Research on Voltage Induced Cascading Fault of Cluster New Energy Grid Connection

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ABSTRACT

The rapid increase of new energy grid-connected capacity in China has brought great challenges to the security and stability of power grid. Firstly, from the two stages of low voltage and high voltage, the mechanism and process of voltage induced cascading off-grid accidents in new energy stations including wind power and photovoltaic stations are analyzed in detail. Then, a complete definition and model of the cascading off-grid path of new energy station are established, and the path search method and accident risk assessment system are proposed. Finally, a hierarchical control strategy of "hierarchical division" and "coordination" is proposed, which aims to block the cascading off-grid path to achieve the purpose of restraining the occurrence of off-grid accidents and is verified by the actual grid data.

1. INTRODUCTION

With the rapid increase of grid connected capacity and quantity of wind power and photovoltaic power generation units in China, the stability of power grid is facing greater challenges. Since 2012, China has vigorously carried out the comprehensive transformation and testing of new energy grid-connected technology. There are 247 wind farms in China that need to be transformed and tested for low voltage ride-through (LVRT). By the end of 2013, 89%, *i.e.,* 219 wind farms have been reconstructed. Among them, 69%, *i.e.,* 151 wind farms have passed the test. The quality of wind power equipment and the operation quality of wind farms have been significantly improved. Large-scale wind and power off-grid accidents have dropped from 8 in 2011 to 1 in 2012, and zero in 2013-2014 [1]-[4]. Although the new energy grid-connected technology in China is becoming more mature and the grid-connected detection is becoming stricter, there are still some new energy units that are not completely transformed or have not been subject to strict LVRT detection in actual operation. The off-grid accident of a single new energy station is likely to cause a large area of cascading off-grid accidents, which has hidden dangers to the grid security.

Based on the analysis of several large-scale cascading off-grid accidents of wind farm in recent years, scholars at home and abroad summarized the detailed evolution process of this kind of trip-off accidents and believed that the main cause of the accident is the low voltage ride-through (LVRT) of wind turbine and the dynamic regulation of reactive compensation device. And a detailed model is established to simulate the accident of wind turbine and reactive compensation power characteristics and dynamic response process [5]-[8]. In view of the reasons of off-grid, some research start from the models and control strategies of the units and compensation equipment, and put forward measures to prevent off-grid accidents, such as the improvement of low penetration strategy of the wind turbine, the delay control of the reactive power compensation device, the reactive power coordination among the units, and more [9]-[13]. Such strategies often need to change the structure and some functions of units and equipment, which increases the cost and difficulty of control, and cannot be widely used in actual operation. In addition, some research put forward various emergency or preventive control strategies and coordinated control strategies of reactive power and voltage for cascading off-trip accidents of cluster wind farms from the perspective of system side, static and transient, and established relevant control system and online early warning system [14]-[18]. Some research on the cascading off-grid of new energy including photovoltaic stations, However, no control strategy was adopted or control strategy is not hierarchical control.

This paper summarizes the mechanism and process of voltage induced cascading off-grid accidents in the centralized access system of large-scale new energy stations, defines the concept of cascading off-grid path

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used to describe the evolution of accidents, establishes the off-grid path model, search method and risk assessment system of off-grid accidents, and combines the existing control means of such accidents, puts forward the points based on multi scene path blocking. Finally, the strategy is applied to a power grid in Northwest China and some results are achieved.

2. CASCADING TRIP-OFF ACCIDENT MECHANISM OF VOLTAGE INDUCED NEW ENERGY STATION

Typical cascading off-grid accidents can be summarized as the gradual process of large-scale cascading off-grid caused by the influence diffusing to the neighboring new energy stations in the region due to external disturbance after voltage or frequency type off-grid of a few new energy stations. The continuous development of this chain effect will eventually lead to the malignant accidents of the power grid. Among them, the occurrence of voltage induced off-trip accident has experienced two stages: low voltage off-grid and high voltage off-grid.

2.1 Low Voltage Off-grid Phase

The ride-through failure of new energy station during voltage drop is the main cause of low dropout. In the period of voltage drop after large disturbance in the power grid, the new energy unit without LVRT will trigger the low-voltage over limit protection action to separate from the power grid when the grid-connected bus voltage drops to 0.9p.u. Most of the doubly-fed fans with Crowbar take the initiative to bypass the rotor and make the fan cut into asynchronous operation in order to protect the rotor side converter from excess current impact during the voltage drop. It absorbs a large amount of reactive power from the grid, resulting in continuous voltage drop; Inducing adjacent doubly-fed fans crowbar protection action or other new energy units ride-through failure, further promoting voltage drop, forming low-voltage cascading off-grid [19]-[21]. The photovoltaic generator set also has similar over-current protection circuit at the inverter side; however, it does not have the process of asynchronous operation and absorption of reactive power in the low-voltage stage, so there is almost no reactive power exchange between the system and other types of fans in the process of off-grid [22]-[24].

