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Positive-sequence-fault-component-based blocking pilot protection for closed-loop distribution network with underground cable

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ABSTRACT

Closed-loop operation of distribution network has attracted more attention recently to improve supply reliability and adopt Distributed Energy Resources (DERs) friendly. Its protection is usually independent of distribution automation system (DAS). This article presents a blocking pilot protection method for closed-loop distribution network with underground cable, that can be accomplished by remote terminal units (RTUs) in DAS. First, operation value of RTUs is designed on the current variation after fault and the RTUs are synchronized automatically based on fault signal. Second, the power direction characteristic of positive-sequence fault component is analyzed when various short circuit fault occurs at different locations. Based on that, the state of Ring Network Cabinet (RNC) are classified into five types and uniform blocking signal exchanging rule between adjacent RTUs is designed. The fault can be located and isolated directly by cooperation of adjacent RTUs. The setting principle and the operation logic for the pilot protection is given and its performance is analyzed. Finally, simulation model based on PSCAD is constructed. The simulation results prove that this protection can locate and isolate faults timely on the premise of high sensitivity. It has strong ability of enduring fault resistance and it can fit closed and open operation mode.

1. Introduction

Power system is playing an important role in modern society. The outage (including short interruption) can cause huge economic losses especially for the high density and mission critical loads [1–4]. Medium voltage distribution networks are usually operated in a radial configure. Simple and inexpensive protection and control measurement is quipped. But the load has to suffer short interruption when the fault is isolated and non-fault area is recovered. It cannot meet the demand of important load for the supplying reliability [5]. Meanwhile, the distributed energy resources (DERs) has been researched and applied worldwide. The short circuit fault current becomes bidirectional. The conventional radical network structure with existing protection technology cannot adopt the DERs friendly [6–10].

Distribution network with closed-loop operation is attracting attentions to improve the supply reliability and adopt DERs friendly [11–15]. Short circuit current in closed loop distribution network becomes bidirectional and traditional over current protection will lose selectivity. Pilot wire instantaneous over-current protection for closed-loop network is proposed [16], that is based on the directional over current protection theory and sectionalized overhead line structure. The blocking signal will be sent to the upstream protection if the fault current is detected as positive direction. The protection that cannot receive the blocking signal within a certain time, will send out the tripping signal to its corresponding breakers. Meanwhile, the possibility of non-communication over-current protection is also investigated for its potential application in closed loop networks [16–19]. Three protection methods for closed loop network are discussed in Ref. [20], including separation based protection, directional over current protection and pilot protection. In Ref. [21], pilot protection is discussed. The protection is equipped at one end of the loop and it can control the breakers at two ends, in order to ensure the implement economy. But all the load supplied by the loop network will suffer outage as fault occurs in the network. Otherwise, three-level centralized differential protection system is presented in Ref. [22], that is accomplished by the cooperation of distribution automation system (DAS) and central protection equipment. Remote Terminal Units (RTU) acquire and send the real time operation data to the central protection equipment. The result is

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determined based on the differential protection theory and the final result is transferred to the master station (MS). Then, MS decides how to recover the system next. In fact, it is similar to the traditional pilot protection for lines.

Underground cable is widely used in most urban distribution networks. Ring network cabinets (RNC) are set to connect the load with the distribution network. RTU is installed in each RNC, that can acquire and transfer the operation data to MS. Generally, centralized decision is made by the master station to locate and isolate the fault, and even restore the normal parts gradually. But fault treating process is usually over 30s because of the communication delay and centralized decision. Distributed intelligence (DI) based multi agent system has been introduced into the DAS [23,24], that can improve the efficiency of fault treating process. But the fault location strategy depends greatly on the specific issue without generality.

Based on DAS, this paper presents a positive-sequence-fault component-based blocking pilot protection for closed-loop distribution network with underground cable. The positive sequence power direction at every RTU of RNC is analyzed when different fault occurs at various location. The RNC state and uniform sending rule of blocking signal among adjacent RTUs is designed according to the positive sequence power direction characteristic. The fault can be located and isolated directly by the cooperation of adjacent RTUs. Simulation results based on PSCAD prove the validity of the presented method.

2. Primary and secondary system of closed loop distribution network with underground cable

Closed-loop distribution network with underground cable is shown in Fig. 1. Where, $\dot{E}_{S1}$ is the equivalent voltage of source 1 and $\dot{E}_{S2}$ is the equivalent voltage of source 2. If the feeders of the closed loop distribution network come from the same bus bar, $\dot{E}_{S1} = \dot{E}_{S2}$. Otherwise, $\dot{E}_{S1} \neq \dot{E}_{S2}$ and there will be loop power that can result in unbalanced output power between the feeders. Some power flow control methods have been researched [11–13,15], to balance the power. Protection is focused on and suppose that there is no big loop current in this article.

