FAST FAULT ISOLATION AND RESTORATION OF THE LOOPED MV CIRCUIT

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ABSTRACT

A new fault isolation and restoration technique for the looped MV circuit, which employs local Ethernet network, is presented. It can isolate all short circuit faults in the loop within 200ms and restore the supply of healthy sections in less than 2 seconds. A reliable fault location method for isolating the single phase to ground fault in the non-effectively earthed network, which makes use of the fault generated transients is also proposed. Laboratory test and simulation results show the proposed techniques are feasible.

1 INTRODUCTION

Fast development of economy and proliferation of sensitive electronic equipments leads to requirements to higher power supply reliability. With application of feeder automation (FA) technology a fault in the looped circuit of MV distribution network can be isolated and the supply of healthy sections can be restored in less than 3 minutes. However, for some critical customers, such as semiconductor factories, even a few cycles long interruption will result in serious consequences and is not acceptable. Power utilities are facing ever-increasing pressure to employ new technology to further reduce the number and duration of supply interruptions.

In some countries, such as China, most their MV distribution networks employ non-effectively earthed neutrals, a large amount of which is Peterson coil compensated. The steady state current induced by single phase to ground fault (SPGF) in the compensated network is very small and can hardly be detected. Therefore, the existing FA technology is not able to locate the SPGF and its role in reducing fault caused outages is largely compromised. It is imperative to devise a reliable SPGF fault location method to improve the performances of FA systems.

2 EXISTING FAULT ISOLATION AND RESTORATION METHODS

Two fault isolation and restoration methods are used in practice.

Type A: Successive Reclosing Method

The successive reclosing method, named as Type A method hereafter, doesn't rely on communication link, and hence is known as a non-communication method. Fault isolation and restoration is completed by successively reclosing the circuit breaker in the infeeding substation and sectionalizing switches in the feeder.

The Type A method doesn't require communication link, and is cost effective. However the multiple reclosing to a permanent fault will cause serious threats to system safety. It is usually used in rural overhead distribution network.

Type B: Telecontrol method

Telecontrol method, named as Type B method hereafter, isolates a fault in the looped circuit through remote control to the field circuit breakers and the sectionalizing switches by a master station.

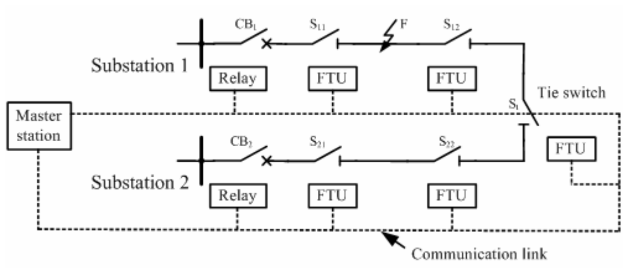


Fig. 1 The diagram of Type B FA system for a overhead line

A FA system of overhead line employing Type B method (Called Type B system) is shown in Fig.1. The sectionalizing switch (SS) in the looped circuit is monitored and controlled by a feeder terminal unit (FTU). The circuit breaker (CB) in substation is either controlled by a microprocessor based relay or a FTU in case the relay can not communicate with the remote control station. All FTUs (including the CB relay) are connected to the master station through communication link. After a permanent fault is cleared, the master station will identify the faulted line section by examining overcurrent detection results sent by FTUs, and send tripping commands to FTUs at both ends of the faulted section to isolate the fault. To restore supply of all healthy sections the master station will close the CB in the substation when the fault is not in the first outgoing section and the tie switch when the fault is not in the section adjacent to it. Take a permanent fault at point F in the feeder of Fig.1 for example. It will be first cleared by CB_1. Then the master station will open S_{11} and S_{12} to isolate the fault, and close CB_1 and tie switch S_1 afterwards to restore supply of the section between CB_1 and S_{11} and the section between S_{12} and tie switch.

A looped cable circuit with four ring main units (RMUs) is shown in Fig.2. Fuses are used in the outgoing circuits of RMU to clear faults on them. The tie switch S_{22} is open in normally. Two incoming switches of the RMU are monitored and controlled by the FTU. For a fault at point F in the feeder of Fig 2, it is first cleared by the circuit breaker CB_1 in substation 1. The master station identifies the fault location and sends commands to FTUs at RMU 1 and RMU 2 to open S_{12} and S_{21}. After the fault is isolated, the master station will send the commands to close CB1 and switch S_{22} to restore supply to RMU1 and RMU2.

