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A Novel Method of Adaptive Phase-to-Phase Protection on Distribution Network with Inverter Interfaced Distributed Generators

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Abstract

For new energy accommodation, a distribution network connected with distributed generators (DG) requires less investment and is environmentally friendly and flexible as regards power supply. However, the integration of DGs changes the characteristics of distribution network and further affects the performance of the original relays. To reveal the relay protection characteristics of a distribution network with DGs, a novel method of adaptive phase-to-phase relay protection on distribution network with inverter interfaced distributed generators (IIDG) was proposed in this study. The influences of IIDG on the fault characteristics of distribution network lines were analyzed. Moreover, this work introduced an adaptive current protection method that took advantage of the IIDG feature of only outputting a positive sequence current under faults. Meanwhile, the real time digital simulation system was adopted in this study to establish a distribution network simulation model to verify the effectiveness of the proposed method. Results demonstrate that the method can identify the fault position according to the fault location algorithm and automatically adjust the inverse time sequence current relay operating characteristics. The upper-stage and lower-stage relay operating times in the distribution network without DG are 0 and 342 ms, respectively, and with DGs are 306 and 710 ms, respectively. Thus, adaptive cooperation is achieved between the operating times of the upper-stage and lower-stage relays. The proposed method ensures operating speed and reliability of the relay and facilitates the protection of the phase-to-phase fault of a distribution network with DGs.

Keywords: Distributed generator, Distribution network, Inverse time current relay, Fault location, Phase-to-phase protection

1. Introduction

As the voltage source converter (VSC) has good control and voltage conversion capabilities, the distributed generation technology with VSC as the grid-connection interface has developed rapidly [1, 2]. However, this type of distributed generator (DG) is sensitive to the voltage change of the power grid and the transient process is short [3]. These features cause increasing problems. In particular, the transient characteristics of fault after the installation of DG and its influence on the electric parameters of distribution network constitute one of the most noteworthy issues. Traditionally, the fault of a distribution network with non-effective grounding was divided into phase-to-phase and ground faults. The characteristics and corresponding analysis methods for the faults differ. Compared with phase-to-ground fault, the phase-to-phase fault causes more severe consequences and thus requires much attention.

Integration of numerous distributed new energy sources into an AC distribution network changes not only the structure of the distribution network, but also the flow distribution and electric characteristics of the distribution network after the fault. Consequently, the operating performance of relays is affected. To reduce the impacts of DG integration on the existing protection system, the *Technical Rule for Distributed Resources Connected to Power Grid* (Q/GDW 480-2012) of the State Grid Corporation of China requires isolating the DG after the fault occurs [4], restoring the network to a radial structure, and removing the fault with a three-stage current relay. This strategy prioritizes the selectivity of current protection but will cause the disconnection of the DG from power grid. Given that most line faults of the power grid are transient faults, the disconnection of the DG will affect power supply reliability and restrict the consumption of large-scale new energy sources. Therefore, many studies have been conducted on power flow characteristics, fault location, and relay protection of distribution network with DGs under short-circuit fault [5-8]. However, these investigations mainly focused on symmetrical faults and the circumstance in which the DG is disconnected after a fault, thereby failing to analyze the phase-to-phase fault and the situation in which the DG remains connected after a fault. Therefore, to utilize the new energy at a larger scale and with greater efficiency, a relay protection method that can work effectively when the DG remains connected at the time of a fault is necessary.

To this end, this study analyzes the phase-to-phase fault current characteristics of a distribution network with DGs and proposes an adaptive inverse time current protection method on the basis of fault location. This method can keep the DG connected to the distribution network at the time of a fault and take advantage of the characteristics whereby DG outputs a positive sequence current to determine the position of fault, thereby achieving adaptive cooperation of the operating times between the upper-stage and lower-stage relays.