The new energy units with LVRT can continuously connect to the grid when the voltage is above 0.2p.u. during the fault period and output the grid-connected voltage of reactive power support to the system. If the low ride-through fails, the reactive power support to the system during the fault period will be lost. The increase of the reactive power loss will further reduce the system voltage, and more adjacent new energy units will get ride-through failure and off-grid.

2.2 High Voltage Off-grid Phase

The lack of dynamic regulation capacity of reactive power compensation devices in new energy stations is the main cause of high voltage off-grid. Most of the regulation capacity and regulation speed of compensation devices do not meet the requirements of grid. After off-grid, the reactive power compensation device in the new energy station of low-voltage off-grid cannot be out of operation in time, resulting in excessive reactive power of the system and the generation of transient over-voltage, causing the voltage of some stations to exceed the limit of off-grid. The reduction of active power in the network leads to the further rise of voltage. More adjacent units reach the conditions of off-grid, and the high-voltage cascading off-grid is formed. In the same way, the lag characteristics of large capacity reactive power compensation device in DC converter station is the root cause of high-voltage cascading off-grid in new energy stations around the channel of DC blocking accident.

The cascading off-grid mechanism of the whole new energy station can be shown as follows:

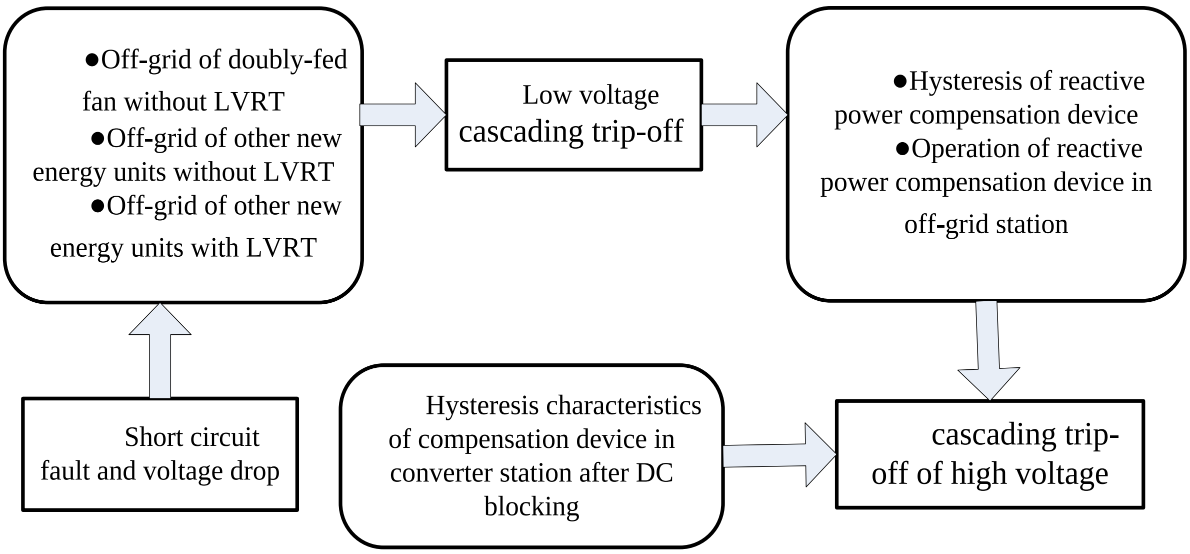


Fig. 1. The mechanism of voltage induced cascading trip-off accidents in new energy station.

3. PATH SEARCH AND RISK ASSESSMENT OF CASCADING OFF-GRID

3.1 Definition and Model of Cascading Off-grid Path in New Energy Station

The evolution process of cascading off-grid accidents in new energy station can be represented by the off-grid node and chain composed of directed connection edges, its model can be expressed as follows: For large-scale new energy centralized access areas, if a new energy station is disconnected from the network first after being disturbed, the station shall be taken as the starting point. Record all the adjacent new energy stations that are affected by each other due to cascading trip-off accidents and mark the time stamp of off-grid respectively. Finally, arrange all the stations in sequence to form a cascading reaction chain.

