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Loss Assessment and Vulnerability Analysis of an Integrated Electricity Natural Gas System Under Load Redistribution Attack

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KEY WORDS: integrated electricity natural gas system; bilateral coordinated LR attack; node vulnerability transfer; cascading failure

Load redistribution (LR) attacks are common false data injection attacks in cyber-physical power systems. Under the background of close coupling between a natural gas network and a power system, the LR attack on the integrated electricity natural gas system (IEGS) may have a more serious impact on the safe operation of the system.

Based on the analysis of the mechanism of bilateral coordinated LR attack under IEGS, the implementation strategy of LR attack was studied. Considering the impact of cascading failures on the power system and taking the maximum economic loss of the IEGS as the objective function, the loss assessment model of LR attacks under IEGS was established. A new node comprehensive vulnerability evaluation index was defined, and the high vulnerability nodes in the IEGS were assessed comprehensively. The proposed loss assessment model can effectively determine the economic loss of the IEGS under cyber attack, which can provide corresponding ideas for the protection strategy on IEGS.

Under the premise that IEGS bad data detection is avoided by the LR attack and the IEGS system scheduling strategy is known, the attacker implements the attack with the maximum economic loss of the IEGS as the target. The objective function is shown in (1).

$$\max\left(\sum_{i=1}^{N_G} c_1 P_{G,1,i} + \sum_{j=1}^{N_{\rm LD}} c_2 L^*_{{\rm elec},1,j} + \sum_{k=1}^{N_{\rm GD}} c_3 L^*_{{\rm gas},k} + \sum_{s}^{N_s}\sum_{j=1}^{N_{\rm LD}} c_2 L^{**}_{{\rm elec},s,j}\right) \tag{1}$$

Where c_1 is the generation cost (in $/MWh) of generator. c_2, c_3 are the load shedding costs (in $/MWh) of power/gas load. $N_{\rm LD}, N_{\rm GD}, N_G$ are the number of loads in power system/natural gas network and the number of generator nodes in power system respectively. s is the stage of power cascading failure. N_S is the number of cascading failures propagated. $P_{G,1,i}$ is the output of generator in stage 1. $L^*_{{\rm elec},1,j}, L^{**}_{{\rm elec},s,j}$ are the load shedding of power load in stage 1/s. $L^*_{{\rm gas},k}$ is the load shedding of gas load. The process of the bilateral LR coordinated attack is shown in Fig. 1.

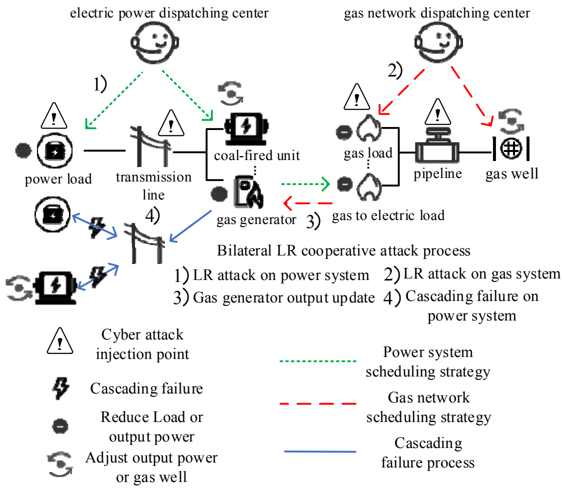

Fig. 1 Mechanism of bilateral coordinated LR attack

Compared to LR attack only on power system, the most serious loss to the IEGS occurs when the attack resources are allocated properly. After providing protection to vulnerable nodes, the ability to resist attacks is improved. High vulnerability nodes of the system will change under different attack resources and attack methods. If only high vulnerability nodes are protected from LR attacks on the power system, the protective effect is not effective. The economic losses of the system with protection strategies are shown in Fig. 2.

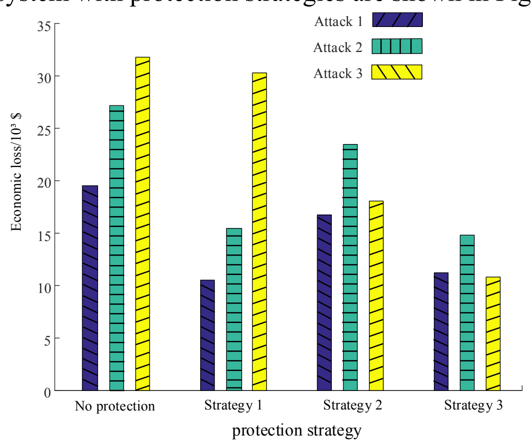

Fig. 2 Effect comparison of three protection strategies

The experimental results showed that the system suffered more serious losses under bilateral coordinated LR attack. However, after adopting the comprehensive protection strategy based on the evaluation and analysis methods proposed in this paper, the system loss is significantly reduced

Design of the Electricity Spot Market Model Based on Renewable Energy Quality Quantification

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KEY WORDS: quality index; quality price; renewable energy market; spot market; market model

The renewable energy power generation is the key in the construction of new power system and the realization of the China's target about "carbon peak and carbon neutral". The establishment of renewable energy power market trading mechanism is an effective way to promote renewable energy development.

This paper proposes a spot market trading model of the electricity market for high proportion of new energy to solve the problem that the traditional market mechanism can't fully reflect the characteristics differences between new energy generation and conventional generation.