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2. State of the art

Scholars all over the world have proposed many solutions for the protection of distribution network with DGs. Li et al. [9] analyzed the distribution characteristics of a positive sequence fault current of an active distribution network and put forward an inverse time current differential protection method on the basis of a positive sequence fault component. However, the authors did not evaluate different fault sections. Ma et al. [10] compared the scope of application and the pros and cons of three protection methods of distribution network with DGs and conducted simulation analysis. On the basis of a complex sequence network at the time of fault, Feng et al. [11] proposed an adaptive branching coefficient calculation of the positive and negative sequence currents at the relay location and determined the impedance setting value of the distance protection. Nevertheless, they did not examine the operating cooperation among multiple protections. An adaptive protection method for a distribution system under distributed power fluctuations was proposed by Yavuz et al. [12] and can perform adaptive protection operating under various fault conditions. Xu et al. [13] developed a novel protection method for a distribution network by comparing the current amplitude difference between the two sides of a faulted line. Note that the comparison of the current value at two ends requires communication between stations. Yan et al. [14] suggested a technique for partitioning a protected feeder according to the installation point of DG and configuring the directional pilot protection and overcurrent protection. However, this approach is not satisfactory in the case of multi-DGs. Wang et al. [15] devised a new pilot protection method according to the phase difference of the current sequence components at the relay location. With their method, the faults section can be quickly identified in accordance to the value of the phase difference of the current sequence components at both ends of the line. Rodriguez [16] proposed a flexible active power control method on the basis of a fast current controller and reconfigurable reference current selector, and that scheme can provide multiple options for fault ride-through by simply changing the reference selection criteria. Starke [17] analyzed the capacity matching problem of DGs in a distribution network. Rezaei et al. [18] created a novel approach using a feed-forward neural network algorithm to realize the fault identification and position of a DG-containing network. Their system, however, requires extensive pre-training. Sharaf [19] realized coordination between inverse time overcurrent relays within meshed systems by adjusting two relay settings: pick up current and time multiplier settings. Wu et al. [20] established an accurate model for analysis of phase-to-phase short-circuit fault in a DG-containing distribution network and developed an original fault analysis method [20]. Wang et al. [21] considered the influence of various factors on the safety protection of a distribution network and suggested a time-phased adaptive overcurrent protection method according to the time-varying characteristics of each factor. Unfortunately, the algorithm and operating setting of their technique are relatively complicated. Arroudi [22] proposed a method to analyze the distributed generation of wind power and improve the performance of the interconnected protection of a power distribution system on the basis of distance relay protection. The suggested technique solves the intermittent problem of DG in distance protection with pre-fault voltage as reference [22]. Kauhaniemi [23] put forward a power flow algorithm of a DG-containing radial distribution system to examine the impacts of DG penetration on a power distribution system. The author did not investigate the specific protection method [23]. Patil et al. [24] proposed a new overcurrent relay scheme which does not require a potential transformer to determine the direction of the fault but which fails to accurately locate the fault.

The above studies mainly focused on traditional protection methods and overlooked the analysis of the unique feature of a DG-containing distribution network, particularly under the circumstance in which DGs remain connected to the network at the time of the fault. According to an evaluation of the DG fault response characteristics, this study employs the feature in which the inverter interfaced distributed generator (IIDG) only outputs a positive sequence current after a fault to put forward an adaptive current protection method. With this technique, the fault point can be determined according to the fault location result. Moreover, the inverse time sequence current protection operating characteristics can be automatically adjusted to achieve the adaptive cooperation between the operating time of the upper-stage and lower-stage relays. This method can ensure the operating speed and reliability of the protection system.

The remainder of this study is organized as follows. Section 3 analyzes the current-mode control strategy of DG. Accordingly, the current characteristics during the phase-to-phase short-circuit fault of the distribution network are then examined and the adaptive inverse time current protection method on the basis of the fault location is proposed. Section 4 verifies the correctness of the suggested technique through simulation with a real time digital simulation system (RTDS). Section 5 presents the summary and relevant conclusions of this study.

3. Methodology

3.1 Mathematical model of DG control strategy

The current control mode is usually adopted in DGs. In the Park coordinate system, if the voltage vector on the AC side of the inverter is oriented to the d axis, then the DG control equation in the normal operation can be expressed as:

$$\begin{cases} P = U_{\mathrm{d}} I_{\mathrm{q}} \\ Q = U_{\mathrm{d}} I_{\mathrm{q}} \end{cases} \tag{1}$$

where P and Q are the output active power and reactive power of the DG, respectively. U_{d} is the d-axis component of the voltage at the DG installation point. I_{d} and I_{q} are the d-axis and q-axis components of the DG current, respectively.

