An Adaptive Reclosing Method for Distribution Networks Based on Active-Passive Fault Detection

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October 28, 2024

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***Abstract*—Traditional non-check reclosing method might operate at continuous short circuit, causing secondary shock to the distribution networks. To this end, an adaptive reclosing method for distribution networks based on active-passive fault detection is proposed in this paper. Firstly, the characteristic of voltage rise accompanied by fault clearance is applied as passive detection criterion. Additionally, active signal is injected by the converter of distributed energy resources to identify the permanent/transient fault. Then the reclosing is completed through adaptive time delay. Simulation results show that the proposed adaptive reclosing method can identify fault state and close reliably.**

Keywords—adaptive reclosing method, active-passive fault detection, signal injection

I. INTRODUCTION

The traditional unchecked reclosing has been unable to meet the demand of new power distribution system under the high proportion of distributed new energy access [1]-[2]. Existing projects usually use the reclosing delay rectification scheme in conjunction with new energy islanding protection and fault ride-through for improvement, and the circuit breaker is reclosed after 2.5~3s after tripping [3]-[5]. However, this method is too time-consuming, and even transient faults will lead to all new energy off-grid, expanding the scope of fault impact, and is not conducive to rapid fault recovery of the distribution system. There is an urgent need to study fast reclosing methods applicable to new energy distribution networks.

Existing research on reclosing improvement for new energy access is mainly categorized into three types: increasing delay adjustment [3]-[5], adding no-voltage detection [6]-[7] and adaptive reclosing [8]-[18]. Among them, the check no-voltage method is difficult to clearly distinguish the no-voltage situation between the three-phase metallic permanent fault and the new energy off-grid, and there is still the problem of too long reclosing delay.

Traditional non-check reclosing method might operate at continuous short circuit, causing secondary shock to the distribution networks. To this end, an adaptive reclosing method for distribution networks based on active-passive fault detection is proposed in this paper. Firstly, the characteristic of voltage rise accompanied by fault clearance is applied as passive detection criterion. However, only using voltage characteristics for passive detection is difficult to reliably identify the fault state in the case of small-capacity access of new energy and trouble-free crossing function, and other fault state detection links still need to be added. Based on the voltage detection of tripping distribution network, the active injection signal of new energy converter is added to identify the permanent/transient fault state accurately, and then the reliable reclosing is completed through adaptive delay. Simulation is carried in PSCAD/EMTDC, the results show that the proposed adaptive reclosing method can identify fault state and close reliably.

This work was supported in part by the National Natural Science Foundation of China under Grant 52407093. This work was supported in part by State Key Laboratory of Reliability and Intelligence of Electrical Equipment (No. EERI_OY2023005), Hebei University of Technology. This work was supported in part by the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (Grant No.LAPS24019).

II. PASSIVE FAULT STATE DETECTION METHOD BASED ON VOLTAGE MUTATION

A. Fault status detection criteria

From the above analysis, it can be seen that even after the fault is cleared, the downstream islanded system voltage is determined by the new energy control strategy and the active power relationship, and the fault state cannot be effectively identified based on the system voltage level alone. In this section, we propose to utilize the positive-sequence voltage amplitude rise feature when the fault disappears to form the fault state detection criterion. In order to avoid unreliable discrimination caused by voltage fluctuation and measurement data jitter during the fault period, a voltage difference integral criterion is constructed to determine whether a voltage rising edge occurs in the time period by calculating the cumulative value of the voltage difference between the voltage amplitude at the determination moment and the voltage difference at the time of tripping, and its expression is as follows:

$$\left\|U^{+}(t)\right\|\cdot(t-t_0)-\int_{t_0}^{t}\left\|U^{+}(t)\right\|dt>0 \tag{1}$$

Where: t is the time (the unit is calculated by substituting ms), $||U+(t)||$ is the positive sequence voltage amplitude of the downstream outlet of the circuit breaker at the moment t. The downstream outlet voltage magnitude of the circuit breaker is calculated by taking the fault moment t_0 as the start of the voltage difference integral. If the fault is cleared during the time period t_0~t, the equivalent impedance of the new energy external circuit will increase significantly and the system voltage will rise, which satisfies the criterion of equation (1).