Firstly, the new energy power generation attributes are divided into power attributes and load attributes, to adapt to the market trading environment, the differences of settlement between real-time market and day-ahead market caused by new energy is defined as the system balance cost.

$$C_{T^{\mathrm{C}}}^{\mathrm{EX}}=\sum_{i=1}^{N^{\mathrm{I}}}\sum_{t=1}^{T^{\mathrm{C}}}\Big(\max\left\{P_{i,t}^{\mathrm{re}}-P_{i,t}^{\mathrm{pr}},0\right\}\cdot\lambda_t^{\mathrm{re}}+\min\left\{P_{i,t}^{\mathrm{re}},P_{i,t}^{\mathrm{pr}}\right\}\cdot\lambda_t^{\mathrm{pr}}-P_{i,t}^{\mathrm{pr}}\lambda_t^{\mathrm{pr}}\Big) \tag{1}$$

where $C_{T^{\mathrm{C}}}^{\mathrm{EX}}$ is the balance cost of the system in T^{C} period, and $T^{\mathrm{C}}\in\left\{T^{\mathrm{H}},T^{\mathrm{F}},T^{\mathrm{L}}\right\}$, T^{H},T^{F},T^{L} is the high, flat and low period of the system; N^{I} is the total number of units participating in the market, equal to the sum of the number of conventional units N^{G} and the number of new energy units N^{W}; $P_{i,t}^{\mathrm{re}}$ and $P_{i,t}^{\mathrm{pr}}$ are the unit i output at the time t of the day under the hypothetical scenario and the unit output under the day-ahead clearing; λ_t^{re} and λ_t^{pr} are the real-time electricity price and the day-ahead electricity price at the time t under the hypothetical scenario.

Secondly, by analyzing the impact mechanism of new energy attributes on the system balance cost, the accuracy index and correlation index are used to describe new energy attributes. And the new energy power quality index is presented by the improved cross-entropy, using this index and system balance cost to constitute the power quality price of new energy for quantifying the power quality of new energy.

$$K_{w,T^{\mathrm{C}},r}=\frac{\sigma}{S_{w,T^{\mathrm{C}},r}^{\mathrm{ac}}}+\frac{\upsilon}{S_{w,T^{\mathrm{C}},r}^{\mathrm{vd}}} \tag{2}$$

where $K_{w,T^{\mathrm{C}},r}$ is power quality index of new energy unit w winning the bid r times in T^{C} period; $S_{w,T^{\mathrm{C}},r}^{\mathrm{ac}}$ and $S_{w,T^{\mathrm{C}},r}^{\mathrm{vd}}$ are the accuracy index and correlation index of the new energy unit w winning the bid r times in T^{C} period ;σ and υ are the weights of accuracy index and correlation index respectively, $\sigma+\upsilon=1$.

$$\lambda_{w,T^{\mathrm{C}}}=\begin{cases}K_{w,T^{\mathrm{C}},r}C_{T^{\mathrm{C}}}^{\mathrm{EX}} & ,C_{T^{\mathrm{C}}}^{\mathrm{EX}}\le 0;\\ \left(\dfrac{1}{K_{w,T^{\mathrm{C}},r}}\Big/\displaystyle\sum_{w=1}^{N^{\mathrm{W}}}\dfrac{1}{K_{w,T^{\mathrm{C}},r}}\right)C_{T^{\mathrm{C}}}^{\mathrm{EX}} & ,C_{T^{\mathrm{C}}}^{\mathrm{EX}}>0\end{cases} \tag{3}$$

Where $\lambda_{w,T^{\mathrm{C}}}$ is the system balance cost allocated by each new energy w according to its own power quality in T^{C} period.

Finally, the improved U.S. PJM market clearing model is proposed, new energy units and conventional units are cleared together after power quality price is added, a market trading environment with competition on the same platform is established and the incentive-compatible settlement rule is proposed. The market transaction flow diagram is shown in Fig. 1.

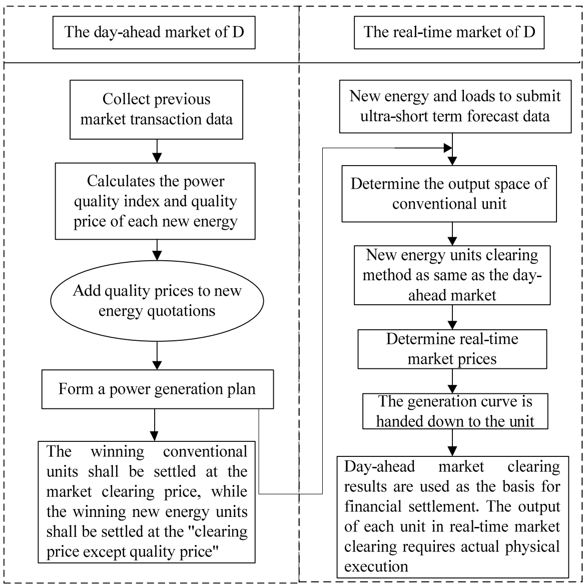

Fig. 1 Clearing flow between new energy and conventional units on the same market

Compared to traditional method, the proposed method is able to reduce amounts of power deviation between day-ahead market and real-time market, and then decrease the system balance cost and the possibility of the strategic bidding. Moreover, The research reflected that high quality new energy is given priority to win the bid, the market average electricity price is reduced, and conventional units can get extral income during the peak load period, which is in favor of quality improvement of new energy and fair competition, provided a reference for the fixed cost recovery of long-term marginal units, guided future capacity investment of conventional units and provided capacity guarantee for the construction of new power system.

