\pi}{4}) & \cos(\theta - \pi) & \cos(\theta - \frac{7\pi}{4}) & \cos(\theta - \frac{\pi}{2}) & \cos(\theta - \frac{5\pi}{4}) \\ -\sin \theta & -\sin(\theta - \frac{3\pi}{4}) & -\sin(\theta - \frac{3\pi}{2}) & -\sin(\theta - \frac{\pi}{4}) & -\sin(\theta - \pi) & -\sin(\theta - \frac{7\pi}{4}) & -\sin(\theta - \frac{\pi}{2}) & -\sin(\theta - \frac{5\pi}{4}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \quad (1)$$

After the zero-sequence current is transformed by the eight-phase Park transform, the PI regulator is used for control, and the output of the inverse transform is added to the twelve-phase modulation wave to achieve zero-sequence current suppression.

The results show that the proposed algorithm can effectively suppress the zero-sequence current in the full speed range, as shown in Fig. 2.

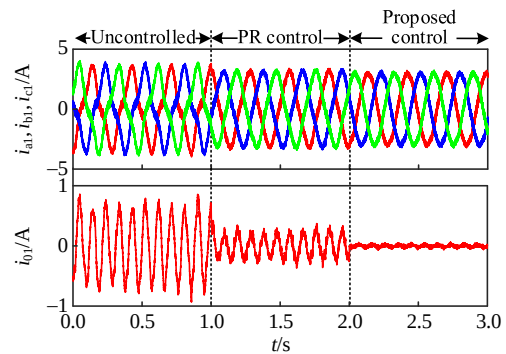


Fig. 2 Simulation comparison of zero sequence current suppression effect at steady state speed of 35 r/min

Energy Flow Analysis of Electromagnetic Coupler in Underwater WPT System Based on Poynting Vector

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KEY WORDS: wireless power transfer (WPT); strip-shaped; magnetic core; power transfer; Poynting vector

Wireless power transfer technology is now widely used in underwater equipment and other fields due to its non-contact charging process and reliability. The underwater electromagnetic coupler (UEC) is a key component of wireless power transfer systems.

The study of energy transfer mechanisms of UEC is crucial for enhancing the transmission performance of WPT systems. In order to study the energy distribution mechanism and transmission characteristics of UEC, this paper analyzes the magnetic flux density, electric field and power distribution of UEC with cylindrical and different numbers of banner-type secondary cores, and uses Poynting vector to study the active power and reactive power distribution characteristics of PLA material area.

Firstly, the structure of the UEC with banner-type on the secondary side is described, as shown in Fig. 1.

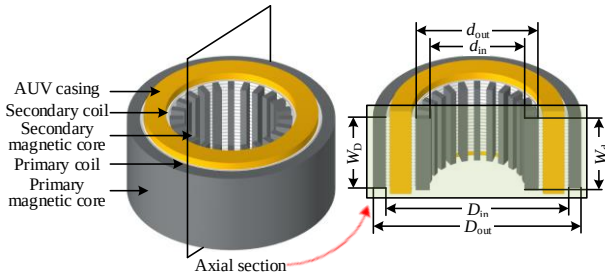


Fig. 1 UEC structure with banner-type secondary core

Based on Poynting vector, the energy calculation formula of UEC internal space is derived. The real and imaginary parts of Poynting vector $\dot{\mathbf{S}}$ are expressed as :