Considering the influence of voltage transformer transmission error and measurement jitter, the dead zone is added to the proposed voltage rising edge criterion, and the fault state detection criterion shown in the repair form (1) is:

$$\eta_{\mathrm{U}}=\left\|U^{+}(t)-v\right\|\cdot(t-t_0)-\int_{t_0}^{t}\left\|U^{+}(t)-v\right\|dt>\sigma \tag{2}$$

where, η_U is the calculated value of the voltage difference integral, v is the error value of the voltage transformer, the accuracy of the voltage transformer in the distribution network is usually ±3%, σ is a minimal positive value, the value is 1. When the calculated value of η_U meets equation (2), it can be considered that the transient fault clears itself, as shown in Figure 1.

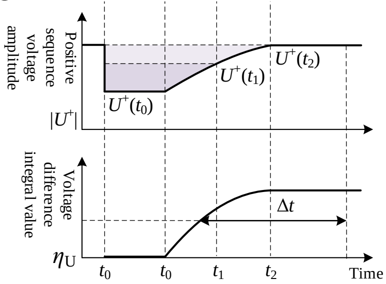


Fig.1 Diagram of the proposed voltage difference integral calculation progress

Although the voltage criterion shown in equation (2) can be utilized to identify the fault state when the new energy is connected to the grid, for permanent faults, the new energy reaches the grid-connected operation limit and goes off-grid, and the downstream system is not pressurized, so the continuous detection loses its significance. Therefore, it is necessary to limit the detection time and block the reclosing gate to avoid reclosing on permanent faults causing a secondary impact.

B. *Reclosing delay adaptive adjustment*

The reclosing time can be effectively shortened by limiting the fault state detection time according to the continuous grid-connected operation time under different abnormal voltage conditions of the new energy. In view of different protection actions and system voltage conditions, the reclosing delay can be specifically divided into the following four types of scenarios to adaptively adjust the reclosing time:

1. when the islanding voltage amplitude $U \geqslant 0.9$p.u., indicating that the fault has been cleared during the period from the protection outlet to the circuit breaker trip, the circuit breaker can be reclosed immediately;

2. when the islanded voltage amplitude $U < 0.9$p.u., and the main protection action, the circuit breaker tripped after the new energy may be a short period of time to continue to connect to the grid, the use of the proposed criteria to detect the fault state, the detection duration should be $T_{\lim}$ be limited to no more than the fault voltage corresponding to the new energy low penetration time and the protection of the difference between the tripping, while taking into account the circuit breaker reclosing time consuming $t_{\min}$ (this paper is recorded as 0.1s):

$$T_{\lim} = \min\left(t_{\mathrm{LVRT}} - t_{\mathrm{Trip}},\ \ t_{\min}\right) \tag{3}$$

$$t_{\mathrm{LVRT}} = \begin{cases} 0.15, & U < 0.2p.u. \\ 1.964 \cdot U + 0.232, & 0.2p.u. \leq U < 0.9p.u. \end{cases} \tag{4}$$

where: t_{LVRT} is the new energy low voltage crossing time limit (unit: s), measured from the time of failure and related to the system voltage level, t_{Trip} is the trip time of protection action. During the detection, if the criterion (2) is satisfied, the fault is cleared and reclosing is performed; Otherwise, the reclossing is blocked beyond the detection time.

3. When the islanding voltage amplitude $U < 0.9$p.u., and the near backup protection action, according to the protection action time and the new energy fault traversal capability can be subdivided into the following two cases:

(1) If 0.2p.u.$\leq U <$ 0.9p.u., calculate the detection duration $T_{\lim}$ according to equation (3), and reclosing if the criterion (2) is satisfied during the detection period, and blocking reclosing if the detection time is exceeded;

(2) If $U <$0.2p.u., the new energy low penetration time is 0.15s, which is less than the near backup protection action time t_{Trip} (about 0.4~0.5s), then the new energy is off-grid after the circuit breaker is tripped, and the reclosing gate is adjusted according to the passive system, and reclosing is done after 0.3s from the moment of tripping.

4.When the remote backup protection operates, similar to the case of category 3, the criterion detection time is limited according to the protection delay (t_{Trip}=1s) and the corresponding new energy low voltage tolerance time. By calculation, the system voltage of 0.391p.u. in this case corresponds to the new energy grid connection time to reach the limit, so for the system voltage is lower than this value set by 0.3s delay reclosing. The proposed reclosing delay adaptive adjustment idea considering the protection action and distributed new energy continuous grid connection time is shown in Figure 2.