Coordination Strategy of Coal-fired Units Decommissioning and Condenser Configuration Considering the Support Capability Constraints of Power Systems

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Key Words: decommissioning of coal-fired units; synchronous condenser; support capability; receiving-end grid; voltage; frequency

The integrated electricity-gas system is one of the most promising approaches to improve the power utilization efficiency and renewable sources accommodation capacity in the future. The optimal dispatching of multi-energy flow is one of the core technologies to realize the efficient operation of integrated energy system.

In order to minimize the impact of coal-fired units (CFUs) retirement and non-synchronous generation installation on the secure and stable operation of receiving-end grids, this paper proposes a coordinated strategy for the retirement of CFUs and configuration of synchronous condensers (SynCons) with considering the grid support capability.

Firstly, the index of DC reactive power support factor was established, the retirement priority order of CFUs in the receiving-end grid was determined by the service life, pollutant discharge, coal consumption, and other general factors. Secondly, the maximum retirement capacity of CFUs was calculated by post-contingency maximum rate-of-change of frequency and frequency nadir constraints. Then, a configuration strategy of SynCons based on the bisection algorithm was proposed to deal with the weakness of voltage support capability caused by the retirement of CFUs, which can achieve the optimal configuration capacity and location of SynCons. Finally, after the configuration strategy of SynCons the maximum retirement capacity of CFUs was updated synchronously, and the decommissioning strategy of CFUs was adjusted, so as to realize the mutual coordination between the decommissioning strategy of CFUs and the configuration strategy of SynCons. The specific process is shown in Fig. 1.

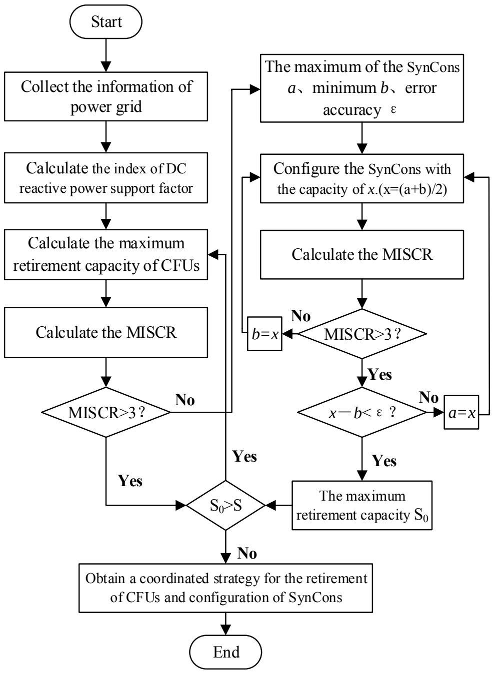

Fig.1 Flow chart of coal power decommissioning and phase-modulating configuration strategy of receiving-end grid

In order to verify the correctness and effectiveness of the strategy proposed in this paper, case studies on a modified IEEE-39 system and the Henan provincial grid were conducted. The calculation results from Tab. 1 of multi-infeed short-circuit ratio (MISCR) shows that the obtained results determined by the proposed strategy can effectively reduce the influence of CFUs retirement on the static voltage stability of the power grids under the same retirement capacity.

Tab.1 MISCR of two decommissioning strategies

name	MISCR	
	Contrast strategy	Proposed strategy
DC1	3.111	3.415
DC2	2.720	2.836

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DC Fault Ride Through Coordinated Control of Wind Power Flexible Direct Grid Connection Based on Decentralized Energy Storage

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KEY WORDS: MMC–MTDC; wind power generation; energy storage system; DC fault ride-through

In order to build a clean energy supply system, the transmission and consumption capacity of high proportion of new energy needs to be improved urgently, and increasing the substitution of electric energy has become the primary task. Multi-terminal flexible DC transmission system based on modular multi-level converter has proved its advantages in wind power grid connection and absorption, island power supply, and improving grid stability, and has become the preferred scheme of DC transmission system, and has broad prospects in offshore wind power grid connection and multi-grid interconnection.

With the improvement of power system voltage level and transmission distance, DC overhead lines have significant economic advantages, but at the same time increase the failure rate. In the flexible direct transmission system, DC fault develops more rapidly and has a greater impact on the power grid. Therefore, improving the DC fault traversal capability of the system has become the focus of current research. In this paper, the topological structure and mathematical model of wind power connected to multi-terminal flexible direct transmission system and energy storage system are established; Based on the analysis of the DC fault characteristics of the multi-terminal flexible and straight system and the power transmission capacity of the non-fault pole converter station, the self-absorption and non-self-absorption cases are determined; Adjust the control mode of the converter station according to the different fault types and power dissipation judged by the reclosing information of the circuit breaker, design the parameters of the pre-installed energy storage equipment scattered in the full-power converter of the wind turbine generator unit, absorb the unbalanced power during the fault, and then propose a complete fault crossing coordination control strategy, effectively reduce the impact range of the fault, and ensure the output of the wind turbine generator unit and the stable operation of the system.

