FAST SELF-HEALING CONTROL OF FAULTS IN MV NETWORKS USING DISTRIBUTED INTELLIGENCE

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ABSTRACT

Feeder automation (FA) technology is now widely used to improve supply reliability. Automatic fault location, isolation and service restoration (FLISR) can be achieved by local, central and distributed control. This paper presents a MV network self-healing system based on distributed control, which can provide significant improvements in reducing the number and duration of interruptions caused by faults. The system comprises of Smart Terminal Units (STUs) installed in substation circuit breakers and sectionalizing switches. The STUs are connected together through a peer-to-peer (p2p) communication network using industrial Ethernet. The STUs detect fault and exchange fault data and control commands with each other to realize FLISR without reliance on the central master station.

Details of the control algorithm are presented in this paper. Successful service restoration requires self-recognition of the normally-open tie switch, the position of which may change due to network reconfiguration. This technique is also presented.

The control algorithm has been implemented in a State Grid Corporation of China (SGCC)'s smart grid pilot project in Xiamen, Fujian province. Field trials have shown that the service restoration time after a fault is within 1s, which is significantly improved as compared to the local and centralised control methods.

INTRODUCTION

Feeder automation (FA) technology is now widely used to improve supply reliability [1]. Automatic fault location, isolation and service restoration (FLISR) can be achieved by local, central and distributed control [2]. Local control is achieved by autonomous open/close operations of sectionalizing switches in a feeder according to local overcurrent or voltage measurements. One technique is to detect and to count overcurrent signatures which is widely use in North America. Another technique is to detect the loss of voltage on feeders which is widely uses in East Asia. In these types of FLISR, the circuit breaker and sectionalizing switches in a feeder operate in a pre-determined sequence, not requiring information from any other device during their protection process. However, data can be exchanged between the master station and sectionalizing switches, which may include configuration values such as overcurrent and voltage settings, operation mode as well as monitoring data. Its performance, however, is limited by local information, typically requiring several automatic closing or switching operations before the fault is finally detected and isolated.

Central control applies to a feeder that has remotely controlled breaker at the main substation and several remotely monitored fault passage indicators located at suitable points along the feeder. The fault passage indicator's information is sent to the control center so that the system and/or operator can decide where the fault is located and send commands to isolate the faulty section. If the fault is successfully isolated, the final step is to send commands to restore power to the healthy sections. Central control relies, therefore, on a supervision control center gathering information from devices installed at sectionalizing switches in MV feeders. Because of the large amount of information transfer, the restoration time can take several seconds which is not totally desirable.

Distributed control relies on the devices at the circuit breakers, sectionalizing switches and tie switches to communicate with each other to achieve the FLISR scheme. It does not require the master station for the control. The decision can be done quickly and precisely. Therefore, it can further reduce the number and duration of interruptions caused by faults, and can provide fast self-healing for distributed feeders. A number of schemes have already been implemented previously [3,4].

This paper presents another distributed control scheme. Apart from performing FLISR, the scheme also automatically detects topology change of the network, thus minimizing the task of reconfiguration of all the devices. The scheme has been on trial on a large scale in China in a project sponsored by the Chinese government.

FAST DISTRIBUTED CONTROL FOR SELF-HEALING OF FAULTS

A typical system for an open-loop MV distribution network is shown in Figure 1. It comprises of smart terminal units (STUs) installed in substation circuit breakers (referred to as power switch in this paper) and sectionalizing switches. In the figure the power switch is represented as a rectangle, capable of breaking fault currents. They are typically installed at the primary substations and are responsible for the clearing of faults. The sectionalizing switch is represented as a circle. They can only break load currents, and are used for isolation of the faulty section and/or outgoing feeders after the fault is cleared. An assembly of a number of switches form a ring main unit (RMU) located in the distribution substation. There is a normally-open sectionalizing switch known as a tie switch (Q32 in Fig. 1). It is responsible for restoring service to the healthy sections after fault isolation. In the figure, a switch which is closed is filled with black color, otherwise it is open.

The STUs are connected together through a peer-to-peer (p2p) industrial Ethernet communication network using optical fibers. The STU detects fault and exchanges fault data and control commands with the adjacent STUs to realize FLISR without any reliance on the central master station. The scheme can also recognize changes of the tie-switch position and reconfigures itself accordingly. The techniques are explained in the following sections.