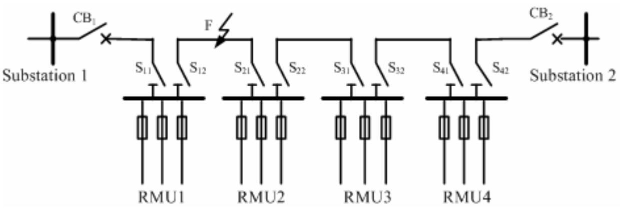


Fig. 2 A looped cable circuit with four RMUs

The Type B method does not require the circuit breaker (switch) reclose to fault several times, and therefore the threats to system safety are reduced. However the investment involved is higher as the communication link is needed. It is usually used in urban area of a city, where the load has high density and requires high supply quality.

3 A NEW FAULT ISOLATION AND RESTORATION METHOD

In both Type A and Type B methods, the fault is cleared by tripping the CBs in the infeeding substation, and therefore result in temporary supply interruption in healthy sections. A new fault isolation method, which can further reduce the number and duration of interruptions, is developed. The method is named as Type C method to distinguish it from other two fault isolation methods. The FA system based on Type C method (Called Type C system) is similar to the Type B system, but the sectionalizing switches are replaced by the CBs which can break fault current. It requires all FTUs (including the relay of substation CB) in the feeder can exchange data each other.

A Type C system for overhead line is shown in Fig.1, where the OESs are switchers of optical industry Ethernet. They are connected by optical fibers and formed a self-healing double ring Ethernet. The FTUs (including the relay for the CBs) are connected to the Ethernet through 10/100M electrical port of OEPs. A communication processor (CP) is used to establish communication between the SCADA master station and the FTUs. When a fault occurs in the feeder the upstream FTUs detects fault current and exchanges overcurrent signals with adjacent FTUs. A section is identified as the faulted one if its upstream FTU sees fault current and the downstream one doesn't. First the upstream FTU of the faulted section trip the CB and reclose after a preset time. The FTUs at both ends of the faulted section will trip the circuit breakers to isolate the fault if the fault is a permanent one and the CB reclose is failed. After a permanent fault is isolated FTU at the open point of the loop will close the tie CB to restore supply of the healthy sections when the fault is not in the section adjacent to it. Assume a fault occurs at the point k in the feeder of Fig.1, the faulted section is identified by FTUs installed at CB_{12} and CB_{13} by exchanging fault detection results each other. CB_{12} trips first to clear the fault, then recloses to restore the supply. If the fault is a permanent one, CB_{12} and CB_{13} will then trip simultaneously to isolate the fault. Finally the tie breaker CB_t closes to restore the supply of the section between CB_{13} and the tie switch CB_t.

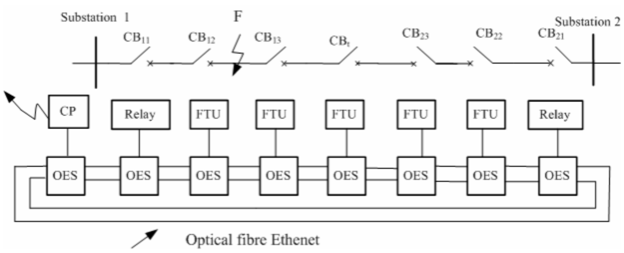


Fig. 3 The diagram of Type C FA system for a overhead line

The fault isolation principle of Type C system for a looped cable circuit is similar for a overhead line circuit. A FTU monitors and controls two incoming CBs in the RMU. When a fault occurs in the cable circuit the FTUs at the RMUs of both ends of the faulted section locate the fault by exchanging fault detection results each other. The breakers at both ends of the faulted section will trip to isolate the fault. Then the tie switch will close to restore supply to the affected RMUs.

A fault in the outgoing circuits of the RMU can also be isolated automatically if it is equipped with an automated load breakers. In this case, the switches in outgoing circuits will also be monitored and controlled by the FTU in the RMU. When a fault occurs in the outgoing circuits, the fault will be cleared first by tripping two incoming CBs. The FTU will find out the faulted circuit by examining the currents of outgoing circuits and open the switch of the faulted circuit to isolate the fault. Then the incoming CBs close to restore supply of the RMU.