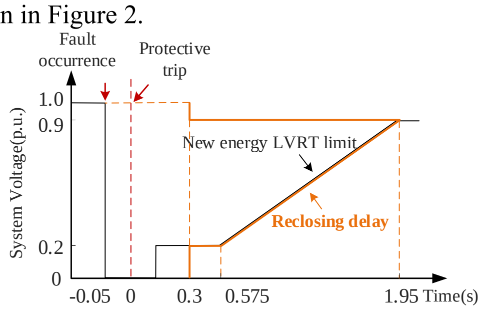


Fig.2 Adaptive tuning scheme of reclosing delay

III. Active Fault State Detection Method Based on Small Current Injection

According to the principle of voltage rise detection method in Section B, this passive method can only detect the removal of transient faults when the new energy is continuously connected to the grid, but it cannot judge the fault status when the new energy is taken off the grid prematurely and the fault with high resistance. In this section, an active fault state detection method using small current injection of new energy grid-connected inverters is proposed for the condition without obvious voltage rise feature.

A. *Small current injection design of distributed new energy inverter*

In view of the controllability of the distributed new energy grid-connected inverter, its modulation link can be modified to control the injection of small current into the distribution network. After the circuit breaker is tripped, the fault state can be determined according to the injection current signal detected at the installation point of the circuit breaker. The inverter outlet voltage based on pulse width modulation control can be expressed as:

$$u_{\mathrm{out}} = \frac{mE_{\mathrm{dc}}}{2} \tag{5}$$

where, u_{out} is the three-phase voltage at the end of the inverter, m is the modulation ratio, E_{dc} is the DC side voltage.

In order to obtain a constant fundamental frequency voltage with a amplitude of U_{am}, the corresponding modulated wave is usually calculated by dividing the outgoing voltage in normal operation by half of the DC voltage rating according to the formula (5), but when there is an asymmetric fault, the DC voltage will not equal its rating. Below, the DC voltage at the time of failure will be derived.

Firstly, the fault negative sequence component causes double frequency fluctuation voltage component on the DC side, and the active power causes double frequency fluctuation in the positive sequence rotating coordinate system.

$$P = P_0 + P_{c2}\cos(2\omega_1 t) + P_{s2}\sin(2\omega_1 t) \tag{6}$$

where P_0 is the average power on the DC side, P_{c2} and P_{s2} are the double frequency components of the active power, and ω_1 is the power frequency electrical angular velocity.

When a fault occurs on the network side and the output power of new energy is blocked, the output active power on the AC side comes from the DC capacitance discharge, so it can be obtained according to the power balance relationship at the DC capacitance

$$C\frac{dE_{dc}}{dt} = -\frac{P}{E_{dc}} \tag{7}$$

By solving (3-7), Edc can be expressed as

$$E_{dc} = \sqrt{\frac{1}{C}\left[-2P_0 t + \frac{1}{\omega_1}\left(P_{s2}\cos 2\omega_1 t - P_{c2}\sin 2\omega_1 t - P_{s2}\right)\right] + E_{dc0}^2} \tag{8}$$

where, E_{dc0} is the initial value of the DC voltage.

It can be seen from (8) that the DC voltage E_{dc} gradually decreases with the frequency doubling fluctuation. At this time, if the modulation wave is still calculated using the DC voltage rating, according to equation (5), the inverter outlet AC voltage will contain a triple frequency component, resulting in a quadrupling of the active power. This, in turn, leads to quadrupling of the DC voltage. In this way, the AC and DC side will produce rich harmonic components. In order to eliminate the effect of the DC voltage change during a fault, the modulation ratio must be calculated in real time based on the actual value of the DC voltage, rather than the rated value. Assuming that the desired AC outlet voltage is u_{cout}, the corresponding modulated wave is

$$m_{cout} = 2u_{cout}/E_{dc} \tag{9}$$

On this basis, the AC outlet voltage of the new energy grid-connected inverter will no longer be affected by the change of DC voltage during the fault period, and the inverter can be regarded as a three-phase fundamental frequency voltage source with the outlet voltage of U_{am}. The fundamental frequency voltage u_{cout} required for control is used as the input signal for inverter control and can be directly generated by the signal generator. If the fault persists, after the circuit breaker of the distribution network is tripped, the injected current must all flow through the fault point, and no signal can be measured upstream of the fault point, so the fault state can be identified by this feature. Because the object of this study is the reclosing of the main outlet of the distribution network, the current measuring point is arranged at the downstream outlet of the outlet circuit breaker. If the response voltage of the injection current is not detected after tripping, it is judged to be a permanent fault. Otherwise, it will be judged as a transient fault. Therefore, the permanent failure criterion can be expressed as

