Development and Implementation of MV-circuit Self-healing System Based on Distributed Intelligences

Mengyou GAO Bingyin XU Tianyou LI Weixin LI
Shandong Univ., China Shandong Univ. of Technology, China Fujian Power Supply Co., China Xiamen Power Supply Co., China.
gaomengyou2007@163.com xuby@china.com ltyxm@163.com xmliweixin@sohu.com

ABSTRACT

A MV-circuit self-healing technology based on distributed intelligences is presented. A local area optical peer to peer communication network is employed to exchange fault and control information among feeder terminal units (FTUs) to achieve fast fault location, isolation and service restoration (FLISR) without the reliance to the central control of master station. Test results showed the system can restore the service of an open loop circuit 1.5s after fault and clear the fault in a closed loop circuit in 150 ms.

INTRODUCTION

With economic development and social progress, the requirement to high power quality is increasing. Feeder automation (FA) technology is now widely used to improve supply reliability. Feeder terminal units (FTUs) are installed along MV feeder. The FTUs detect the faults in the feeder and report the fault information to supervision master station via the communication network. The master station will locate the fault and send control instructions to the field FTUs to isolate fault and restore service [1~3]. The whole restoration process normally takes more than one minute as the communication and the processing of fault data in the master station will take time. Nevertheless, for some critical loads, such as semiconductor manufacturing factories, important civic conference centres, even a short interruption lasting in few seconds will cause serious consequences and is not acceptable.

Reference [4 5] introduced the application of peer to peer communication in FA system. The peer to peer system has faster fault location, isolation and service restoration speed as the control is achieved by exchanging fault information among FTUs without the intervention of the master station. However， the developed FA system uses radio communication and still takes tens seconds to complete the restoration. Reference [6] proposed a GOOSE (as described in IEC 61850 standards) based FA technology. A prototype system is developed and being tested in laboratory. It can achieve fast fault isolation and restoration in an open loop circuit and fast fault clearance in a closed loop circuit. The system identifies the faulty section of a closed loop circuit by detecting the direction of fault current. It requires the measurement of voltage signal and therefore the installation of voltage transformers (PTs) in the sectionalizing switches， which is difficult in practical application for cost and installation space reasons.

A MV-circuit self-healing system based on the distributed intelligence, which can further reduce the number and duration of interruptions caused by fault, is presented in this paper. A FLISR method for the open loop circuit based on the distributed intelligence and a faulty section location algorithm for the closed loop circuit based on comparison of the phase angles of fault current are proposed.

THE SELF-HEALING SYSTEM BASED ON THE DISTRIBUTED INTELLIGENCE FOR OPEN-LOOP CIRCUIT

SYSTEM DESCRIPTION

A typical self-healing system based on the distributed intelligence for an open-loop MV cable system is shown in Fig.1. It comprises relays installed in substation circuit breakers and FTUs in sectionalizing switches. The FTUs (including the relay) are connected together through a peer to peer communication network, i.e. the industrial optical Ethernet. The FTU detects fault and exchanges fault data and control commands with the adjacent FTUs to realize fault location, isolation and service restoration without any reliance on the central control of master station. The results of the fault processing will be reported to the master station through a communication processor (CP).

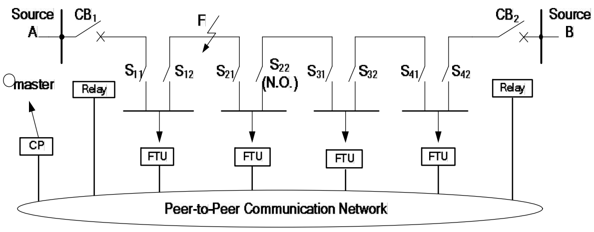

Fig.1 The self-healing system for open-loop MV circuit

Fault location, isolation and service restoration algorithm

There are several sectionalizing switches in a looped circuit. In the convenience of description of the algorithm the switches of MV feeder are classified as follows: The circuit breaker (equipped with the relay) in substation is named as source breaker. The switch that directly faces the load (e.g. the lateral switch) is named as end switch. The switch before and after which there is at least one switch is named as medium switch.