Finally, the effectiveness of the control strategy proposed in this paper is verified by digital simulation. The strategy can keep the system running in parallel during the fault without locking, overload and other problems, and improve the stability of the system. Finally, the above simulation model is built on the PSCAD/EMTDC simulation platform, and the DC fault traversal strategy of the wind farm through the MMC–MTDC grid-connected system is studied in detail. It is verified that the DC fault traversal strategy based on the energy storage system proposed in this paper can maintain the power balance during the fault, realize the rapid recovery of the fault, and realize the DC fault traversal smoothly. The fault traversal strategy proposed in this paper is expected to provide necessary basis and reference for the flexible and direct grid connection of new energy.

Research on "Grid-Source-Storage-Vehicle" Dynamic Threshold Energy Management Strategy Based on Fuzzy Petri Nets

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KEY WORDS: rail transit; energy storage system (ESS); fuzzy Petri nets; dynamic threshold

As one of the main energy users of the electric power system, rail transit consumes a large amount of electricity for electric locomotive traction every year. Therefore, it is of great practical significance to reduce traction energy consumption and improve the resilience and efficiency of the energy supply system to promote carbon peaking and carbon neutrality. The rail transit "grid-source-storage-vehicle" collaborative energy supply system introduces an energy storage system (ESS) and a new energy power generation system on the basis structure of the traditional traction power supply system (TPSS), which is shown in Fig. 1. However, how to reduce the influence of two-way volatility and uncertainty on ESS have become new issues.

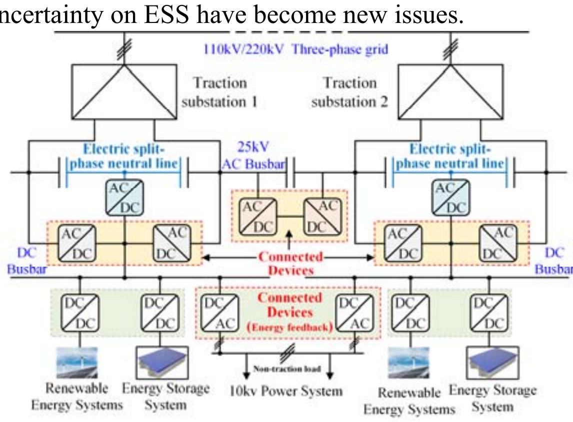

Fig. 1 "Grid-source-storage-vehicle" structure based on power integration architecture

In order to achieve the above these goals, reduce the power impact of the traction load on the traction network, and prolong the service life of the ESS, a dynamic threshold energy management strategy based on the fuzzy Petri networks (FPN) was proposed in this paper, and the structure of that is shown in Fig.2.

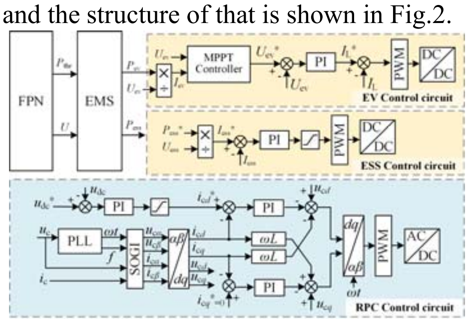

Fig.2 ESS/EV voltage and current double loop control

In this model, the power of electric locomotive and the life of the ESS were set as the input parameters of the FPN. The adaptive dynamic adjustment of the discharge threshold was realized after the operations of fuzzification, Petri networks reasoning, and de-fuzzification. On this basis, adaptive control is implemented.

In this paper, the measured data of a traction substation was used as a test case. The simulation results showed that, compared with other energy management strategies, the energy feedback efficiency and regenerative braking energy storage efficiency could be effectively improved by the strategy based on FPN The power exchange curve is shown in Fig. 3.

At the same time, the utilization of photovoltaic power generation system was increased, and the average energy taken by electric locomotives from the power system and the average discharge depth of the ESS were reduced as well, which could prolong the expected life of the energy storage system and improve the energy utilization of the collaborative energy supply system. The life drop curve is shown in Fig. 4.

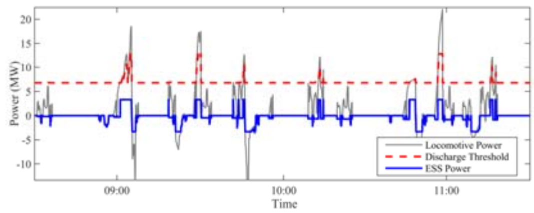

Fig.3 The power exchange curve of ESS

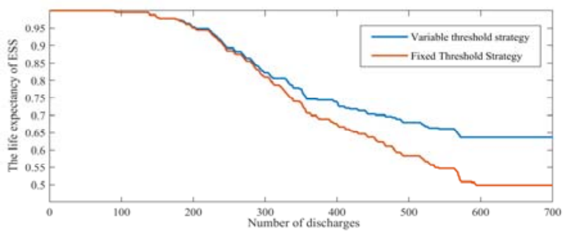

Fig.4 The life drop curve of ESS

To sum up, the strategy based on FPN has positive significance for extending the expected life of the energy storage system and improving the energy utilization efficiency and operating economy of the collaborative energy supply system.