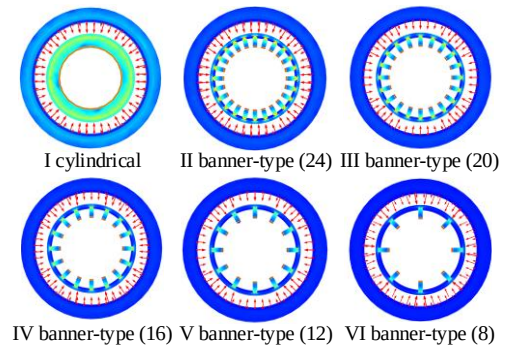
$$\mathbf{S}_{av} = \text{Re}(\dot{\mathbf{S}}) = \omega I_1 I_2 [(K_{\phi 1} T_{z2} - K_{\phi 2} T_{z1}) \mathbf{e}_{\rho} + (K_{\phi 2} T_{\rho 1} - K_{\phi 1} T_{\rho 2}) \mathbf{e}_z] \quad (1)$$

$$\mathbf{S}_{im} = \text{Im}(\dot{\mathbf{S}}) = \omega [- (I_1^2 K_{\phi 1} T_{z1} + I_2^2 K_{\phi 2} T_{z2}) \mathbf{e}_{\rho} + (I_1^2 K_{\phi 1} T_{\rho 1} + I_2^2 K_{\phi 2} T_{\rho 2}) \mathbf{e}_z] \quad (2)$$

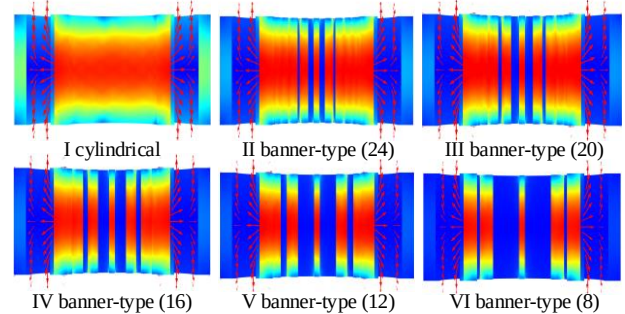
In the formula, $\mathbf{S}_{av,\rho}$ ($\mathbf{S}_{im,\rho}$) and $\mathbf{S}_{av,z}$ ($\mathbf{S}_{im,z}$) are the effective values of ρ and z components of active and reactive power density respectively.

Secondly, the electromagnetic field and energy distribution characteristics of the cylindrical and banner-type structure are compared by simulation, and the influence of the number of strips on the active and

reactive power distribution of the system is analyzed. In particular, the spatial distribution characteristics of active and reactive power are quantitatively analyzed for the primary and secondary coil regions. As shown in Fig. 2.



(a) Body arrow distribution of active power



(b) Reactive power body arrow distribution

Fig. 2 UEC power direction distribution

Finally, analysis of simulation and experimental results indicate that as the number of secondary side banners increases to a certain threshold, the growth rate of power reception in the vicinity of the secondary side gradually slows down. Although adopting a banner-type structure for the secondary side incurs a slight energy loss compared to a cylindrical structure, it significantly reduces the UEC's own weight and cost. The output power and receiving power of the UEC with 24 stripe cores have been restored to more than 96 % of the cylindrical power, and its own weight has been reduced by nearly 500g. Therefore, the analysis method described in this paper can provide some reference for the structural optimization of UEC, and has certain engineering value.

Molecule Structure Design of Novel Polymer Dielectrics for Film Capacitors Under High Temperature and Electric Field

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KEY WORDS: dielectric; polymer; molecular structure; capacitor; high electric field; high temperature

The core of film capacitors lies in polymer dielectrics, which have become the preferred choice in essential fields such as flexible DC transmission, electric vehicles, and electromagnetic power equipment. High-performance dielectric film materials capable of withstanding harsh electrothermal coupling conditions are critical to advancing film capacitor performance. Current commercial polymer film materials, however, fail to adequately meet the requirements for operation under both high temperatures and strong electric fields. This paper presents a novel research approach for polymer dielectric materials based on targeted molecular structure design. The approach begins by establishing the desired material performance metrics according to specific application needs. Subsequently, structure-property relationships are derived through extensive experimental testing, simulations, and mechanistic analysis of various typical polymers. From this, essential design metrics and structural features for polymers capable of enduring both high temperatures and strong electric fields are identified. Through computational screening and predictive methods, several promising molecular structures are selected, which are then validated through synthesis and testing.