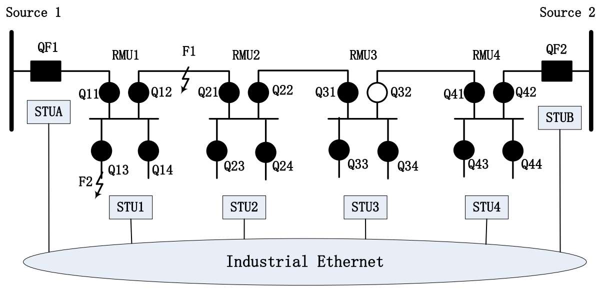

Figure 1 MV Distribution network with distributed FLISR

SELF RECOGNITION OF NETWORK TOPOLOGY

Successful service restoration requires self-recognition of the normally-open tie switch, the position of which may change due to network reconfiguration. A tie switch can be identified through detecting voltages from both sides of the switch. If voltages exist on both sides of the switch's feeder line and the switch is open, it is a tie switch. This method is simple and reliable, but it requires voltage transformers or sensors to be installed on both sides of the switch.

In this paper, this function is performed by the STU at the sectionalizing switch which initiates a real-time line topology query when the switch is open. If the responses show that both sides of the switch are connected to the power sources, the tie switch is identified [5]. Voltage measurements are not needed, and the process can be completed within the normal operation time of power distribution network. Therefore, the speed of the power supply recovery will not be affected by topology changes of the distribution network. The process is as follows:

Initialization of the STUs

Each STU is initialized manually with the configuration of the switch attributes which it is monitoring. The switch attributes include the switch's own property and its location property. Its own property refers to whether it is a power switch or a sectionalizing switch. Its location property means the position of the switch in the network, represented by its own network address and the network addresses of its adjacent switches.

Queries to identify the network topology

With the line running normally, the STU at a healthy and open switch (Q32 in Figure 1) will start to conduct a query of the network, in order to establish the position of the tie switch. The query commands are sent to both side of the switch. Each command is passed from one switch to the next one, until the power switch at the primary substation is reached. In this example, STU3 will send the query command to STU2, STU2 will resend the command to STU1, STU1 will resend the command to STUA. The query process on the left hand side will stop at STUA since it is at the power source. The same process occurs on the right-hand side of Q32.

Confirmation of the tie switch

At the end of the query process, each STU which has been queried would have been responded with its own status to the STU3 at Q32. STU3 thus understands the condition and the topology of the network. Assuming that the power sources on both sides are identified, STU3 can then confirm that Q32 is a tie switch. It is responsible for service restoration if required.

The query and the response paths are shown in Figure 2. The result of the network self-identification is shown in Figure 3.

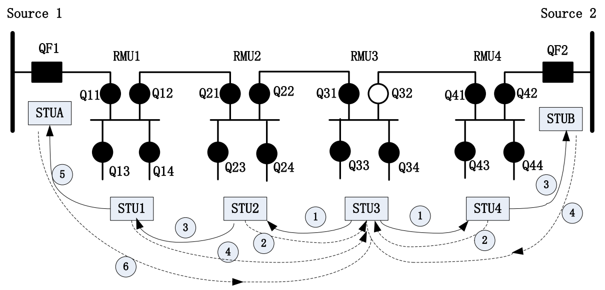

Figure 2 Communication paths during the query process

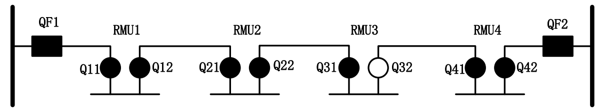

Figure 3 Results of the network self-identification

Assuming that QF2 is now open, STU4 will start the query process. The result condition of the network topology is shown in Figure 4. It can be seen that there is no tie switch in the network and service restoration cannot be carried out.

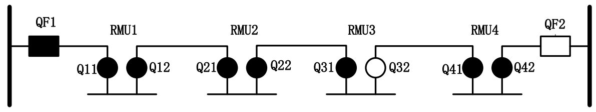

Figure 4 Network configuration with no tie switch

FAULT LOCATION, ISOLATION AND SERVICE RESTORATION PROCESS

Fault location

If a fault current flows through the local switch for a period of time and then disappears, the STU will initiate the fault location algorithm. For a line with auto-reclosers, the STU will start the algorithm after the local switch has undergone a pre-set number of fault current flows and then disappears. The STU will check its neighboring switches to find out whether they have detected the fault current. The principle of fault location is that, if the upstream switch detects fault current and the downstream doesn't, the fault must be in the immediate downstream section.

For example, after fault F1 has been cleared, STUA queries STU1 about fault detection. STU1 responds indicating that the fault has been detected. STU1 detects that Q11 and Q12 has fault current flow, but not Q13 and Q14, therefore the fault is not at RMU1. It queries STU2 and finds that no current flows through Q21 and Q22, therefore the fault must be at the line section between Q12 and Q21. For fault F2, STU1 detects that the fault current flows through Q11 and Q13, therefore the fault must be downstream from Q13.

After the fault has been located, a fault located message will be broadcasted to all STUs to initiate the fault isolation process.

Fault isolation

After a STU has identified the fault in the immediate downstream section, it will issue the open command to all the switches and/or STUs within the boundary of that faulty section to isolate the fault. For fault F1, STU1 will issue an open command to Q12. It will also issue a command to STU2 to open switch Q21. For fault F2, STU1 will issue an open command to open switch Q13. In both cases the fault isolated message will be broadcasted to initiate the service restoration process.