$$\left\|\dot{I}_\varphi \cdot Z_\Sigma\right\| = U_\varphi < U_{set} \tag{10}$$

where, $\dot{I}_\varphi$ is the injected current phasor of the new energy inverter, Z_Σ is the sum of impediments flowing through the injected current, including load, distribution feeder, transformer, etc. U_φ represents the response voltage amplitude measured by each tripping phase in the downstream of the circuit breaker, U_{set} is the corresponding voltage threshold of the injected current at the circuit breaker outlet, and its determination is discussed in the next subsection.

For 10kV distribution lines, the sum of protection action time and breaker breaking time is usually 300ms. In addition, the arc extinguishing time (insulation recovery time) at the fault location is usually 200~300ms, which is affected by many factors such as wind speed, humidity, arc length, etc. Taking these characteristics into account, the reclosing time after failure is set to 500ms. In order to provide sufficient power frequency current for data extraction, the time for fault state identification is set to 40ms.

B. *Set the response voltage threshold*

After the circuit breaker trip and before the reclosing, because the main station of the distribution network has been disconnected from the downstream system, after the instantaneous fault is cleared, the injection current of the distributed new energy inverter will flow through the load to form a voltage drop, and there is a voltage response at the downstream of the circuit breaker. Since the distribution line impedance is much smaller than the load impedance, only the response voltage of the injected current on the load equivalent impedance is considered here. In addition, since the load is seen in parallel between the circuit breaker trip point and the grounding circuit, the more the load is connected to the grid, the smaller the impedance, and the smaller the voltage drop generated by the same injection current, so the response voltage $\dot{U}_{Re}$ is calculated by the total load power of the distribution feeder.

$$\dot{U}_{Re} = \dot{I}_\varphi\left(Z_{Load} + Z_{Line}\right) \approx \dot{I}_\varphi Z_{Load} = \dot{I}_\varphi \frac{U_N^2}{P_{Load} + jQ_{Load}} \tag{11}$$

where, Z_{Load} and Z_{Line} are load and line impedance respectively, U_N is rated voltage amplitude of distribution network, P_{Load} and Q_{Load} are active and reactive power of load respectively. When the downstream load of the circuit breaker is fully connected, the equivalent impedance is minimum, the response voltage amplitude of the injection current is lowest, and the measurement error is considered, the voltage threshold can be set as follows:

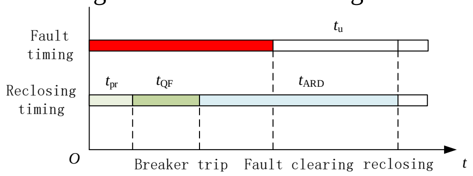
$$U_{set} = k_{rel}U_\varphi = k_{rel}\left\|\dot{I}_\varphi \frac{U_N^2}{P_{Load} + jQ_{Load}}\right\| \tag{12}$$

Where: k_{rel} is the reliability coefficient, which is taken as 0.85 in this study to avoid the influence of measurement error and transient fluctuation on the fault state discrimination.

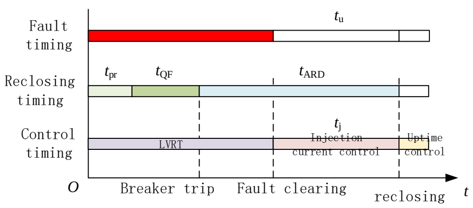
C. *Reclosing action sequence*

The traditional three-phase reclosing method for distribution networks is to reclosing after tripping by a fixed time delay, and its time delay is adjusted to take into account the time of recovery of fault insulation capacity, and the specific action time sequence is shown in Figure 3(a). In the figure, t_{pr} is the protection action time, t_{QF} is the circuit breaker opening time, t_u is the arc extinguishing time at the point of fault and the sum of the surrounding medium deionization time, and t_{ARD} is the delay time before the circuit breaker reclosing.