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Circulating Current Suppression Method of Modular Multilevel Converter Based on SOGI Under Unbalanced Grid Conditions

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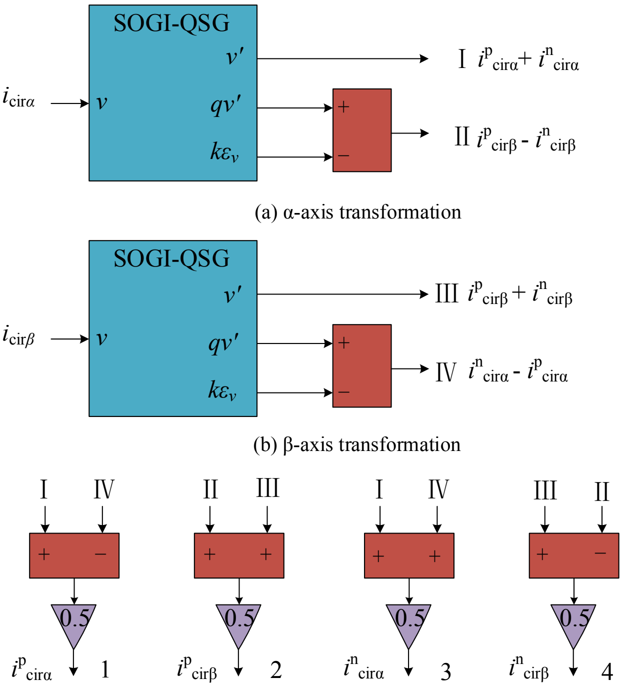
KEY WORDS: unbalanced grid; modular multilevel converter; second order generalized integrator; circulating current suppression strategy

The design and analysis of modular multilevel converter is usually carried out under the condition of power grid balance, but the AC power grid is unbalanced in actual operation. The imbalance of the power grid will cause the DC components of the circulating current of the MMC bridge arm to be no longer equal, including the positive sequence, negative sequence, and zero sequence components of the double frequency, which will increase the system loss and affect the system performance.

In this paper, a circulating current suppression strategy based on second order generalized integrator (SOGI) was proposed under unbalanced power grid. This strategy can suppress the second harmonic component of three-phase circulating current and the unequal DC component separately. Based on SOGI, the proposed strategy uses proportional integral (PI) control to extract the positive sequence and negative sequence second harmonic components of bridge arm circulating current. Meanwhile, quasi proportional resonance (PR) is applied to control the zero sequence second harmonic component of the circulation.

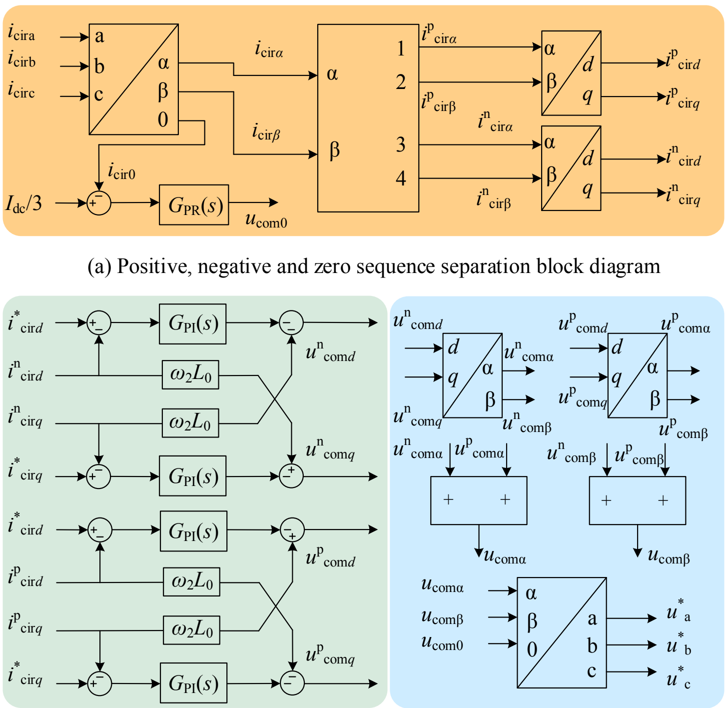


(a) α-axis transformation

(b) β-axis transformation

(c) Positive and negative sequence separation

Fig. 1 Block diagram of positive and negative sequence separation based on SOGI–QSG



(a) Positive, negative and zero sequence separation block diagram

(b) Circulation control block diagram

(c) Modulating voltage generating block diagram

Fig. 2 Circulation suppression strategy control block diagram

In the case of single-phase nonmetallic grounding fault, compared with the other three circulation suppression strategies, the proposed strategy can suppress the double frequency component of the circulation to 0.0006 kA and reduce the harmonic distortion rate to 0.03%, which shows the superiority of the proposed strategy. At the same time, when the two-phase nonmetallic ground fault occurs, the proposed strategy can reduce the frequency double component of the circulation to 0.0039 kA and the harmonic distortion rate to 0.22%. Based on SOGI circulation suppression strategy, avoid using low pass filter and band pass filter, its control principle is clear, the structure is simple, the stability is strong.

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Black Start Method and Coordinated Restoration Strategy of DC Receiving-end Power Grid Based on Hybrid Direct Current

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KEY WORDS: hybrid DC; black start; recovery stages; virtual synchronous; coordinated control

In order to combine the advantages of traditional and flexible HVDC systems, hybrid DC is a new direction of DC transmission technology and plays an important role in the power grid black start.

