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Adaptive protection scheme for distributed systems with DG

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Abstract: A new adaptive protection method for distribution network is proposed, which is suitable for distributed generation (DG) access. According to the operation mode of the system and the topology of the network, this method performs an equivalent transformation on the protection backside network and eliminates the influence of DG on each branch current according to the branch contribution factor matrix. On this basis, adaptive main protection and backup protection are constructed. Compared to the traditional current protection, this method increases the protection range of the main protection and the backup protection, and the calculation is simple and easy to be set. The simulation results show that this method is not affected by DG access, and can satisfy the adaptive functions of protection in the case of symmetric or asymmetric faults.

1 Introduction

With the increasing problems of energy and environment, distributed generation (DG) is increasingly becoming a hot topic for its high efficiency, compatible environment and adaptability to renewable energy. The combined operation of DG and large grid have the characteristics of power supply flexibility, reliability and security [1] and other social benefits, which also with the peak load shifting, reduce network losses and improve the utilisation of existing equipment [2] and other economic benefits. However, the access of DG changed the single-source radiating structure [3] of the distribution network, the running status of the power system and the level of fault, which posed a new challenge to relay protection [4–6].

Brahma and Girgis [7] pointed out that small capacitor of DGs has little impact on relay protection, while some large DGs may cause the traditional three-phase current protection to malfunction. At the same time, the flexible and diverse methods of DG access will also make the protection relationship more complicated. The existing protection scheme [8–10] for distribution network is that: when the fault occurs, all the DGs in the grid cut off immediately to ensure that the original protection operates correctly. The statistical results show that 80% of the faults in the distribution network are instantaneous failures [11]; therefore, the removal of DGs blindly will limit the normal operation of DGs and impair the reliability of power supply [12].

To solve the above problems, some papers have been devoted to the research and development on a new scheme for the adaptive protection of distribution network with DG [13–16], and some results have obtained. Gomez and Morcos [13] and Dugan and McDermott [14] put forward a method of fault location using DG current in DG distribution network. Ackermann and Knyazkin [15] proposed an adaptive protection scheme that introduces the power direction information at the end of the line into the beginning current. Doyle [16] proposed a scheme of directional pilot protection in the upstream region of DG, with the installing equipment of directional elements in overcurrent protection.

With the analysis of the impact from DG on the relationship between traditional protection setting and cooperation, this paper proposes a new scheme of adaptive protection for the distribution network. According to the system operation mode and network topology, this method performs an equivalent transformation on the protection backside network and eliminates the influence of DG on each branch current (BC) according to the branch contribution factor matrix. On this basis, the main protection and backup protection criteria are constructed. Simulation results show that the methods are not affected by DG access and the fault types, and it can effectively increase the protection range of the main protection and backup protection. Moreover, the calculation is simple and easy to achieve.

2 Influence on setting and cooperation of traditional protection with DG access

As shown in Fig. 1, in the radial distribution network, the power supply G supplies the load E via lines AB, BC and CD. When fault F1 occurs, the protection 1 acts immediately to achieve the main protection function and protection 2 provides backup protection for protection 1.

In the distribution network with DG, the above-mentioned coordination of the protection needs to consider the following factors as well:

(i) *The uncertainty of system operation mode*: As shown in Fig. 2, DG1 and DG2 are connected to bus C and bus B, respectively. When fault F1 occurs, the fault current consists of two parts, one is supplied by power supply G, another part is supplied by DG1 and DG2. The operating statuses of DG1 and DG2 directly affect the fault current flowing through protection 1 and protection 2. Therefore, the settings of protection 1 and protection 2 must be able to adapt to changes in DG operating mode.