Using this approach illustrated in Fig. 1, this paper develops a new series of poly-norbornene film materials exhibiting excellent performance under demanding electrothermal coupling conditions ($>150\text{ }^{\circ}\text{C}$, $>700\text{ MV/m}$). Additionally, energy storage density is further improved by incorporating functional groups into the main and side chains. This methodology provides a quantitative and reliable foundation for designing new materials, significantly reducing the time and resources required by traditional trial-and-error experimentation. Consequently, this approach enhances the efficiency of material development, presenting a new paradigm for dielectric material research under multi-objective

constraints by shifting from conventional trial-validation models to a structured, molecular design-based strategy.

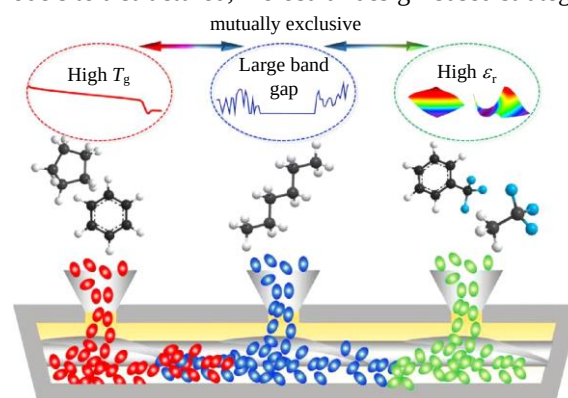


Fig. 1 Method of the design of film capacitor dielectric molecular structure (POFNB) and new materials

Given the wide variety of polymers, this paper adopts a data-driven approach to explore structure-property relationships, which requires converting structural and performance data into machine-readable formats by encoding these properties into numerical fingerprint vectors. Machine learning is then employed to model the relationship between structure and performance, enabling predictions for the properties of novel molecular structures not present in the database. The targeted properties include a high relative dielectric constant (≥ 3 at 100 Hz, room temperature), high glass transition temperature ($\geq 450\text{ K}$), wide bandgap ($\geq 4\text{ eV}$), high electron injection barrier ($\geq 2.5\text{ eV}$), and low cohesive energy ($\leq 130\text{ cal/cm}^3$). Analysis reveal that polymers suited for high-temperature and high-electric-field environments should incorporate precisely engineered benzene rings, saturated ring structures, and polar functional groups. Based on these insights, this paper designs a new molecular structure, polyoxafluoronorbornene (POFNB), which demonstrates a larger bandgap and higher glass transition temperature compared to commercial polymers, thus offering notable performance advantages.

Power Frequency Breakdown Characteristics of $\text{CF}_3\text{SO}_2\text{F}$ Ternary Mixed Gas

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KEY WORDS: SF_6 alternative gas; replacement at equal pressure; $\text{CF}_3\text{SO}_2\text{F}$ ternary gas mixture; discharge characteristics; liquefaction temperature

It is of great significance to find a mixed insulating gas configuration scheme that can be used in low temperature environment and replace SF_6 with equal pressure to replace SF_6 in existing equipment. $\text{CF}_3\text{SO}_2\text{F}$ gas is superior in liquefaction temperature, insulation strength, GWP, gas toxicity and stability characteristics, and its gas mixture is a potential isobaric alternative to SF_6 gas.