When the system is in fault state, the control equation on the basis of the fault ride-through control requirements is as follows:

$$\begin{cases} I_{\mathrm{qref}} = I_{\mathrm{q}[0]} + K_{\mathrm{q}} \dfrac{\Delta U}{U_{\mathrm{n}}} \\ I_{\mathrm{dref}} = (K_{\mathrm{P}} + \dfrac{K_{\mathrm{I}}}{sT_{\mathrm{d}}})(P_{\mathrm{ref}} - P_f) \\ \Delta U = U_{[0]} - U \end{cases} \tag{2}$$

where U_n, $U_{[0]}$, and U are the system rated voltage for reference, the voltage at the DG installation point when the system is normal, and the voltage at the DG installation point when the system is in fault state, respectively. ΔU denotes the voltage change at the DG installation point at the time of the fault. I_{qref} and I_{dref} represent the reactive current and active current command of the DG under a fault, respectively. $I_{q[0]}$ is the pre-fault reactive current of the DG. K_q signifies the slope of the reactive power support curve. K_P and K_I are the proportionality coefficients of the PI control link. T_d is the PI control time constant. P_{ref} and P_f indicate the reference active power value and the active power of the DG under a fault, respectively.

3.2 Analysis of the fault characteristics of the distribution network with DG integration

The characteristics of the phase-to-phase short-circuit fault in a distribution network is analyzed according to the DG control strategy model in Section 3.1. The voltage under a fault can be decomposed into a positive and a negative sequence component. Since the negative sequence component will produce double frequency component in the active and reactive power of DG, as well as the control variables I_d and I_q. The current output by DG will not only contain the negative sequence component but also a large number of harmonic components if the conventional control strategy is adopted. Therefore, to improve the output characteristics of a DG, the positive sequence control strategy is usually adopted. With that strategy, only the positive sequence component of the voltage at the DG installation point is accepted as a reference of the control system. Meanwhile, the double frequency component produced by the negative sequence component of the voltage at the DG installation point is filtered out.

Under asymmetrical faults, the output fault current of the positive sequence component controlled DG is determined by the output power of a pre-fault DG and the positive sequence voltage at the DG installation point. Therefore, the DG can be equivalent to a current source controlled by the positive sequence voltage at the installation point. Additionally, the output fault current of the DG only contains a positive sequence component.

Further, Fig. 1 is taken as an example for analysis. In Fig. 1, the Power Source S supplies power to the load through Lines 1 and 2. The DG is connected to the distribution network through Bus 2. The relays are located at Points 1 and 2. Relay 1 and 2 are considered as the upper-stage and lower-stage relays respectively. F1 and F2 are the fault points on Lines 1 and 2, respectively. The current flowing through Relays 1 and 2 are I_1 and I_2, respectively. The output current of the DG is I_{DG}.

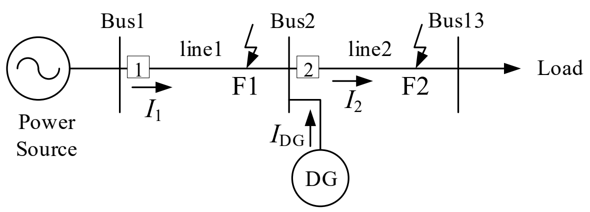


Fig. 1. Schematic of the distribution network with a DG

The positive sequence component network of the distribution network shown in Fig. 1 is detailed in Fig. 2. I_1 and I_2 are the positive sequence currents of Relays 1 and 2 under a fault. The DG is effective only in the positive sequence network.