(ii) *The uncertainty trend of load flow*: As shown in Fig. 2, when fault F2 occurs, protection 2 is required to be prior to protection 1, while fault F1 occurs, protection 1 must operate before protection 2. Therefore, in order to achieve the selectivity of

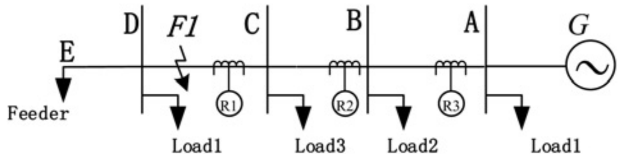

Fig. 1 *Industrial distribution network*

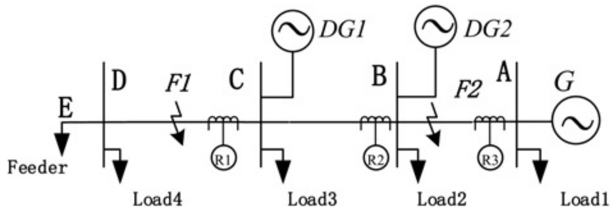

Fig. 2 *Industrial distribution network with DG*

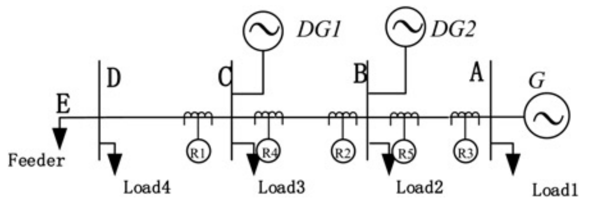

Fig. 3 *Industrial distribution network with directional protection devices*

protection, a directional protective device is installed at the end of each line, as shown in Fig. 3.

3 Distribution network adaptive protection scheme

3.1 Adaptive main protection scheme for distribution network with DG access

In traditional distribution networks, the substation is the only source of power and far from the large generator. In view of this, it can be approximately regarded as that the fault current does not contain the sub-transient components. In this case, the substation can be equivalent to a series voltage with voltage source.

For conventional DGs which only consist of rotary motors, it can be equivalent to the Thevenin model [17]. However, for inverting DGs, they cannot be directly equivalent to their different responses to failures while comparing with the conventional DGs [18]. In response to this situation, this paper proposed a suitable scheme for all types of DGs. As shown in Fig. 3, DG1 is equivalent to the injection current i_1, lines CD? line DE and load 4 are represented by series impedance $Z_{\rm CE}$, and load 3 is represented by its equivalent impedance Z_{d3}. Norton's equivalent model for part of protection backside system as shown in Fig. 4 and its Thevenin equivalent model as shown in Fig. 5.

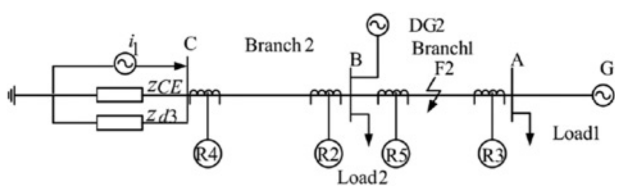

Fig. 4 *Norton equivalent model behind the fourth relay*

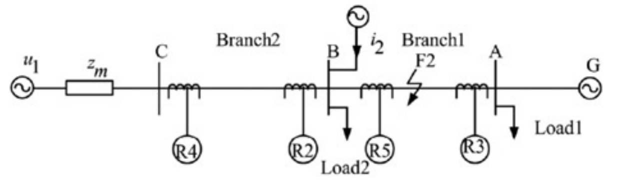

Fig. 5 *Thevenin equivalent model behind the fourth relay*

The voltage in Fig. 5 can be expressed as

$$u_1 = i_1 \frac{z_{\rm CE} z_{d3}}{z_{\rm CE} + z_{d3}} \tag{1}$$

Thevenin equivalent impedance Z_m is

$$z_m = \frac{z_{\rm CE} z_{d3}}{z_{\rm CE} + z_{d3}} \tag{2}$$

Thus, the main protection on protection 4 can be set according to the following formula:

$$i_{\rm ps4} = \frac{k_k k_d u_1}{z_m + z_{\rm BC}} \tag{3}$$

where $i_{\rm ps4}$ is the adaptive setting of the main protection on protection 4; $Z_{\rm BC}$ is the impedance of the protected line BC; k_d is the fault type factor that can be determined before the fault occurs; and k_k is the reliability factor.