To clarify the technical conditions and control methods of hybrid DC participating in black start, a black start method based on hybrid DC and a coordinated recovery strategy of the receiving power grid in the case of major power outage for LCC－MMC hybrid DC transmission system is proposed.

According to the characteristics of different recovery stages of black start, firstly, the start-up method of the hybrid DC transmission system when the receiving-end system is completely black in the initial stage is investigated, including the start-up and control methods of the sending LCC converter and the receiving MMC converter.

Then, for the weak AC system at the early stage of black start, the virtual synchronization coordination recovery strategy of hybrid DC is adopted to enhance the system stability. Furthermore, after the system reaches a certain strength, corresponding control strategies and smooth switching methods between different control modes are proposed. The receiving end's recovery coordination control diagram is shown in Fig. 1. The successful realization of the recovery phase is achieved by switching the control strategy at different stages through the control switch.

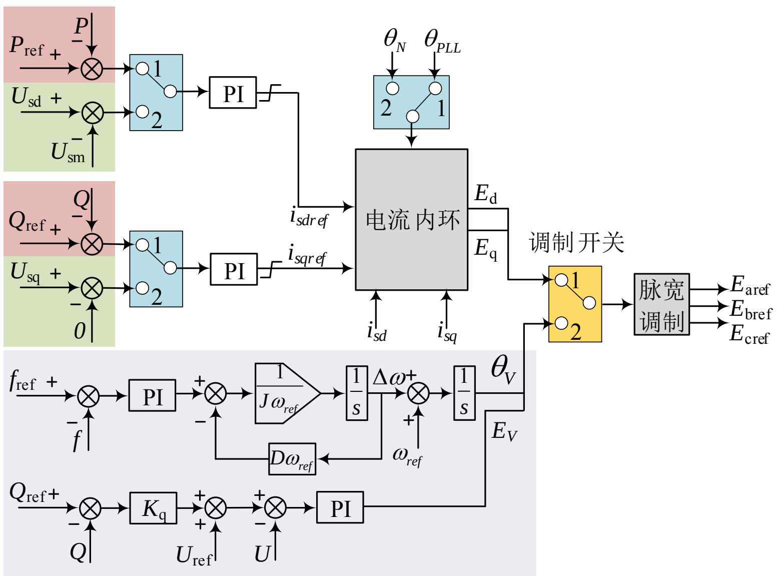

Fig. 1 Receiving end's recovery coordination control diagram

With energy consuming resistor at the initial stage of black start, LCC converter can effectively meet the minimum starting current limit. The MMC converter can establish the AC voltage at the passive end by using passive network control and maintain the system voltage and frequency within a stable range. After the non-black start power unit and load are connected to the grid, the AC system strength changes, the proposed three-stage control switching strategy can effectively achieve smooth transition of each stage, and virtual synchronous control in the weak AC system stage can ensure the system stability in the weak AC system stage, the three-stage control strategy has significant advantages over the two-stage recovery strategy, thus, the effectiveness of the proposed black start method and coordinated recovery strategy are verified.

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Distributionally Robust Expansion Planning of Integrated Gas–electricity Distribution System Considering System Resilience Constraints Under Extreme Disasters

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KEY WORDS: electric vehicle charging station; distributed gas-fired units; energy storage equipment; extreme disaster; resilience; distributionally robust optimization

In recent years, under the background of multi energy complementation and integrated energy systems, the gas–electricity distribution network has been developed rapidly. However, the frequently occurrence of extreme disasters around the world has brought serious challenges to the security of the energy system.

In order to reduce the impact of load shed caused by extreme disasters on the system, a distributionally robust expansion planning model of integrated gas–electricity distribution considering system resilience constraints under extreme disasters was proposed. First, taking the minimum planning cost and annual operating cost as the objective function, an expansion planning model of the integrated gas–electricity distribution system considering electric vehicle charging stations, distributed gas units and energy storage equipment was established.

$$\min(C^{\mathrm{I}} + C^{\mathrm{O}} + c^{\mathrm{ele}} \cdot \Delta P + c^{\mathrm{gas}} \cdot \Delta G + c^{\mathrm{wind}} \cdot \Delta W) \quad (1)$$

Secondly, considering the role of extreme disasters, a distributionally robust expansion planning model of the integrated gas–electricity distribution system considering resilience constraints was put forward. The model included the base scenario and the worst scenario for extreme disasters. Among them, the economy of the system was considered in the basic scenario, the minimum planning cost and the minimum operating cost of the basic scenario were taken as the objective function, the worst scenario for extreme disasters were realized through resilience constraints to ensure the resilience of the system.

$$\begin{aligned} &\min_{x \in F(x)} \boldsymbol{a}^{\mathrm{T}} \boldsymbol{x} + \boldsymbol{b}^{\mathrm{T}} \boldsymbol{y} \\ &\text{s.t. } \boldsymbol{A}\boldsymbol{x} \le \boldsymbol{e}, \boldsymbol{x} \in \{0,1\}; \\ &\quad \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{y} \le \boldsymbol{f}; \\ &\quad \|\boldsymbol{U}\boldsymbol{y}\|_2 \le \boldsymbol{h}^{\mathrm{T}} \boldsymbol{y} \end{aligned} \quad (2)$$

$$F(\boldsymbol{x}) = \begin{cases} \max \sum_{k=1}^{K} p_k \min(\boldsymbol{J} \cdot \boldsymbol{\delta}^k) \le R \\ \text{s.t. } \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{y}^k + \boldsymbol{J}\boldsymbol{\delta}^k \le \boldsymbol{f}; \\ \quad \|\boldsymbol{U}\boldsymbol{y}^k\|_2 \le \boldsymbol{h}^{\mathrm{T}} \boldsymbol{y}^k \end{cases} \quad (3)$$

Finally, the case simulation results showed that, by increasing the planning and construction of electric vehicle charging stations, distributed gas-fired units and energy storage equipment, the economy of the system could be effectively improved, which is given in Tab.1.