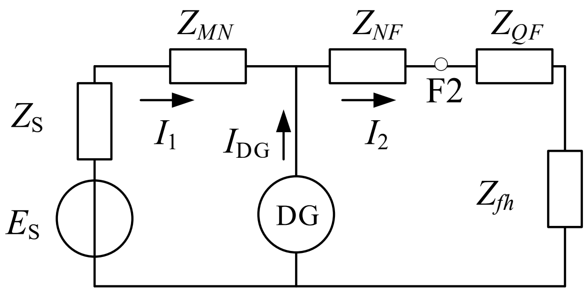
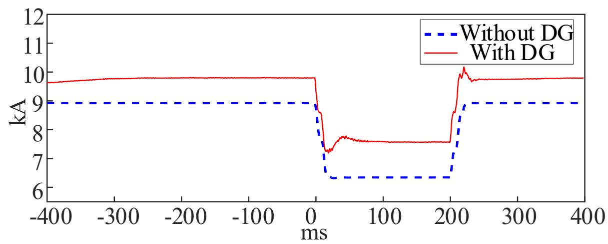
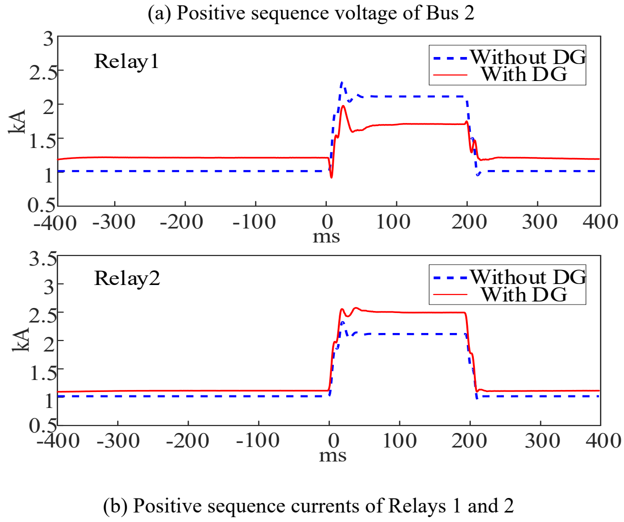


Fig. 2. Positive sequence fault network

The output current of the DG is correlated to the positive sequence voltage at its installation point, namely, the location of the fault point. In addition, the DG not only provides a positive sequence current, but also offers reactive power support. Taking the fault at Point F2 on Line 2 as an example and in comparison with the lines of a distribution network without DG, the DG increases the voltage U_2 of Bus 2, reduces current I_1 flowing through Relay 1, and increases current I_2 flowing through Relay 2. Fig. 3 shows the curves of U_2, I_1, and I_2 before and after the DG installation. Note that after the DG installation, U_2 increases from 6.3 kV to 7.6 kV, I_1 decreases from 2.1 kV to 1.7 kA, and I_2 rises from 2.1 kA to 2.5 kA.



(a) Positive sequence voltage of Bus 2



(b) Positive sequence currents of Relays 1 and 2

Fig. 3. Influence of the DG installation on the electrical parameters of the distribution network

Given that I_{DG} is correlated to the positive sequence voltage at the DG installation point, Fig. 4 shows the I_{DG} at different fault points. When the fault point is farther from the DG, I_{DG} decreases from 2.3 kA to 2.2 kA.

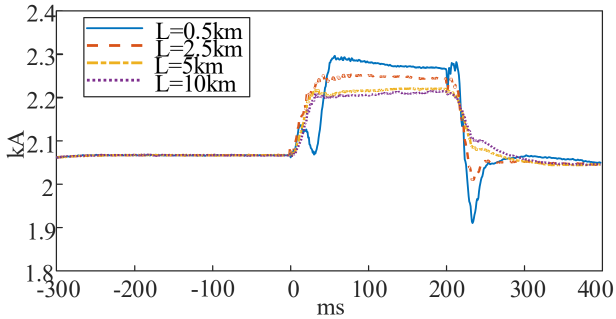


Fig. 4. Schematic of the DG output currents at different fault points

3.3 Adaptive inverse time current relay protection with fault location

On the basis of the fault current characteristics deduced in Section 3.2, the characteristics of the fault current will differ in line with the different locations of the fault point and whether the DG is connected or not. Moreover, the relay protection system should be adjusted accordingly.

The existing stage overcurrent relay protection of the distribution network is affected by the system operation mode and extensive time is necessary for the cooperation between the upper-stage and lower-stage relays. The configuration of the longitudinal relay requires an increase of channels and investment in other equipment. Therefore, improving the selectivity and operating speed of the distribution network protection system while adapting to the DG installation is one of the difficulties in the distribution network protection.

This study proposed a distribution network protection method in which the fault location cooperates with an inverse time current relay. This technique determines the position of the fault point according to the fault location results, and then automatically adjusts the operating characteristics of inverse time sequence current relay to achieve adaptive cooperation between the operating times of the upper-stage and lower-stage relays. This approach ensures the operating speed and selectivity of the protection system.