(1) Off-grid path node

In the description of cascading off-grid path, the off-grid node can be defined as the event in the cascading failures, which should include the triggering K, the occurrence time T, the new energy output loss P caused by the event and the current stability A of the system. Suppose that a cascading off-grid accident starts from the off-grid event S1 of N1 at T1, the triggering of event is K1, and the loss output is P1; Off-grid of N1 induces the off-grid event S2 of N2 at T2, loss of output P2; event S2 induced S3, and so on. The induction of event SN at TN can be induced as follows:

$$S_N = K_N S(T_N, P_N, A_N) \tag{1}$$

Where, the values of K and A are both 1 and 0. The former indicates the occurrence and non-occurrence of the event and the latter indicates the instability and non-instability of the system after the occurrence of the current event.

(2) Directed edge

In the cascading off-grid accident, the triggering of off-grid event in a new energy station causes the off-grid event of adjacent stations, and then the edge between the two events is established. The edge direction between the nodes of adjacent off-grid path is determined by the off-grid time of the events on both sides, and its direction also reflects the spreading direction of the off-grid accidents. A node can have multiple connecting edges. The more connected edges is, the stronger diffusion of the node, and the greater impact on the off grid path [13].

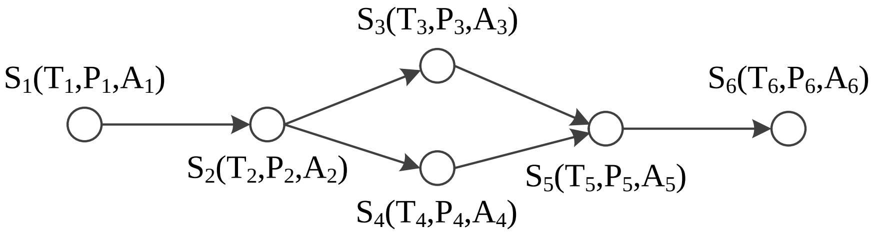


Fig. 2. Schematic diagram of cascading off-grid path model.

Figure 2 shows a path model with node number N=6. Assuming that the length of the path is LP; the severity of the path is PP; the time sequence of the path is TP, and the system instability event is AP, the cascading off-grid path can be fully expressed as:

$$\begin{cases} S_P = \sum_{i=1}^{N} S_i \\ L_P = \sum_{i=1}^{N} K_i S_i \\ T_P = \{K_1T_1, K_2T_2 ... K_NT_N\} \\ P_P = \sum_{i=1}^{N} K_i P_i \\ A_P = \sum_{i=1}^{N} K_i A_i \end{cases} \tag{2}$$

It can be seen that the length and severity of the off-grid path are determined by the total number of off-grid nodes and the output loss of new energy stations. When each off-grid node Si does not appear (Si = 0), the whole cascading off-grid path will not appear (SP = 0). When AP ≠ 0, the path will cause system instability [14].

3.2 Cascading Off-grid Path Search and Risk Assessment System

According to the above analysis, factors such as the new energy stations with LVRT level R_{LV} and output level R_{GP}, capacity level RCQ of reactive power compensation device, fault type and location directly affect each attribute of the cascading off-grid path. RLV, RP and RQ can be calculated by the following formula:

$$\begin{aligned} & R_{LV} = \frac{N_{LV}}{N_G} \times 100\%, \quad R_{GP} = \frac{P_{GR}}{P_{GN}} \times 100\% \\ & R_{CQ} = \frac{Q_{CR}}{Q_{CN}} \times 100\% \end{aligned} \tag{3}$$

Where, N_{LV} and N_G are the number of units and the total number of units that successfully realize LVRT in actual operation. P_{GR} and P_{GN} are the actual output and rated power of new energy station respectively. Q_{CR} and Q_{CN} are the actual input capacity and rated capacity of reactive compensation device respectively. In this paper, a calculation and risk assessment system of cascading off-grid path in new energy station based on PSASP is proposed. It is characterized by a system of off-grid path search and risk assessment under a variety of predictive scenes, in which new energy stations are divided into centralized access zones. Among them, the predictive scene includes the predictive fault set, the predictive value of new energy output level, the LVRT level of the predictive new energy station and the capacity level of the predictive reactive power compensation device. The predictive fault set is the line fault set that may cause the cascading off-grid accident under the actual operation condition. The fault types include single-phase, three-phase short circuit fault as well as single and double pole blocking fault of DC line. The fault point location includes the near and far end of 110kV and the above outgoing lines at the grid-connected point of new energy stations. The implementation of the whole system can be shown as follows Figure 3.