Tab.1 Cost comparison of case 1~4

Case	Planning cost/ (10^6 yuan)	Operating cost/ (10^6 yuan)	Total cost/ (10^6 yuan)
1	0.2000	2.0948	2.2948
2	0.3000	1.8626	2.1626
3	0.3100	1.8510	2.1610
4	0.3630	1.8504	2.2134

From Tab.2, in the face of extreme disasters, the system loss could be reduced through the discharge of electric vehicle charging stations, distributed gas-fired units and energy storage equipment. But the unit planning costs required will increase significantly as the system resilience increases, which is given in Tab.3.

Tab.2 Comparison of load shedding cost under extreme disaster of case 1~4

Case	Load shedding cost/ (10^5 yuan)
1	3.8796
2	3.8743
3	3.8724
4	1.4978

Tab.3 Comparison of results with different *R* values

R/ (10^4 yuan)	Planning results	Total cost/ (10^6 yuan)
35	E_6, E_{12}, G_6, S_2, L_{15}	2.1710
25	E_6, E_{13}, G_6, S_2, L_{15}, L_{10}	2.1810
20	E_6, E_{12}, G_6, S_2, L_6, L_{15}, L_{10}	2.1909
15	E_6, E_{12}, G_6, S_2, S_{17}, S_{28}, L_6, L_{11}, L_{10}, L_{15}	2.2134
12.5	E_6, E_{11}, G_6, G_{13}, G_{30}, S_2, S_{17}, S_{24}, S_{28}, L_6, L_{11}, L_{10}, L_{15}	2.4110

In this paper, considering the impact of extreme disasters, a distributed robust expansion planning model for the integrated gas–electricity distribution network under the flexibility constraint is proposed. Through the planning and construction of electric vehicle charging stations, distributed gas units and energy storage equipment, the economy and security of the system are improved. Finally, the effectiveness and practicability of the model are verified by the analysis of an example.

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Collaborative Optimal Dispatch of Electricity–Hydrogen Coupling System in Chemical Industry Park Considering Hydrogen Load Response

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KEYWORDS:electricity–hydrogen coupling system; hydrogen production by water electrolysis; hydrogen load

Hydrogen production by water electrolysis is one of the most important approaches to achieving new energy accommodation. Considering the response of hydrogen load could significantly improve the new energy accommodation capacity and decrease the operation cost of the electricity-hydrogen coupling system.

This paper constructs the framework of the electricity-hydrogen coupling system in the chemical industry park as shown in Fig. 1. Power grid, distributed wind power, and photovoltaic are the park power sources. Hydrogen is produced by coal to hydrogen and electrolytic cell. The hydrogen is first stored in hydrogen storage tanks and then transported to each hydrogen load through pipelines. Electrolytic cells, hydrogen fuel generators, and hydrogen ammonia productions could adjust their operating power by tracking the changes of power supply and electrical load, and response to the time-of-use electricity price at the same time, so as to maximize the chemical industry park revenue.

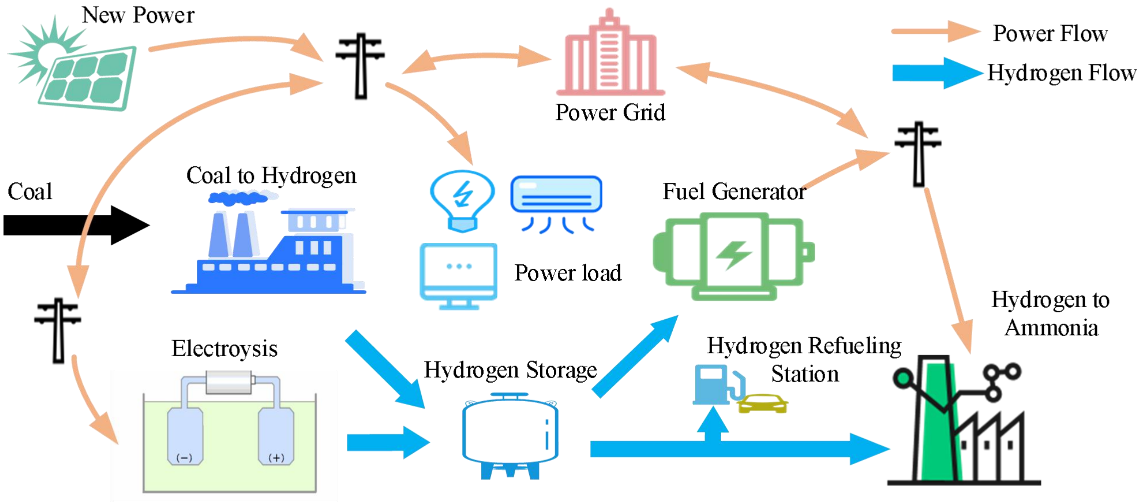

Fig. 1 Park-level electricity–hydrogen coupling system

In order to improve the economic benefits and new energy accommodation capacity of the park, the objective function is established as follows.