With reference to the phase-to-phase fault location algorithm in distance protection, the location algorithm is as follows:

$$Z_{ij} = \frac{\dot{U}_{ij}}{\dot{I}_{ij}} = \frac{\dot{U}_i - \dot{U}_j}{\dot{I}_i - \dot{I}_j} \quad (i \neq j) \tag{3}$$

where $\dot{U}_i$ and $\dot{U}_j$ denotes the voltages at the relay locations, $\dot{I}_i$ and $\dot{I}_j$ represent the current at the relay location. Z_{ij} is the phase-to-phase measured impedance.

The measured and the full-length impedances of the line are compared to determine the fault location.

The operating characteristic of the inverse time current relay means the protection operating time is in a non-linear inverse relation with the fault current. The greater the fault current is, the faster the relay operates, and vice versa. The relay operating time can reflect fault severity. Therefore, the performance of the inverse time current relay is better than that of the stage overcurrent protection. However, when the DG is not connected and a fault occurs at F2, as Fig. 1 shows, the same current flows through Relays 1 and 2, and inverse time Relays 1 and 2 have the same operating time. Therefore, Relay 1 may have a leapfrog trip.

To overcome the above problems, the operating characteristics of inverse time current relay are improved in combination with the results of fault location. According to the analysis of Section 3, the influence on relays after the DG integration is reflected by changing the positive sequence current flowing through the upper and lower lines under a fault. Moreover, the positive sequence current is used in the algorithm. The operating characteristics of the improved inverse time current relay protection are:

$$t = \begin{cases} 0 & 0 \le Z_{ij} < 0.7\mathrm{Z_L} \\ T\dfrac{k}{(I/I_S)^{\alpha} - 1} & Z_{ij} \ge 0.7\mathrm{Z_L} \end{cases} \tag{4}$$

where t is the operating time of the inverse time current relay. I is the positive sequence current at the relay location. T is the time adjustment coefficient. k and α are constants, and $k = 0.14$ and $\alpha = 1.18$. I_S is the initial current of 300 A.

The operating characteristics of improved inverse time current relay are shown in Fig. 5. By taking 0.3 s as the operating time when a phase-to-phase short circuit occurs at the end of the line under the minimum mode of the system, Eq. (4) can be solved. Then, the time adjustment coefficient is obtained as $T = 30$.

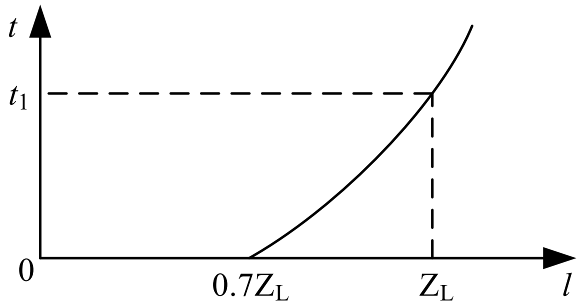


Fig. 5. Operating characteristics of adaptive inverse time current relay

3.4 Simulation model for verification

A fault protection simulation model in RTDS is established according to the above analysis of fault characteristics and algorithm principles. The evaluation in Section 3.2 shows that fault current characteristics are related to whether a DG is connected or not. So the analysis in this section is also conducted for two cases, namely, whether the DG is connected or not.

(1) Distribution network without DG

As shown in Fig. 6, fault occurs at F1 on Line 1. The fault location result Z_{ij1} of Relay 1 is located at [0, 0.7 Z_1], and the operating time of Relay 1 is 0 s. When Z_{ij1}>0.7 Z_1, the operating time t_1 of the inverse time current Relay 1 can be obtained by Eq. (4). The fault phase current of Relay 2 is reduced to zero from the load current, and the inverse time current Relay 1 does not act.

When a fault emerges at F2 on Line 2, the fault location result of Relay 1 is that Z_{ij1}> Z_1, and the operating time t_1 of the inverse time current Relay 1 can be obtained by Eq. (4). The fault location result Z_{ij2} of Relay 2 is smaller than

Z_{ij1} of Relay 1. Consequently, the operating time t_2 of the inverse time current Relay 2 is smaller than t_1 of Relay 1.