Type C system can isolate all faults in the loop within 200ms, and restore the supply of healthy sections in less than 2 seconds. The number of interruptions is significantly reduced as the fault is cleared by tripping the upstream CB of the faulted section instead of the CB in the substation. Take the system in Fig.3 for example. A fault at any point of the feeder will result in interruptions of whole feeder in Type A and Type B systems. For Type C system, a fault in the section adjacent to the tie breaker will not cause interruptions in any healthy sections. For a fault in the sections between CB_{11} and CB_{13} only the sections between the fault and the tie breaker will experience short interruptions. Assume the fault probability is uniformly distributed along the feeder, the Type C system will reduce the number of short interruptions by half compared with Type A and Type B systems. Meanwhile, the fault restoration time of Type C method will be reduced to seconds from minutes required by Type A and Type B methods. The investment of Type C system is relatively larger than Type B system as it requires peer to peer communication link among FTUs.

4 SPGF ISOLATION IN NON-EFFECTIVELY EARTHED NETWORK

A single phase to ground fault (SPGF) in non-effectively earthed network will generate zero mode transient current (ZMTC) that has much larger magnitude than steady state current. It is almost not affected by Peterson coil as the transient signal has much higher frequency. A faulty feeder identification method using transient signals has been developed and proved to be more sensitive and reliable than conventional methods by practical field results. The transient technique can also be adapted to locate the section with a SPGF.

Characteristics of ZMTC

The equivalent circuit of zero mode network for a SPGF at the point F in the feeder sectionalized by three CBs (or load breaking switches) is shown is Fig.4. The ZMTC is generated by a superimposed voltage source e_{0f} energizing the zero mode network. The ZMTC i_{01} through CB_1 is the current flowing into the network behind it, which is sum of the current i_{C01} flowing into C_{01} (the distributed capacitance of feeder section from CB_1 to busbar) and the current i_{0b} flowing into the whole network excluding the faulted feeder. Similarly, the ZMTC i_{02} through CB_2 is the current flowing into the network behind it, which is actually the current i_{02} through CB_1 plus the current i_{C02} flowing into C_{02} (the distributed capacitance of section between the CB_1 and CB_2). The ZMTC i_{03} through downstream CB_3 is the current flowing into distributed capacitance of the downstream section (sections) before it, i.e. the part of the feeder from CB_3 to the end. The characteristics of ZMTC through sectionalizing CBs can be summarized as follows:

1) The ZMTC through upstream CB of the fault is larger in magnitude than ZMTC through downstream CB.
2) The ZMTCs through two adjacent upstream CBs are very close in magnitude and similar in waveform
3) The ZMTC through upstream CB of the faulted section has opposite initial polarity with the ZMTC of the downstream CB. The two currents are dissimilar significantly in waveform.

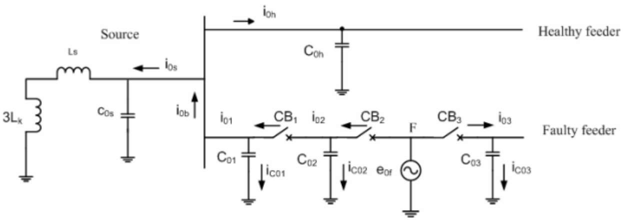


Fig.4 The equivalent circuit of zero mode network of a SPGF

Fault location principle

Theoretically the faulted section could be identified simply by comparing the magnitude of ZMTC at each sectionalizing point. In order to ensure the fault location reliability and sensitivity a more sophisticated cross correlation algorithm is proposed for Type C system.

First the FTU in the faulty feeder will record the ZMTC when its deviation exceeds a preset threshold. The ZMTC can be obtained either indirectly by summing up three phase currents or directly by a specially designed zero mode (sequence) current transformer. Then the FTU that captured the ZMTC will exchange the recorded signal with adjacent FTUs. Assume the locally recorded ZMTC is $i_l(k)$ and the signal received from the adjacent FTU is $i_a(k)$, the cross correlation coefficient of two waveforms can be calculated as

$$r(n) = \frac{\left(\sum_{i=1}^{i=N} i_l(k) i_a(k+n)\right)^2}{\sum_{k=1}^{i=N} i_l^2(k) \sum_{i=1}^{i=N} i_a^2(k)}$$

Where k is sampling sequence; N is total samples recorded; n is samples shifted to the received signal. Practically it is difficult to synchronize recording of ZMTC of each FTU. Therefore, a several samples long left and right shift to the received signals is introduced to align it with the local ZMTC in time. The correlation coefficient $r(n)$ will reach a maximum value $?_{max}$ when two similar waveforms are aligned in time.