At the beginning of the off-grid path search, the real-time operation data of the power grid and the parameters of the predictive scene should be input first, and the distributed parallel power flow and stability calculation should be carried out on the PSASP platform according to the new energy area. Finally, the off-grid path sets under different predictive scenes should be collected and stored, and a risk assessment system should be established to analyze the severity of the accident. The system includes the following assessment indicators:

(1) Severity index of cascading off-grid. The severity of off-grid P_P directly determines the index. The larger the P_P is, the greater the severity of the accident will be.

(2) System transient stability index. After each transient operation, the current system voltage, frequency and power angle should be output to evaluate the transient stability event A_P of the system under the predictive fault.

3.3 Application Example

The calculation and risk assessment system of cascading off-grid path in new energy station proposed in this paper has been applied in a Power Grid in Northwest of China. In this power grid, there are about 35 wind farms with an installed capacity of 3833mw, 70 photovoltaic farms with an installed capacity of 1674mw. The installed capacity of new energy accounts for 24% of the total installed capacity of the whole grid. The grid structure and new energy station zoning are shown in Figure 4.

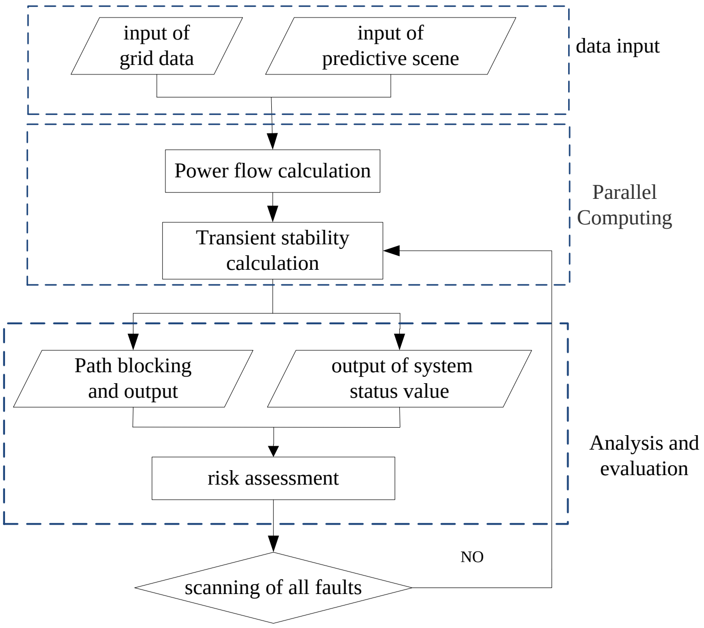


Fig. 3. Cascading off-grid path search and risk assessment.

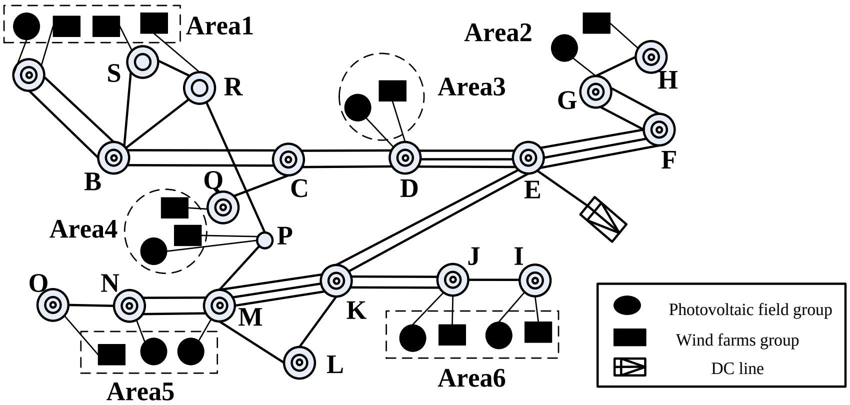


Fig. 4. Grid structure and regional distribution of new energy in a region.

In this case, 96 kinds of faults are stored centrally. The following models are adopted for each new energy unit in PSASP: 4-type model are adopted for squirrel cage fan, 10-type model, 11-type model and 1-type model are adopted for direct drive, doubly-fed fan and photovoltaic unit respectively. After storing the off-grid paths in each scene, the risk assessment are carried out. The simulation results in several scenes are listed in Table 1.

From the results, it can be concluded that the cascading off-line path length and the stability degree of the system are different in different scenes. When RLV=50%, the off-line path length and the number are the largest, which leads to the system instability. At that time, Area5 and Area6 are likely to have the maximum off-grid path in various scenes, which indicates that the new energy grid in this area is relatively weak, and the probability of cascading off-grid accidents is relatively high. This needs to be focused on. In the first scene in the table, the detailed path of new energy station off-grid in Area6 is listed, and the situation is summarized as follows Figure 5.