In this paper, the proportional constraints of $\text{CF}_3\text{SO}_2\text{F}$ and $\text{C}_4\text{F}_7\text{N}$ in $\text{CF}_3\text{SO}_2\text{F}/\text{C}_4\text{F}_7\text{N}/\text{N}_2$ (CO_2) ternary gas mixture are calculated according to the minimum operating temperature requirement, and a specific proportion of $\text{CF}_3\text{SO}_2\text{F}/\text{C}_4\text{F}_7\text{N}/\text{N}_2$ (CO_2) ternary gas mixture is used for power frequency breakdown test. The effects of mixing ratio and air pressure on the power frequency insulation strength of $\text{CF}_3\text{SO}_2\text{F}$ ternary gas mixture are studied. Then, the power frequency breakdown test of 20% $\text{CF}_3\text{SO}_2\text{F}/10\%\text{C}_4\text{F}_7\text{N}/70\%\text{N}_2$ is carried out at different temperatures, and the influence of temperature on the power frequency insulation strength of $\text{CF}_3\text{SO}_2\text{F}$ ternary gas mixture is studied. The gas composition is analyzed and GWP value of ternary gas mixture is calculated. The feasibility that $\text{CF}_3\text{SO}_2\text{F}/\text{C}_4\text{F}_7\text{N}/\text{N}_2$ (CO_2) ternary gas mixture can be used in low temperature environment and can replace SF_6 gas by isobaric is analyzed based on insulation, liquefaction temperature, decomposition and environmental protection characteristics.

The power frequency breakdown voltage of $\text{CF}_3\text{SO}_2\text{F}/\text{C}_4\text{F}_7\text{N}/\text{N}_2$ ternary gas mixture at room temperature and low temperature is shown in Fig. 1.

Under the conditions of 0.3~0.5MPa absolute pressure, the power frequency insulation strength of 20% $\text{CF}_3\text{SO}_2\text{F}/10\%\text{C}_4\text{F}_7\text{N}/70\%\text{N}_2$ ternary gas mixture is stronger than that of SF_6 gas under constant pressure. At 0.5MPa, the liquefaction temperature can reach -20°C , which can meet most application environments. The decomposition gas after 70 power frequency

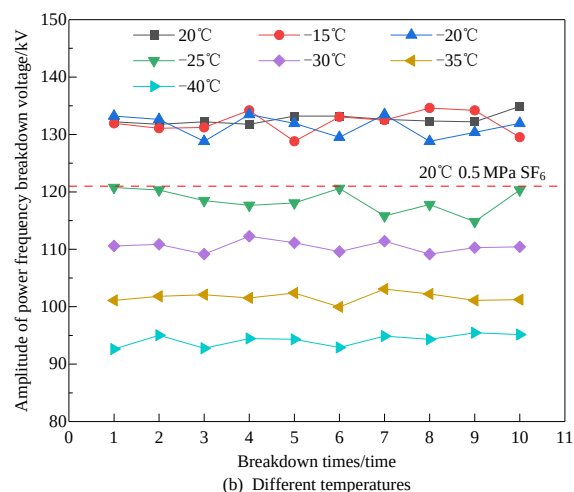
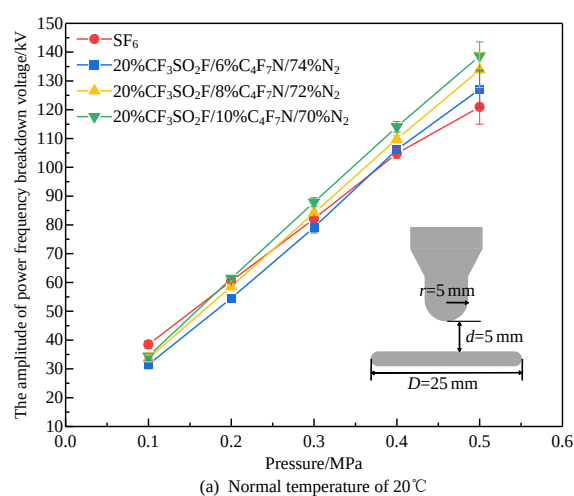


Fig. 1 Power frequency breakdown characteristics of $\text{CF}_3\text{SO}_2\text{F}/\text{C}_4\text{F}_7\text{N}/\text{N}_2$

breakdown is mainly CF_4 , with a small content of 47 $\mu\text{L}/\text{L}$, and no other decomposition gas is detected. Its GWP value is 1209, which is only 5.0% of SF_6 gas. The 0.5MPa 20% $\text{CF}_3\text{SO}_2\text{F}/10\%\text{C}_4\text{F}_7\text{N}/70\%\text{N}_2$ mixture is expected to be an alternative isobaric configuration scheme for SF_6 gas at 0.5MPa. The research on gas composition selection and proportion configuration of ternary gas mixture is a possible research direction to realize isobaric replacement of SF_6 gas in addition to finding new environmentally friendly insulating gases.