In Fig. 1, the positive direction of the closed loop network is defined from bus bar M to N. M side is the upstream and N side is the downstream. RTU is installed in each RNC. QF_{iM} and QF_{iN} is the circuit breaker quipped in the RNCi, which can be controlled

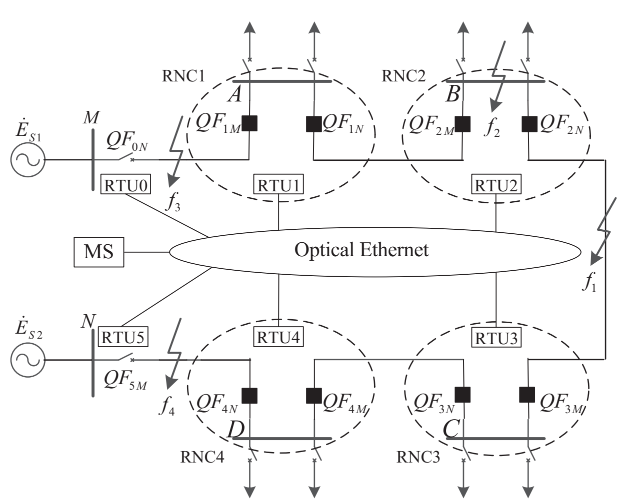

Fig. 1. Primary and secondary system of closed-loop distribution network with underground cable.

by RTUi. QF_{0N} is the circuit breaker for feeder from M Bus and QF_{5M} is that for feeder from N Bus. They can be controlled respectively by RTU0 and RTU5. RTUi can monitor the voltage at RNCi bus bar and the current through QF_{iM} and QF_{iN} (i = 1–4). All the RTUs can support peer-peer communication, exchanging information directly with each other by Optical Ethernet. Meanwhile, all the RTUs can make their time synchronized based on the fault occurring time [25]. RTUs can also communicate with MS.

3. Positive-sequence-fault-components-based blocking pilot protection for closed loop distribution network

Short circuit fault current consists of load current and fault components. Load current is helpless to design the protection. Positive sequence fault component can reflect all types of short circuit fault, that can overcome the influence of load current effectively. It has been adopted widely in the power system protection [25]. For the closed-loop distribution network with underground cable, the power characteristic of positive sequence fault component when different fault occurs at various location is analyzed in this section. Then the state of RNCs and the uniform sending principle for blocking signal is designed. Moreover, the setting principle and protection logic is proposed.

3.1. Analysis of fault characteristics

The closed loop distribution network with four RNCs is shown in Fig. 1. Suppose that the short circuit fault occurs respectively at f_1, f_2, f_3 and f_4.

When short circuit fault occurs at various locations, the corresponding positive sequence current and voltage fault components are shown in Fig. 2(a)-(d). Where, $\dot{U}_1$ is supposed as the positive sequence voltage fault component at the fault spot. $\dot{U}_{1-i}$ is the positive sequence voltage fault component at RNCi bus bar. $\dot{I}_{1-iM}$ and $\dot{I}_{1-iN}$ is the positive sequence current fault component through QF_{iM} and QF_{iN} $(i = 1, 2, 3, 4)$. Suppose that the reference positive direction in RNCi is from its internal bus bar to the feeder. The positive direction of the substation is from the bus bar to the feeder. The reference current is expressed as $\dot{I}_{r1-5M}$, $\dot{I}_{r1-0N}$, $\dot{I}_{r1-iM}$ and $\dot{I}_{r1-iN}$ $(i = 1, 2, 3, 4)$, as shown in Fig. 2.

Because the equivalent resistance is usually greater than the inductive reactance in the distribution system (ratio is over 5). Their impedance angle can be regarded nearly as 0°. Considering actual measuring, transforming and time synchronizing error, the angle between reference positive sequence voltage and current in Fig. 2 can be expressed as

$$\begin{cases} -90^\circ < \frac{\dot{U}_{1-i}}{\dot{I}_{r1-iM}} < 90^\circ \\ -90^\circ < \frac{\dot{U}_{1-i}}{\dot{I}_{r1-iN}} < 90^\circ \end{cases} \tag{1}$$

For the fault at different spot, the actual power direction of positive sequence fault components can be concluded based on (1) and Fig. 2(a)-(d), as shown in Table 1.

Obviously, the short circuit fault can be located by comparing the power direction of positive sequence fault components, that can be calculated by the RTUs with local voltage and current information, and the fault can be located by adjacent RTUs. But it is necessary to design uniform protection principle for RTUs firstly.

3.2. Classification of RNC state and uniform sending rule of blocking signal

The state of RNCs is used to determined the cooperation mode of RUTs, that can be classified based on the power direction