Table 1. Path calculation results in 7 scenes.

No.	Parameters (%)			Total path	Maximum severity corresponding path			
	R_{GP}	R_{LV}	R_{CQ}		L_P	P_P / MW	Area involved	A_P
1	50	90	100	33	7	432	Area6	0
2	100	90	100	37	8	623	Area5	>1
3	20	90	100	34	8	121	Area6	0
4	50	90	50	33	10	485	Area5	0
5	50	50	50	77	42	1382	Multi-area	>1
6	100	50	50	81	45	2832	Multi-area	>1
7	50	90	100	0	Double pole blocking of DC line			

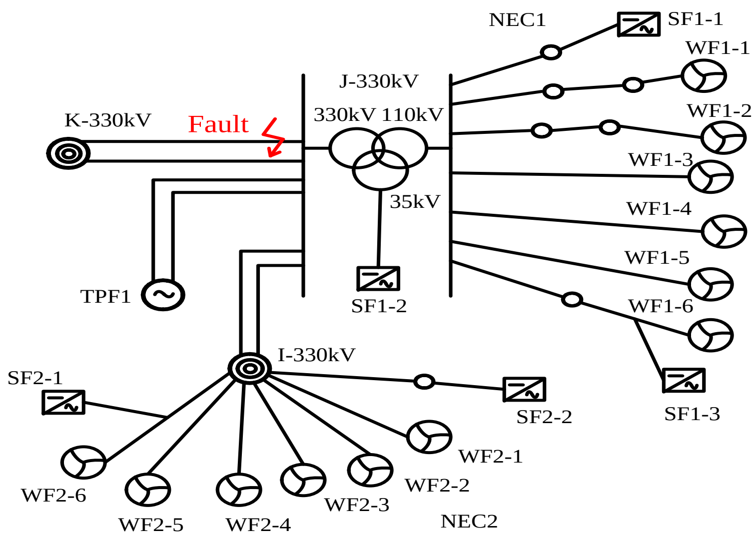


Fig. 5. The grid structure of Area6.

Table 2 Detailed path of new energy station off-grid in Area6.

Off-grid station	Off-grid time (s)	Grid-connected voltage when off-grid (p.u.)	Off-grid type
WF1-3	1.01	0.3175	Low voltage off-grid
SF1-2	1.01	0.1223	Low voltage off-grid
WF1-5	1.015	0.1891	Low voltage off-grid
WF2-6	1.028	0.1933	Low voltage off-grid
SF2-1	1.032	0.1965	Low voltage off-grid
WF1-1	1.165	1.1021	High voltage off-grid
WF2-5	1.172	1.1013	High voltage off-grid

The area is composed of new energy field group NEC1 and NEC2 (as shown in Figure 5). The predictive failure is set at the single-cycle triphase short circuit near the 330kV of outgoing AC line, and the fault period is 1-1.1s. Table 2 shows the off-grid path after the failure. At the moment of the failure, WF1-3 (mainly the doubly-fed fan without low ride-through capacity) and SF1-2 (low ride-through failure) in EFC1 are off-grid first and the system voltage drops then. Then WF1-5 is off-grid due to low ride-through failure respectively, which affects WF2-

6 and SF2-1 in NEC2. After the fault is removed, WF1-1and WF2-5 are respectively off-grid due to high voltage ride-through failure, thus forming a complete off-grid path in this scene:WF1-3(1.003s,94.5MW,0)→SF1-2(1.007s,50 MW,0)→WF1-5(1.015s,49.5MW,0)→WF2-6(1.028s,49.5MW, 0)→SF2-1(1.032s, 40MW, 0)→WF1-1(1.165s, 99MW, 0)→WF2-5(1.172s,49.5MW, 0).

4. HIERARCHICAL CONTROL STRATEGY OF CASCADING OFF-GRID IN NEW ENERGY STATION

Referring to Equations (1) and (2), the relationship between two adjacent nodes in the off-grid path is as follows:

$$S_{i+1} = if\,(S_i = 0, 0) \tag{4}$$

The entire off-grid path can also be expressed as:

$$S_P = \sum_{i=1}^{i} S_i + \prod_{i=i}^{N-1} S_{i+1} \tag{5}$$

It can be seen that if there is no off-grid event Si at any position of the path, all subsequent off-grid events will not occur. Meanwhile, it also blocks the spread of off-grid accidents, reduces the number of nodes, length LP and severity PP of path SP, and reduces the risk of system instability in this area. Therefore, taking control measures at any position in the off-grid path can change the impact of off-grid accidents. The more forward the control position, the lower the accident severity and the lower the cost. In this paper, a two-level control strategy of "layered area" and "coordinated cooperation" is proposed, the core of which is to block the possible new energy off-grid path at the front end.