Fixed-point Time Step Finite Element Method Considering Hysteresis and Study of Excitation Characteristics of Composite Core

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KEY WORDS: fixed-point method; time step finite element method; J-A hysteresis model; field-circuit coupling model; composite core

Time domain finite element method is widely used to analyze the excitation characteristics of transformer core. Considering the hysteresis effect of the core in the field coupling calculation is of great significance for the accurate analysis of the excitation characteristics and the improvement of the calculation accuracy. The research focus of this problem is which hysteresis model to choose and which method to deal with the nonlinear iterative problem in the magnetic field.

This paper presents a method to deal with the nonlinear iteration cannot converge caused by inappropriate selection of permeability in the time-step finite element method considering hysteresis. In this method, the convergence factor is dynamically adjusted at each time step by setting the threshold. Firstly, the two-dimensional magnetic field finite element equation of magnetic vector potential and excitation current is established using the fixed-point method, and the fixed-point permeability is introduced to address the nonlinear issue. Secondly, the field-circuit coupling relationship is established based on the electromagnetic induction law, and the Jiles-Atherton hysteresis model is utilized to characterize the core's hysteresis characteristics, thus a field-circuit coupling model considering hysteresis is formed. Then, the threshold is introduced to solve the convergence difficulties in the nonlinear iterative process. Finally, the proposed method is used to solve for the excitation current, magnetic flux density distribution, and no-load loss of the amorphous alloy and oriented silicon steel composite core in order to verify its effectiveness.

The complete fixed-point finite element time-step iteration format is

$$\begin{bmatrix} \mathbf{K} & \mathbf{P} \\ \frac{\mathbf{C}_w}{\Delta t} & \mathbf{K}_R + \frac{\mathbf{K}_L}{\Delta t} \end{bmatrix} \begin{bmatrix} \mathbf{A}(t_k) \\ \mathbf{I}(t_k) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\frac{\mathbf{C}_w}{\Delta t} & -\frac{\mathbf{K}_L}{\Delta t} \end{bmatrix} \begin{bmatrix} \mathbf{A}(t_{k-1}) \\ \mathbf{I}(t_{k-1}) \end{bmatrix} = \begin{bmatrix} \mathbf{M}(t_k) \\ \mathbf{U}(t_k) \end{bmatrix} \quad (1)$$

The algorithm flow chart is shown in Fig. 1.