Service restoration

Restoration from the source

After fault isolation, the STU at the primary substation checks to make sure that the fault is not in its immediate downstream section, it will close the circuit breaker to restore service upstream from the fault.

In this example, for both F1 and F2, STUA checks that the faults are not in the section immediately after QF1, it will issue a close command to QF1 to restore service to all the sections upstream from the fault.

Restoration from the tie switch

The STU at the tie switch, after receiving the fault isolation command, will first check the nature of the fault by examining the location of switch upstream from the fault. If the upstream switch is located at a branch, and has been isolated, there is no need to close the tie switch, since the restoration from the source should have restored supply to all the RMUs.

For example, for F2 fault, STU3 checks that the location of the switch upstream from the fault is Q13. Since Q13 is a switch at a branch, STU3 decides not to close the tie switch.

If the STU at the tie switch checks that the switch upstream from the fault is on the main feeder, it will check to make sure that this switch is not a neighbor to the tie switch. This is to prevent the tie switch to close onto a fault. If the switch is not a neighboring switch, the STU will check whether there is sufficient capacity in the primary substation to supply power to the rest of the healthy sections. If spare capacity is available, it will issue a command to close the tie switch.

For example, for F1 fault, STU3 checks that the switch upstream from F1 is Q12. Q12 is on the main feeder and is not a neighbor to Q32, it will close Q32 provided there is sufficient spare capacity from the substation to feed the healthy sections.

SITE INSTALLATION AND EXPERIENCE

The distributed FLISR has been implemented in a State Grid Corporation of China (SGCC)'s smart grid pilot project in Xiamen, Fujian province. The project automates the MV distribution networks of two urban districts covering the area of 134km^2. There are 22 110kV/10kV primary substations, 525 10kV feeders, 269 distribution substations, 830 ring main units and 1053 10kV/400v secondary substations. By the end of 2010, the project has installed 1178 STUs and a SCADA/DA master station. Field trials have shown that the service restoration time after a fault is typically within 1s, which is significantly improved as compared to the local or the centralized control methods.

Figure 5 Installation of the STU at the 10kV ring main unit

In an installation there are 4 RMUs. The #901 switches in RMU 1 and RMU4 are power switches, the rest are sectionalizing switches. Switch #902 in RMU3 is the normally-open tie switch.

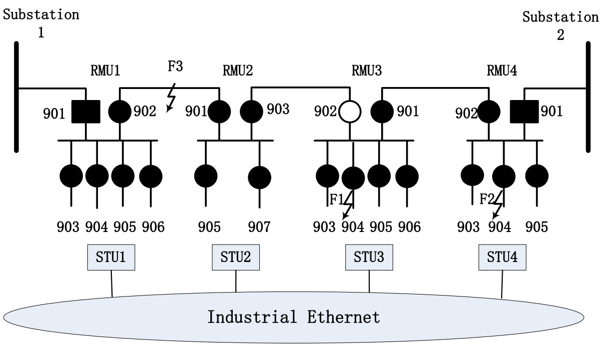

Figure 6 Fault incidents at an open loop feeder

There have been two incidences of outgoing feeder faults (F1 and F2) at RMU3 and RMU4. There have been one main line fault (F3) between RMU1 and RMU2. The protection operating times and the sequence of operations are as follows

Fault position	**R3-904 (F1)**	**R4-904 (F2)**	**R1-902 and R2-901 (F3)**
Sequence of events	R4-901 open R3-904 open R4-901 close	R4-901 open R4-904 open R4-901 close	R1-901 open R1-902 open R2-901 open R1-901 close R3-902 close
Trip time	152ms	176ms	149ms
Fault isolation	225ms	242ms	402ms
CB close	502ms	499ms	641ms
Tie switch close	-	-	755ms

Table 1 Performance results of the field trial

From the table it can be seen that the service restoration for outgoing feeders are 502ms and 499ms. For the fault on the main feeder between two primary substations, the upstream service restoration time is 641ms, the downstream (tie switch) service restoration time is 755ms. They can all be achieved within 1s interval.

CONCLUSIONS

A FLISR system using distributed control has been developed for the MV distribution network. The system is composed of a number of smart terminal units (STUs) monitoring and controlling the circuit breakers and the sectionalising switches of the looped feeders. The STUs communicate with each other through industrial Ethernet with optical fibres, and can achieve high speed FLISR without relying on the master station. In addition, the system can self-recognise the topology of the network and can reconfigure itself when the normally-open tie switch changes position. This scheme can perform service restoration within 1s, and is therefore more efficient compared with the local or the centralized control methods. Large scale site trial has been carried out by SGCC to prove its practicality and its effectiveness.

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