In the same way, the main protection adaptive setting value of protection 2, protection 3 and protection 5 can be obtained.

3.2 Adaptive backup protection setting for distribution network with DG access

When the main protection failure or circuit breakers refuse to move, the protection of superior lines must provide backup protection for the line. As shown in Fig. 5, when the fault F2 occurs, the protection 4 achieves the backup protection function of the line AB if the current measurement value of the protection 5 is still greater than the setting value after a certain delay and the main protection is not operated. In view of the changes of DG2 in the operation mode and cause the incorrect operation of protection 4, this paper presents a new method to eliminate the impact of DG2 on protection 4.

First, DG is equivalent to the node injection current and the node voltage equation of distribution network can express as

$$\boldsymbol{I}_{\rm N} = \boldsymbol{Y}_{\rm N} \boldsymbol{U}_{\rm N} \tag{4}$$

$$\boldsymbol{Y}_{\rm N} = \boldsymbol{A} \boldsymbol{Y} \boldsymbol{A}^{\rm T} \tag{5}$$

where $\boldsymbol{Y}_{\rm N}$ is the node admittance matrix, $\boldsymbol{U}_{\rm N}$ is the node voltage column vector, $\boldsymbol{I}_{\rm N}$ is the node injection current column vector, $\boldsymbol{A}$ is the node correlation matrix and $\boldsymbol{Y}$ is the branch admittance matrix.

According to the electric network theory, the relationship between BC $\boldsymbol{I}_{\rm B}$ and node voltage $\boldsymbol{U}_{\rm N}$ can express as

$$\boldsymbol{I}_{\rm B} = \boldsymbol{Y} \boldsymbol{A}^{\rm T} \boldsymbol{U}_{\rm N} \tag{6}$$

According to (4)–(6), the relationship between BC $\boldsymbol{I}_{\rm B}$ and node injection current $\boldsymbol{I}_{\rm N}$ can express as

$$\boldsymbol{I}_{\rm B} = \boldsymbol{Y} \boldsymbol{A}^{\rm T} \boldsymbol{Y}_{\rm N}^{-1} \boldsymbol{I}_{\rm N} \tag{7}$$

Define the formula $\boldsymbol{C}(\lambda) = \boldsymbol{Y} \boldsymbol{A}^{\rm T} \boldsymbol{Y}_{\rm N}^{-1}$ as the branch contribution factor array. With (7), the branch AB current $i_{\rm AB,\ DG2}$ can be calculated, which is contributed by DG2 injection current i_2, that is

$$i_{\mathrm{AB,DG2}} = \lambda_{\mathrm{AB},2} i_2 \tag{8}$$

where $\lambda_{\mathrm{AB},2}$ is an element of the branch contribution factor matrix $\boldsymbol{C}(\lambda)$.

From (9), the AB BC $i_{\mathrm{AB},M}$ can be obtained, which is not influenced by DG2

$$i_{\mathrm{AB},M} = i_{\mathrm{AB},d} - i_{\mathrm{AB,DG2}} \tag{9}$$

where $i_{\mathrm{AB},d}$ is the measured value of AB BC, $i_{\mathrm{AB},M}$ is the AB BC which is not influenced by DG2.

The adaptive value of the backup protection on protection 4 can be calculated as follows:

$$i_{\mathrm{bs4}} = k_{\mathrm{rel}} i_{\mathrm{ps5}} / k_{\mathrm{b}} \tag{10}$$

$$k_{\mathrm{b}} = i_{\mathrm{AB},M} / i_{\mathrm{BC},M} \tag{11}$$

where i_{bs4} is the backup protection adaptive setting value of protection 4, i_{ps5} is the main protection adaptive setting value of protection 5, which can be calculated by (3). k_{b} is the branching coefficient, k_{rel} is the reliability coefficient, $i_{\mathrm{AB,M}}$ is the AB BC, $i_{\mathrm{BC,M}}$ is the BC BC and both $i_{\mathrm{AB,M}}$ and $i_{\mathrm{BC,M}}$ are not affected by DG2.