4.1 Control Measures

4.1.1 Primary control

In the above calculation of off-grid path in a certain area, the steady-state voltage level of most of the new energy units with off-grid is higher or lower to some extent. If it is at a lower voltage level, the voltage is more likely to fall to the low voltage protection limit of the new energy units after the fault, which results in low off-grid. Similarly, the new energy units that are at a high voltage level are more likely to have high-voltage off-grid. The primary control of this strategy is a prevention strategy, which aims to adjust the steady-state voltage level of new energy stations on the path according to the off-grid nature in the steady-state state and realize the early blocking of the path. According to the actual working condition, the steady-state voltage level control domain of new energy station is set as 0.95-1.05 p.u. According to the control cost, the voltage regulating measure can be divided into active and reactive output regulation of new energy station, switching capacity regulation of reactive compensation device in the station and coordination regulation of adjacent reactive power supply [15].

4.1.2 Secondary control

If the primary control measures fail to be blocked, the secondary emergency measures should be put into operation. In case of off-grid accident, the station close to the fault point will be off-grid within a few milliseconds. The affected neighboring new energy stations are usually off-grid within tens to hundreds of milliseconds, and the system instability is generally within a few minutes, so it is a great challenge to realize emergency control in such a short time scale [3]. The secondary control purpose of this strategy is to block the off-grid path at the front end of the time series as much as possible during the evolution process of the anticipated accident. According to the response speed, the control measures can be divided into emergency cut-off of new energy station feeders, emergency load cut, maximum reactive power support and delay locking of reactive compensation device [9] [15].

The final blocking effect of these two-level controls can be expressed as follows:

$$S_{PC} \le S_{PMIN}, P_{PC} \le P_{PMIN} \tag{6}$$

Where, S_{PC} and P_{PC} are the node number and severity of the off-grid path after each control; S_{PMIN} is the minimum value of path node after control and P_{PMIN} is the minimum severity of the path after control.

4.2 Policy Framework

This strategy is the hierarchical control with "data layer-decision layer-implementation layer", and the contents of each control layer are as follows:

(1) The data layer implements the content described in Section 2, mainly completing data input and new energy zoning, cascading off-grid path calculation and storage, risk assessment and more.

(2) The decision-making layer calculates the optimal *control* strategy in real time and stores it in the decision-making database. For each off-grid path, first of all, various voltage regulating measures in the primary control are carried out for the new energy station in the front-end event S_1 of the path. If it cannot be blocked after calculation, the event is marked as M_1, and the control object is transformed into the station in the event S_2, and so on.

$$M_P = \{M_1, M_2, M_3 ... M_N\} \tag{7}$$

When it is still not blocked after the primary control finishes scanning of all events on the path, it means the primary control fails to block. First, a set of marked events is generated, as shown in equation (7); and then the secondary control measures are formulated on the results of the primary control. The starting point of the secondary control is the first marked event in the primary control, and the control objects is the whole set of marked events. Before the secondary control, the response speed of all emergency control measures applicable to the current path shall be compared with the time series T_P of the path to determine the control time point and select the appropriate control measures. Finally, all the generated predictive control policies are stored in the policy set, and the decision-making layer can be shown as follows Figure 6:

(3) The implementation layer implements various control strategies proposed by the decision-making layer, as shown in Figure 7.

The main control center completes all the contents in data layer and decision layer, and classifies the strategies calculated by decision-making layer according to remote control strategy, coordination control strategy and local control strategy. In order to improve the response time of the strategy, the regional control center stores and executes the remote and coordinated control strategy, the new energy station of each control object stores and executes the local control strategy, and each unit controls through the instructions. Closely monitor all new energy stations that need to adopt secondary control path concentration. Once the predictive accident actually occurs, the control unit does not need to wait for the command of the main control center and carries out the local control according to the local stored strategy set at the first time. Meanwhile, the fault information is fed back to the regional control center and the main control center, and the remote control is started and involved in the control. In addition, the adjacent area can coordinate and control through information and instruction exchange to improve the path blocking rate, such as the active and reactive power support of the new energy station in the adjacent area and the coordination and regulation of the reactive power compensation device.