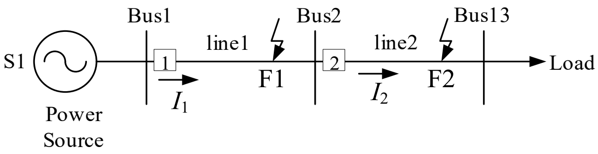


Fig. 6. Schematic of the distribution network

(2) Distribution network with a DG

When the fault occurs at F1 on Line 1, the fault location result Z_{ij1} of Relay 1 is at [0, 0.7 Z_1], and the operating time of Relay 1 is 0 s. When Z_{ij1}>0.7 Z_1, the operating time t_1 of the inverse time current Relay 1 can be obtained by Eq. (4). The positive sequence current of Relay 2 is the current I_{DG} supplied to the load by the DG. I_{DG} is smaller than I_1 at Relay 1, and the fault location result at Relay 2 is a negative value. The adaptive inverse time Relay 2 does not act.

When a fault occurs at F2 on Line 2, the fault location result of Relay 1 is Z_{ij1}> Z_1, and the operating time of the inverse time current Relay 1 can be obtained by Eq. (4). The fault location result Z_{ij2} of Relay 2 is smaller than Z_{ij1} of Relay 1. The current flowing through Relay 2 is supplied by the DG and Power Source S1. The current flowing through Relay 1 is a positive sequence current supplied by Power Source S1 and is smaller than that flowing through Relay 2. Therefore, the operating time of the inverse time current Relay 2 is smaller than that of Relay 1.

In summary, the adaptive inverse time current relay protection proposed in this study is suitable not only for distribution lines with a DG, but also for those without DG. Meanwhile, this technique increases the operating speed of the protection system and ensures selectivity between the upper-stage and lower-stage protections.

4 Result Analysis and Discussion

RTDS simulation software was employed to establish a DG-containing distribution network model according to Fig. 1 and Fig. 6 so as to verify the adaptive current protection method. We took the system reference capacity as 100 MVA, the reference voltage as 10.5 kV, the short-circuit capacity as 400 MVA; the inductance and resistance of the unit length of the line as 0.346 and 0.27 Ω/km, respectively; and the length of Lines 1 and 2 as 3 and 2 km, respectively. The simulated results are as follows.

4.1 Distribution network without DG

When the AB phase-to-phase fault occurs at F1 (1.5 km away from Relay 1) (Fig. 6), the positive sequence current at Relays 1 and 2 are shown in Fig. 7. At Relay 1, the AB phase-to-phase measured fault distance is 1.505 km, the BC phase-to-phase distance is 6.661 km, and the CA phase-to-phase distance is 3.204 km. According to Eq. (4), the operating time of Relay 1 is 0 ms and Relay 2 does not act.

When the AB phase-to-phase fault occurs at F2 (1 km away from Relay 2) (Fig. 2), the positive sequence current at Relays 1 and 2 are shown in Fig. 8. At Relay 1, the AB phase-to-phase measured fault distance is 3.356 km, the BC phase-to-phase distance is 12.341 km, and the CA phase-to-phase distance is 5.058 km. At Relay 2, the AB phase-to-phase measured fault distance is 1.005 km, the BC phase-to-phase distance is 11.270 km, and the CA phase-to-phase distance is 5.352 km. According to Eq. (4), the operating time of Relay 1 is 342 ms and that of Relay 2 is 0 ms.

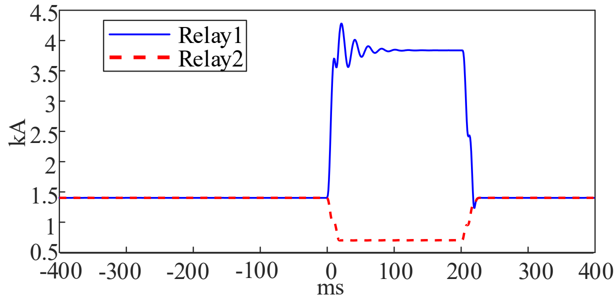


Fig. 7. Positive sequence currents at Relays 1 and 2 when the BC phase-to-phase short circuit occurs at F1

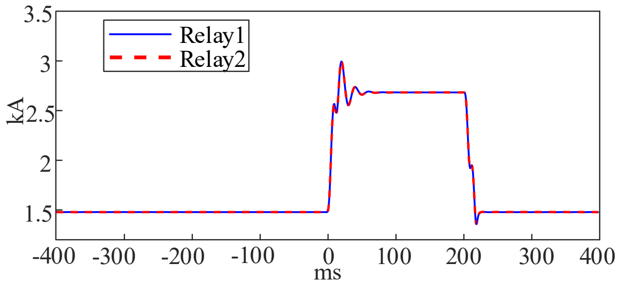


Fig. 8. Positive sequence currents at Relays 1 and 2 when the BC phase-to-phase short circuits occur at F2