4 Simulation verification

4.1 Test systems

A 10.5 kV distribution network in Tianjin is used as the test system, which is shown in Fig. 6.

The base capacity of the system is 500 MVA and the reference voltage is 10.5 kV. DG1 and DG2 are connected to bus C and bus B, respectively. The rated power is 10 MVA and the current-mode constant power (PQ) control method is used. Lines AB, BC and AF are overhead lines with line resistance $r1$ as 0.27 Ω/km and line reactance $x1$ as 0.347 Ω/km. Lines CD, DE and FG are cable lines with line resistance $r1$ as 0.259 Ω/km and line reactance $x1$ as 0.093 Ω/km. The rated power of load is 6 MVA and the rated power factor is 0.85. In addition, the current direction protection device is installed at both ends of the line, where bidirectional power flow may occur, and only one protection device is provided on the one-way flow line in order to save investment. The power systems computer-aided design/electromagnetic transient design and control software is used for simulation.

Take the set of main protection and backup protection on protection 5 as an example. The main protection settings and measured values for protection 5 are I_{ps5} and I_{pm5}, respectively, and the backup protection settings and measurements are I_{bs5} and I_{bm5}, respectively.

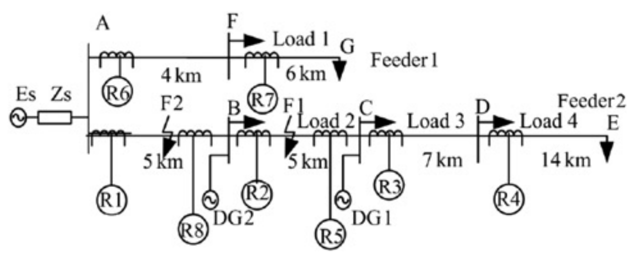

Fig. 6 *Realistic 10.5 kV distribution network in Tianjin power system*

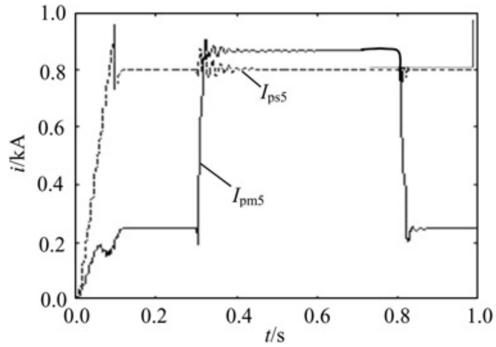

Fig. 7 *Characteristic curve of adaptive primary protection of the 5th relay when a three-phase fault occurs in the middle of section BC*

4.2 Adaptive main protection system

Figs. 7 and 8 show the main protection adaptive operating characteristic curve of protection 5 in the case of three-phase short circuit and two-phase short-circuit fault in the midpoint of the line BC (in the main protection zone).

The faults in Figs. 7 and 8 occurred at $T = 0.30$ s and disappeared at $T = 0.80$ s. The simulation results show that after the fault occurs, the current measurement value I_{pm5} of protection 5 rapidly increases and exceeds the main protection setting value I_{ps5}, and the main protection issues the tripping signal.

4.3 Adaptive backup protection system

When the fault F2 occurs on the line AB and which is near the bus B (in the main protection zone), the protection 5 will be the backup protection of line AB if the current measurement on protection 8 is still greater than the action threshold after a certain delay and the main protection is not active. Figs. 9 and 10 show the adaptive operating characteristic curve of protection 5 under the condition of three-phase short circuit and short circuit.

According to Figs. 9 and 10, it can be seen that the current measurement I_{bm5} is greater than the backup protection setting I_{bs5}, no matter what type of fault occurs (symmetrical fault or asymmetrical fault), and the protection 5 can achieve the backup protection function.