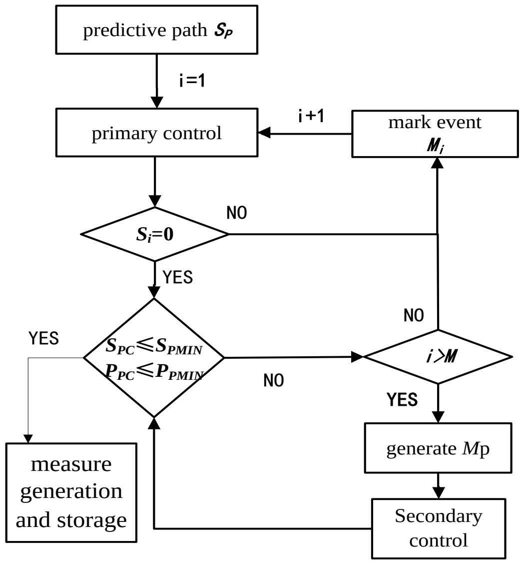


Fig. 6 The diagram of decision-making layer.

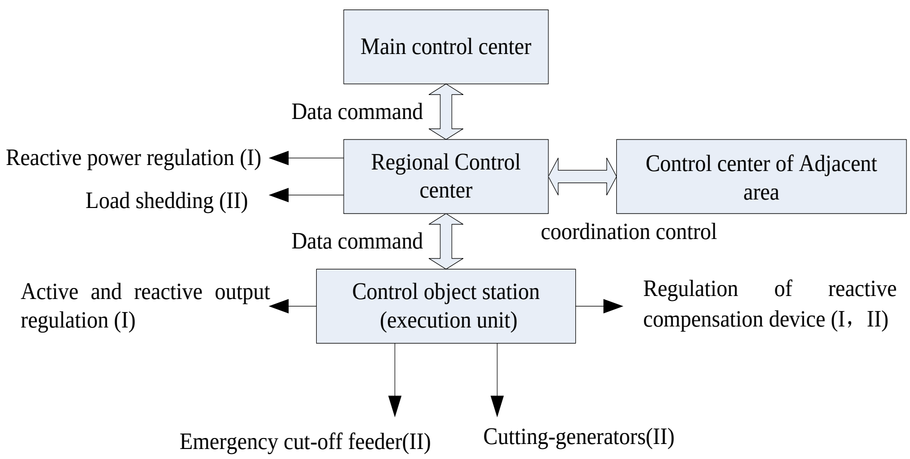


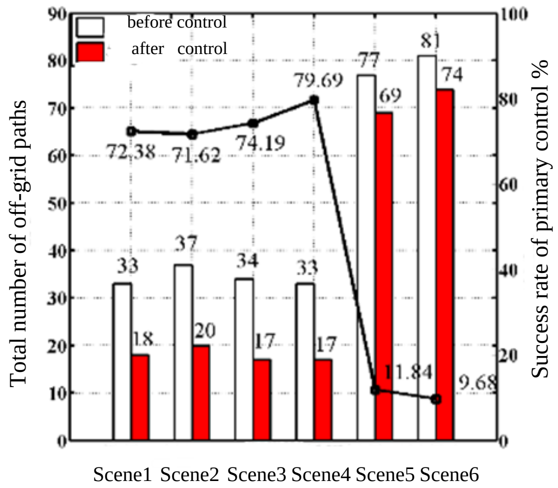
Fig. 7 Framework diagram of implementation layer.

4.3 Application Example

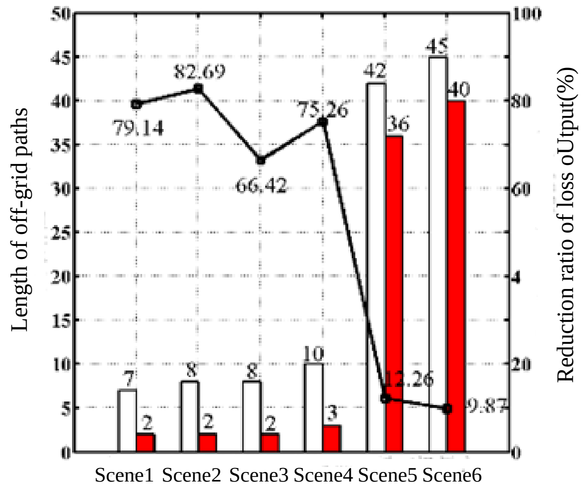
The control strategy proposed in this section is applied to the system of section 2, taking the blocking effect S_{PMIN}=2 and P_{PMIN}=100MW after control, that is, the allowable path has no more than 2 nodes and 100MW output loss. The comparison results between control and without control after simulation calculation in scenes 1 to 6 are as follows Figure 8.