When a grid fault occurs, the distributed new energy plant performs fault ride-through control to provide reactive power support. In the reclosing method proposed in this study, the new energy inverter will perform current injection control when the distribution circuit breaker trips and before reclosing so that the inverter acts as a weak voltage source. The reclosing is carried out after the fault trip has passed the adaptive time delay in Section B. During this period, if an induced voltage is detected at the breaker outlet, the reclosing will be blocked, and the new energy inverter will stop current injection control after 500ms; if the fault is judged to be cleared, the reclosing will be successful, and the new energy inverter will restart the normal grid-connecting control strategy and gradually restore power supply. Since the injected current provided by the distributed new energy is much smaller than the fault feeder provided by the distribution network, the secondary impact on the system will be reduced for permanent fault situations. The specific action timing diagram of the proposed adaptive reclosing is shown in Figure 3-3(b). In the diagram, tj is the fault state detection time and Re is the breaker reclosing moment. Compared with the action sequence of traditional reclosing, in the case of transient faults, adaptive reclosing can effectively shorten the reclosing time by tens of milliseconds under the premise of identifying the fault state.The process of the proposed adaptive reclosing method is shown in Figure 4.



(a) Traditional distribution network reclosing



(b) Adaptive reclosing

Fig.3 Time sequence for different reclosing methods

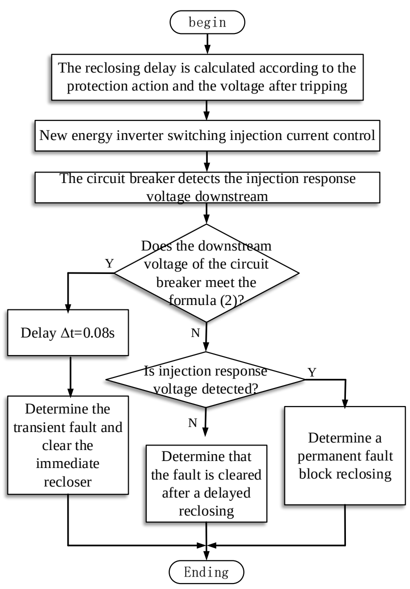


Fig.4 Flow chart of the proposed adaptive reclosing method

IV. EXAMPLE VERIFICATION

In order to verify the correctness and effectiveness of the proposed adaptive reclosion method, a distribution network with distributed photovoltaic access was built in PSCAD, as shown in Figure 5. The total access load was 2MW+0.5Mvar, the capacity of the photovoltaic power station was 400kW, and the substation outlet circuit breaker was equipped with overcurrent protection and the proposed adaptive reclosing strategy. Distributed photovoltaic by medium voltage grid connection, according to the national standard with low voltage crossing ability, injection current control of the modulated phase voltage RMS U_m set to 220V. The faults occurred on the outlet line of the distribution power station. The voltage monitoring point was placed at the outlet of the circuit breaker. The sampling frequency was 3kHz, and the 40ms window length data was collected in a cycle to extract the power frequency component by fast Fourier transform.

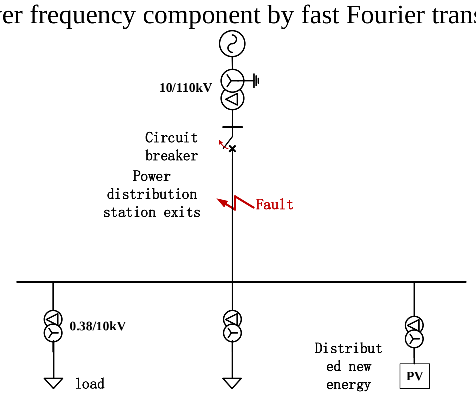
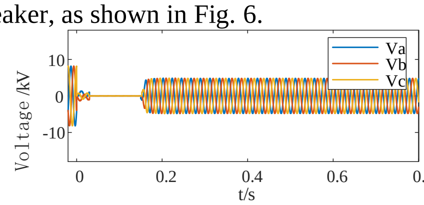
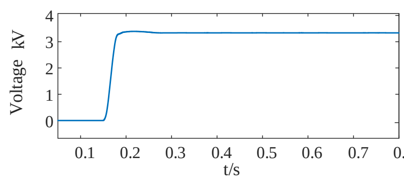