$$\max \sum_{t=1}^{24}[c_{\mathrm{NH_3}} m_{\mathrm{NH_3},t} - c_{\mathrm{e},t} \mid P_{j,t}^{\mathrm{tr}} \mid] - c_{\mathrm{m}} M^{\mathrm{C}} \tag{1}$$

where $P_{j,t}^{\mathrm{tr}}$ is the transaction power between the park and the power grid. $c_{\mathrm{e},t} \mid P_{j,t}^{\mathrm{tr}} \mid$ is the electricity cost, when $P_{j,t}^{\mathrm{tr}} > 0$, it represents the cost of purchasing electricity from the power grid; when $P_{j,t}^{\mathrm{tr}} < 0$, which means that park injects the excess energy into the park, it represents the equivalent penalty cost. $c_{\mathrm{e},t}$ is the electricity price at time *t*. $m_{\mathrm{NH_3},t}$ is the ammonia production at time *t*. M^{C} is the total coal consumption. $c_{\mathrm{NH_3}}$ is the ammonia price. c_{m} is the coal price.

The case studies show that the transactional power between the power grid and the park is reduced, and the new energy accommodation capacity has been significantly improved. Furthermore, it can be concluded that the basis of the coordinated operation of the electricity-hydrogen coupling system is that the electrolytic cells track the changes of the power supply and electrical load, which can significantly reduce the power purchase and wind and light curtailment in the park. On this basis, considering the hydrogen load response can fully excavate the system flexibility and further enhance the economic benefits of the park.

Output Allocation Optimization Method for the Wind Photovoltaic Energy Storage Power Station in the Multi-time-scale Electricity Spot Market Under Portfolio Theory

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KEY WORDS: portfolio theory; wind photovoltaic energy storage power station; output allocation; risk aversion

With the proposal of "double-carbon" goal, the wind photovoltaic energy storage power station(WPS) had developed rapidly and became the mainstream trend of new energy station construction. However, due to the uncertainty of wind and photovoltaic power output and the fluctuation of market price, it was difficult for WPSs to reasonably arrange the output in the day-ahead, day-time and real-time markets, which restricted the economy and flexibility of WPS. Therefore, it was necessary to research the optimal distribution of the output of the WPS participating in the electricity spot market.

In order to consider the influence of market price fluctuation and renewable energy uncertainty on the output allocation of the WPS, this paper introduced portfolio theory from economics as a trade-off tool for the profit and risk, and put forward the output allocation method of the WPS participating in the day-ahead, day-time and real-time markets. Firstly, considering the uncertainty of wind power and photovoltaic, a multi-time scale revenue model was constructed based on the market price. Secondly, the variance and covariance of market price was used to describe the risk and the correlation of risks between markets, and the optimization model of output allocation was constructed with the maximum profit and minimum risk as the objective function. Finally, the problem was solved by the augmented Lagrange method to get the optimal output allocation over daily operation time.

According to the profit and risk of WPS in each market, the objective function of WPS was put forward. The uncertainty of wind power and photovoltaic were expressed by multi-scenario output, and the coordinated regulation of wind power, photovoltaic and energy storage was considered. The goal of the WPS was to maximize profit and minimize risk. According to the portfolio theory, an objective function including the profit and risk of the station was put forward, which was expressed as the weighted sum of each optimization scenario:

$$\max U = \max\left[\sum_{s=1}^{S}\pi_s\sum_{t=1}^{T}\left(E_{t,s}^{\mathrm{mp}}-\frac{1}{2}A^{\mathrm{m}}\sigma_t^2\right)\right] \quad (1)$$

where U is the general goal of WPS, S is the number of scenes, T is a time period, π_s is the probability of each typical scenery scene, A^{m} is the risk aversion index of WPS, its positive value stands for avoiding risks, negative value stands for liking risks, and zero value stands for not considering risks. $E_{t,s}^{\mathrm{mp}}$ is the expected profit of WPS, σ is the market risk of WPS. the augmented Lagrangian methods and Karush-Kuhn-Tucker conditions are used to solve the model.

The market risk, optimal output allocation and sensitivity of risk aversion index were analyzed, and the relationship between market price and risk was explored. Compared with participating in a single market, the profit of WPS increased by 13.3%, the risk decreased by 84.1%. The risks and expected profits of different markets can be effectively reflected in the portfolio theory, which provided more choices for the WPS to obtain profits and avoid risks. WPS can also allocate its efforts to the day-ahead, day-time and real-time markets according to the price and risk of different markets and the degree of risk avoidance.

With the increase of risk aversion index, WPS was more sensitive to market risks and reduced its participation in high-risk markets. Through the method, WPS can selectively participate in the market according to the risks and expected profits of different markets, and realize the maximization of profits and the minimization of risks according to its own risk aversion degree.

The work in this paper provided a theoretical basis and algorithm for the profit and risk management of WPS in the spot market. By dynamically adjusting the participation of WPS in different markets, the profit of WPS was maximized, which provided a new market participation model for WPS.