It can be seen from the comparison results that in the scenes (1-4) with high LVRT of new energy stations, the success rate of the primary control strategy is high, and the total number of off-grid, the maximum length of off-grid path and the proportion of loss of output reduction are greatly improved. However, in the low-level scene (5 and 6), the unit has a large drop depth, poor ride-through ability, and large voltage rise deficiency in the low-voltage stage, so it is difficult to achieve the purpose by means of voltage regulation.

Meanwhile, most of the doubly-fed fans of this kind of units greatly increase the reactive power of the system in the asynchronous operation process after Crowbar, resulting in further expansion of the scope of off-grid, and it is difficult to block the current path by the primary control. At this time, on the basis of the primary control measures, various emergency control strategies in the secondary control are formulated to reduce the path severity to the minimum.



(a) Comparison of the off-grid paths in each scene and success rate of the primary control.



(b) Comparison of the maximum path length and the reduction ratio of output loss in each scene.

Fig. 8. Comparison of results with and without control.

Table 3. Results of primary control in Area 6(scene one).

Off-grid station	Grid-connected point voltage when new energy station is off-grid(p.u.)					*Control result*
	Before control	Measure 1	Measure 2	Measure 3	Measure 4	
WF1-3	0.3175	0.3622	0.3721	0.3836	0.3836	Path blocked successfully
SF1-2	0.1223	0.1787	0.1842	0.1898	0.1898	
WF1-5	0.1891	0.1932	0.1943	\	\	
WF2-6	0.1933	0.1940	0.1944	\	\	
SF2-1	0.1965	1.1973	0.1979	\	\	
WF1-1	1.1021	1.1035	1.1046	\	\	
WF2-5	1.1013	1.1021	1.1028	\	\	

Table 3 shows the results of hierarchical control of Area6 in scene 1. When the predictive fault occurs, the first level control is adopted, and the control starting point is wf1-3. Because most of the fans in the station do not have LVRT, and the voltage drop depth of the grid-connected point is large after the failure, the voltage regulation measure in measure 1 cannot make the low voltage value higher than the cutting-generators value by 0.9p.u., so this object control failed. Turn to SF1-2 for voltage regulation measure 2, reduce the active output of the photovoltaic station by 50%. Because the capacity of the reactive power compensation device is fully put into operation in this scene, and the reactive power support can only be conducted through the adjacent thermal power units of SF1-2, so as to increase the stable voltage of SF1-2 by about 0.05p. U. The lowest point of voltage drop is raised to 0.1787p.u. in the fault period, but it was still lower than its ride-through value of 0.2p.u. The control failed and turned to WF1-5 for measure 3. At this time, the voltage of WF1-5 grid-connected node is 0.1943p.u. After similar voltage regulation measures, the voltage of the station rises to 0.2286p.u. during the fault period, and the low-voltage ride-through is successfully realized. At the same time, the change of the off-grid node leads to the successful ride-through of each station on the node in different fault stages. Therefore, under the primary control, the blocking effect of the off-grid path is SPC=2 and PPC=89.5MW, that is, the blocking effect is successful at node 3.

Although the path is blocked by three measures in the primary control, it does not achieve the optimal blocking (S_C=0 and P_{PC}=0). Therefore, after the primary control, try to use the secondary control to optimize the blocking effect. The secondary emergency control object is the marked events WF1-3and SF1-2, and the state of the two stations after measure 3 is the initial situation. Since the time sequence of off-grid of two stations is within 10ms from the time of fault occurrence, the triggering time sequence of all measures in the secondary emergency control measure 4 cannot meet such a short time scale. The state of the path node has not changed after the implementation of measure 4. Therefore, the implementation of the secondary control does not have a good effect on the optimal blocking of the path.

5. CONCLUSION

In this paper, in view of many large-scale new energy stations in China's voltage induced cascading off-grid accidents, we summarize the induced mechanism and process of voltage induced off-grid accidents in new energy stations, model the chain off-grid path, and search and risk assessment the cascading off-grid path of new energy stations in Northwest China through PSASP platform. In view of all kinds of predictive off-line paths, a hierarchical control strategy is proposed, which combines a variety of control measure and control opportunities to block the path in a hierarchical way. The strategy has been verified in a certain area of Northwest China and achieved some results. In the future work, the system and control strategy proposed in this paper will be software based, and an online monitoring and control platform for voltage induced cascading off-grid accidents in new energy stations will be built, which can be safely and accurately applied to the actual power grid operation.

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