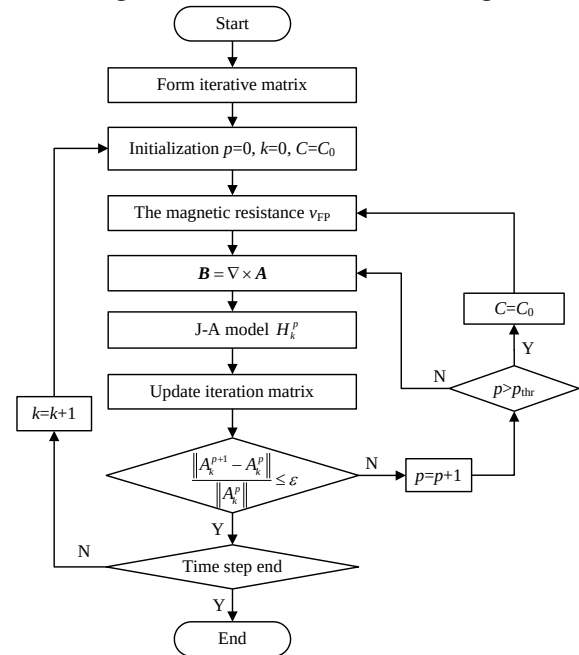


Fig. 1 Program flow chart

This paper solves the excitation current of amorphous alloy-oriented silicon steel composite core under different excitation voltages. And it analyzes the distribution of magnetic flux density and no-load loss of composite core. Compared with the global coefficient method and the local coefficient method, the average relative error of each excitation voltage and the relative error of no-load loss calculated by this method are smaller than the other two methods, which verifies the effectiveness of this method.

Research on Damaging Mechanisms of Insulation Shield Induced by Buffer Layer Ablation in High-voltage Cables

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KEY WORDS: buffer layer ablation; insulation shield; current heating effect; electrochemical corrosion; finite element simulation

In recent years, the breakdown accidents of cable body caused by the ablation of water-blocking buffer layer frequently occur in major cities, and there are still a large number of cables in service with latent buffer layer ablation defects. Existing studies mainly focus on the ablative damage process of buffer layer itself, and the mechanism of how buffer layer ablative further develops inward and causes damage of cable insulation shield is still unclear. Therefore, it is urgent to carry out relevant studies to improve the understanding of buffer layer ablative damage to cable deterioration.

This paper conducts a three-dimensional finite element simulation of high voltage cable to analyze the damage mechanism caused by white powder on the insulation shield. The simulation results indicate that extensive coverage of high-resistance white powder generated by electrochemical corrosion along the cable axis leads to significant concentration of current density at the edge of the white powder and a subsequent rise in temperature, as shown in Fig. 1. When the current density at the buffer layer surface reaches 185 A/m^2 , the temperature rises to 204°C , exceeding both the thermal decomposition temperature of the buffer layer and melting temperature of the insulation shield layer (90.5°C). Consequently, under elevated temperatures and pressure, penetration and embedding of white powder into the insulation shield surface occur, resulting in damage to this layer.

The damage process of insulation shield caused by white powder during ablative process is analyzed and reproduced through the simulation test of the damage process of insulation shield in laboratory and the ablation

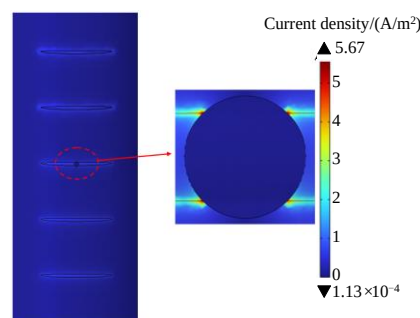


Fig. 1 Current density distribution of the buffer layer when white powder covers the surface of buffer layer

simulation test of the temperature measurement at both sides of the actual ablative cable.

The temperature at the trough of the aluminum sheath on the white powder side of the actual cable increases gradually with the increase of pressure time, the temperature distribution of the middle ring area is low, and the surrounding temperature is high, which proves the rationality of the simulation analysis of the white powder damage insulation shield layer.

The simulation results correspond well with the simulation test of the damage process of the insulation shield in the laboratory and the actual ablative fault cable disintegration, which verifies the rationality of the analysis results in this paper, as shown in Fig. 2. The research results in this paper are of great significance for revealing the development mechanism of the ablative defects of the buffer layer.

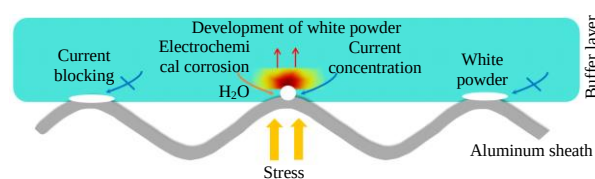


Fig. 2 Development mechanism of white powder through buffer layer