In this paper, with different capacities of DG access, a variety of fault is simulated in distribution network. The simulation results are shown in Tables 1 and 2. As can be seen from Table 1, even in the adverse case of two-phase short circuit, the protection range of the main protection can still reach 80% of the current line. Table 2 shows that in the case of different capacity DG accesses, the scope of protection of backup protection can be extended to more than 40% of the subordinate lines. In addition, the method in this

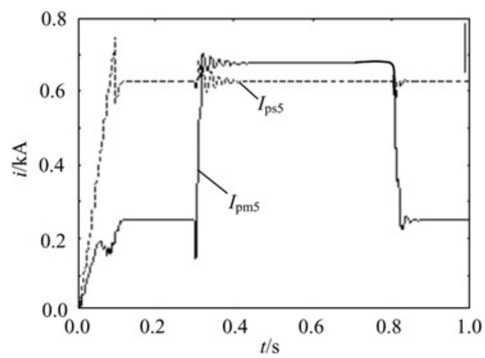

Fig. 8 *Characteristic curve of adaptive primary protection of the 5th relay when a phase-to-phase fault occurs in the middle of section BC*

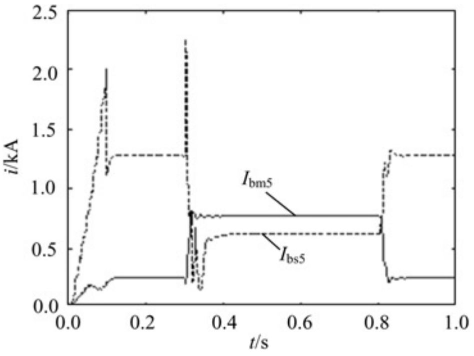

Fig. 9 *Characteristic curve of adaptive backup protection of the 5th relay when a three-phase fault occurs on section AB close to bus B*

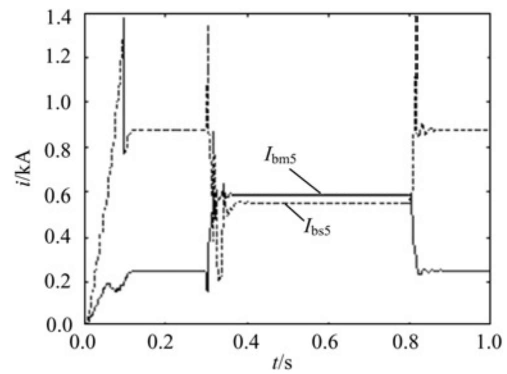

Fig. 10 *Characteristic curve of adaptive backup protection of the 5th relay when a phase-to-phase fault occurs on section AB close to bus B*

Table 1 Measured currents and settings of adaptive primary protection of the fifth relay during phase-to-phase fault

DG_1 capacity, MVA	Fault location, %	Setting current, A	Measured current, A
10	50	628	675
	80	621	622
	100	619	587
5	50	173	185
	80	176	176
	100	179	168
1	50	196	206
	80	204	205
	100	222	205

Table 2 Measured currents and settings of adaptive backup protection of the fifth relay during three-phase fault

DG_1 capacity, MVA	Fault location, %	Setting current, A	Measured current, A
10	100	619	764
	120	639	730
	140	652	700
5	100	171	210
	120	165	187
	140	178	192
1	100	34	42
	120	34	40
	140	35	38

paper is not affected by the type of fault, and the protection performance has been greatly improved.

5 Conclusion

On the basis of the influence from DG on the relationship between traditional protection setting and cooperation, a new adaptive protection method for distribution network is proposed in this paper. Simulation results show that this method has the following characteristics:

(i) Not affected by the DG access, and therefore solving the problem of distribution network protection with DG distribution feeder.
(ii) The protection range of the main protection can still reach 80% of the line, and the protection range of the backup protection can extend to more than 40% of the subordinate line under the adverse situation of two-phase short circuit. Compared to the traditional current protection, this method significantly increases the protection scope of the main protection and backup protection.
(iii) Not affected by the type of fault and satisfied with reliability of protection under both symmetrical and asymmetrical faults.

6 Acknowledgment

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