4.2 Distribution network with DG installation

When a BC phase-to-phase fault occurs at F1 (1.5 km away from Relay 1) (Fig. 1), the positive sequence currents at Relays 1 and 2 are shown in Fig. 9. At Relay 1, the AB phase-to-phase measured fault distance is 4.800 km, the BC phase-to-phase distance is 1.505 km, and the CA phase-to-phase distance is 4.407 km. According to Eq. (4), the operating time of Relay 1 is 0 ms and Relay 2 does not act.

When a BC phase-to-phase fault occurs at F2 (2 km away from Relay 2) (Fig. 1), the positive sequence currents at Relays 1 and 2 are shown in Fig. 10. At Relay 1, the AB phase-to-phase measured fault distance is 14.865 km, the BC phase-to-phase distance is 4.895 km, and the CA phase-to-phase distance is 9.128 km. At Relay 2, the AB phase-to-phase measured fault distance is 2.74 km, the BC phase-to-phase distance is 0.908 km, and the CA phase-to-phase distance is 6.056 km. According to Eq. (4), the operating time of Relay 1 is 710 ms and that of Relay 2 is 306 ms.

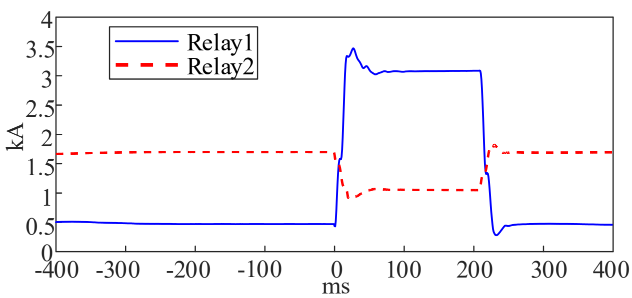


Fig. 9. Positive sequence currents at Relays 1 and 2 when the AB phase-to-phase short circuit occurs at F1

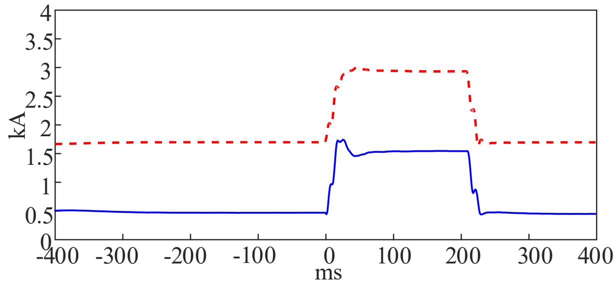


Fig. 10. Positive sequence currents at Relays 1 and 2 when the AB phase-to-phase short circuit occurs at F2

5. Conclusions

To deal with the changes of the electric parameters of a distribution network and the negative impacts on relay protection performance after DG integration, a novel method of phase-to-phase fault protection for a distribution network with IIDG was proposed in this study. The fault location algorithm of distance protection was adopted to determine the fault position. Then, the operating time of the inverse time positive sequence current protection adjusts automatically, thereby achieving adaptive cooperation between the upper-stage and lower-stage protection systems. Simulation verification was conducted to verify the method, and the following conclusions were drawn.

(1) This method can be implemented simply with single-end electric information and does not require data communication. With this technique, the fault can be accurately positioned and thus attain adaptive protection of the system under different fault conditions.

(2) With this method, distribution networks with and without DG can be effectively protected from phase-to-phase fault with rapid protection operation. The operating times of Relays 1 and 2 without DG are 0 and 342 ms, respectively, and those of the distribution network with a DG are 306 and 710 ms, respectively.

(3) This method takes advantage of the characteristics that the DG presents a controlled current source at the time of fault to achieve protection goals. That feature can keep the DG connected to the network when a fault occurs, thereby further improving the utilization efficiency of new energy and the power supply reliability.

The proposed phase-to-phase fault protection method for distribution network with DGs realizes fault location and inverse time current relay protection, achieves good protection performance, and is therefore of practical significance in engineering application. However, given the limitations on research conditions, field testing has yet to be conducted. In follow-up studies, the effectiveness of this technique will be verified through field tests, with the setting parameters optimized to achieve general applicability.

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