The faulted section can be identified by examining the maximum correlation coefficient $?_{max}$ of two ZMTCs captured by FTUs at both ends of a section. A section is identified as the faulted one if following conditions are met:

1) The $?_{max}$ between the ZMTCs recorded by upstream and downstream FTUs respectively is less than the threshold value.
2) The ZMTC recorded by the upstream FTU has significant magnitude and the upstream FTU did not pick up as ZMTC there has very small magnitude.

Implementation

The Type C system can locate the SPGF employing the proposed method. As the network with a SPGF is allowed to operate for 2 hours the fault isolation is usually done by the manual operation. The FTU of Type C system will identify the faulted section and send the results to the master station to notify the operator. Then the operator will isolate the fault when needed

The proposed method can also be employed by the Type B system. The master station of the Type B system identifies the faulted section by processing the ZMTCs collected from the FTUs in the faulty feeder.

5 TEST AND SIMULATION RESULTS

A prototype Type C system has been developed and tested in a mimic looped distribution cable circuit as shown in Fig.2. Fig.5 is the picture of test site. The results shown all short circuit faults can be isolated in less than 400ms and supply of healthy sections is restored in less than 2 seconds. The FTU in the prototype system has only RS/EIA-232 port and an Ethernet adapter is used to connect it to the communication network. Therefore, the exchange speed of fault detection result is limited by slow baud rate of communication between the FTU and the Ethernet. The fault isolation speed could be reduced to 200ms if the FTU is designed with a direct Ethernet communication port. The system has been put into trial operation recently in a looped cable circuit of Xiamen Power Bureau, Fujian, China.

Fig.5 Test site

The SPGF location method is also tested by ATP simulation results of a compensated 10kV overhead line network as shown in Fig.6. A SPGF is placed at point F of feeder 6. The typical ZMTCs captured by FTUs at sectionalizing points CB_2, CB_3 are shown in Fig. 7. The ?$_{max}$ between the ZMTCs recorded by FTUs at CB_1 and CB_2 is 0.99 and ?$_{max}$ between the ZMTCs recorded by FTUs at CB_2 and CB_3 is 0.08. The threshold is set as 0.7 and therefore the faulted section is identified reliably.

6 CONCLUSIONS

A new fault isolation and restoration technique is presented. All short circuit faults in the loop can be isolated within 200ms and the supply of healthy line sections can be restored in less than 2 seconds. It can also locate the SPGF in non-effectively earthed network reliably. Its application to the MV distribution network will significantly improve power quality and customers satisfaction.

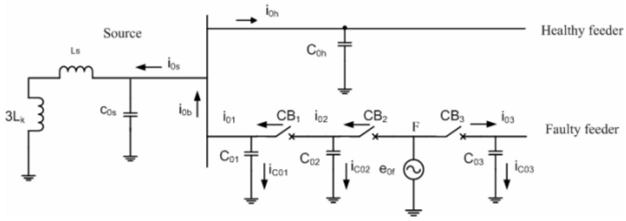
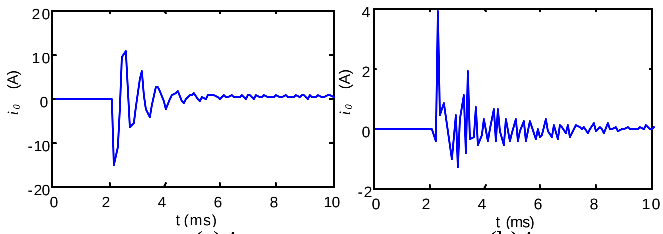


Fig.6 The simulated compensated overhead line network



(a) i_{02} (b) i_{03}

Fig.7 the ZMTCs of sectionalizing points

Mr Li Weixin, Tu Guoliang of Xiamen Power Bureau and Mr. Lu Guanglin, Liu Xinyi, Wang Junjiang, Xue Yongduan and Ma Shicong of Shandong Power Automation Ltd. are also involved with the development of Type C FA system. The author is grateful to their contributions to the paper.

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