Fig.5 Diagram of distribution system with distributed energy resources

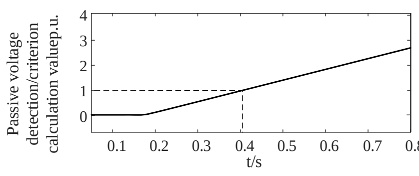
The fault discrimination capability of the proposed adaptive recloser is verified for different types of transient fault cases. A three-phase short-circuit fault is set up on the outgoing line of the distribution substation, and the fault occurs at the moment of 0, the breaker trips at 30ms, and the fault is cleared at 0.15s, and the voltage waveforms and the calculated values of the voltage passive fault detection criterion are detected at the downstream measurement points of the breaker, as shown in Fig. 6.



(a) Three-phase voltage of distribution network after tripping



(b) Voltage amplitude of distribution network after tripping



(c) Calculated value of passive voltage detection criterion

Fig.6 Downstream distribution network voltage and the calculation value of passive detection criterion after tripping

As can be seen from Figures 6, as the fault clears, the voltage of the distribution system downstream of the circuit breaker disconnected from the main station rises due to the continuous grid connection voltage of the distributed new energy sources, and the calculated value of the proposed voltage passive detection criterion grows over time, completing the detection process at 0.41s and determining that the transient fault clears.

Further, transient fault simulations of common types of phase-to-phase faults, two-phase ground faults, and three-phase faults distribution networks were carried out on the outgoing lines of the distribution station to test the effectiveness of the proposed passive fault detection technique based on the voltage rise discrimination, and three fault clearing moments of 50, 80, and 100 ms were set up (with the occurrence of the fault as the 0 moment) to observe the moment when the fault criterion completes the detection, and the results of the transient fault detection The transient fault detection results are shown in Table 1.

TABLE I. TEST RESULTS OF VOLTAGE CRITERION UNDER VARIOUS TYPES OF TRANSIENT FAULTS

Transient fault type	***Troubleshooting time /ms***	***Voltage criterion test results***	***Detection time /ms***
AB phase short circuit	50	Criterion satisfaction	61.25
BC phase short circuit	80	Criterion satisfaction	93.75
AC phase short circuit	100	Criterion satisfaction	110.20
AB two phase short circuit	50	Criterion satisfaction	61.55
BC two phase short circuit	80	Criterion satisfaction	94.05
AC two phase short circuit	100	Criterion satisfaction	110.20
ABC three-phase short circuit	50	Criterion satisfaction	55.10
ABC three-phase short circuit	100	Criterion satisfaction	105.10

[a] Note: If the fault occurs at 0, the following table is the same.

As shown in Table 1, the proposed fault state detection criterion can effectively identify the clearing of transient faults after circuit breaker tripping. After the transient fault is cleared, the reclosing can be accelerated, and compared with the traditional reclosing method that requires a fixed time delay of 3s, the proposed criterion can effectively shorten the power supply restoration time.

V. SUMMARY

In this paper, oriented to the demand for reliable restoration of distribution network faults with distributed new energy access, an adaptive reclosing method based on active-passive fault detection is proposed, and the following conclusions are obtained:

(1) This chapter proposes a passive fault detection method based on voltage magnitude characteristics, for the case of continuous grid connection of distributed new energy, the identification is realized by detecting the voltage rise characteristics after the transient faults are cleared downstream of the circuit breaker; for the case of new energy off-grid, an active detection method using the injection current of the new energy inverter is designed, and the combination of active and passive detection can realize the reliable identification of the fault status in various cases. The combination of active and passive detection can realize reliable identification of fault state in various cases. After theoretical analysis and simulation verification, it can be seen that the proposed fault detection method can correctly identify various types of short-circuit fault states after tripping, and has the ability to withstand certain transition resistance and measurement errors, effectively shortening the reclosing time within 1 second, greatly reducing the risk of reclosing on permanent faults, resulting in a secondary impact on the system.

(2) This chapter proposes to use the blocked distributed new energy inverter as an excitation source to inject a small current signal to identify the fault state, and through the analysis of the circulation circuit of the small current in the fault/non-fault situation, it gives the modulation voltage setting method of the inverter active injection control; at the same time, it gives the calculation method of the threshold value of the voltage at the detecting point taking into account the measurement error, and the timing of the adaptive reclosing action. After simulation verification, the proposed active injection control strategy can effectively realize small current injection and fault discrimination after tripping.

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