The algorithm is started after the FTU detects overcurrent in a switch and the fault is cleared by the source breaker. One FTU may monitor one or more switches in practical application. If a neighbour switch is not a locally monitored one, the FTU will communicate to its neighbour FTU to acquire the needed overcurrent detection results.

Fault next to medium switch

For a medium switch, if it sees overcurrent and none of the neighbour switches in its one side does, it indicates the fault lies on this side of the switch. FTU will send the fault isolation command to open all switches bordering on the faulty section. After making sure the fault is successfully isolated, the FTU will send a "medium switch fault isolated" message to notify the source breaker. The source breaker will reclose to restore supply after receiving the message. The tie switch will check the voltages of its both sides after receiving the fault isolation message. If one side of the tie switch has no voltage, and the fault does not occur at the neighbourhood, FTU controls the tie switch to close to restore the service.

Fault next to sourec breaker

For the source breaker, the FLISR algorithm is similar as medium switch. The difference is that it has neighbour switches in its one side only and the source breaker remaining open after the fault is confirmed in its next section.

Fault after end switch

If the switch is end switch, the FTU will directly send the fault isolation command. After making sure the fault is successfully isolated, the FTU will send an "end switch fault isolated" message to notify the source breaker. The source breaker will reclose to restore supply after receiving the message.

THE SELF-HEALING SYSTEM BASED ON THE DISTRIBUTED INTELLIGENCE FOR CLOSED-LOOP CIRCUIT

Operation principle

If the tie switch of a looped circuit is closed in normal operation, the system will operate in closed loop mode. With differential protection a fault in the circuit can be cleared instantaneously without causing any supply interruption and therefore seamless self healing is achieved. To avoid cycling current through the circuit the two infeed sources shall be from same bus. The load switch of the circuit should be replaced with circuit breaker to interrupt fault current.

A typical self-healing system for a closed loop cable circuit is shown in Fig.2. When fault occurs, the fault currents are not as in radial distribution, but they gather together to the fault point from different sources. The conventional fault location method based on overcurrent detection is no longer valid. A possible solution is to compare fault current direction. But it requires the measurement of the three phase voltage which may not be available in the sectionalizing switch of MV network. To simplify the differential protection, a new fault location method which compares the initial phase angle of fault currents at both ends of a section, is developed for the closed-loop cable circuit. As there is no any interruption in the fault isolation process, it is also called seamless self-healing technology.

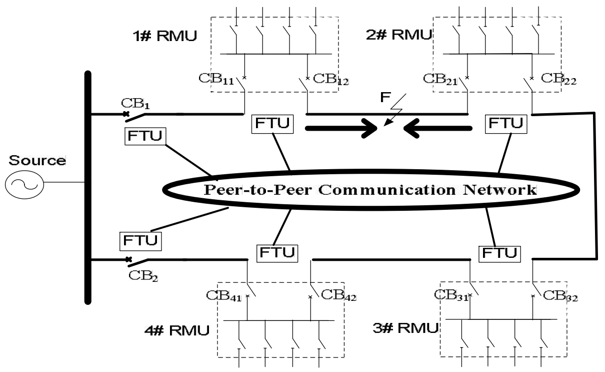

Fig.2 The self-healing system for closed-loop MV circuit

For a fault at point F in the feeder of Fig.2, the FTUs at both ends of a section of the feeder identify the fault location and send command to open breaker CB_{12} and CB_{21}. And the fault is isolated without any interruption as 1# RMU is still fed by left infeed circuit and 2# RMU by right infeed circuit after fault is cleared. The peer to peer communication network for the self-healing system of closed-loop circuit is similar to the communication network for the open-loop circuit.

Fault location algorithm of closed-loop network

For a fault in a closed-loop network as shown in Fig.2, the currents at both ends of a section exceed overcurrent setting. But the phase angles of fault currents are almost same for the healthy section, and opposite for the faulty section. It can locate fault by comparing the detection result of phase angles of the fault currents.

Time synchronization is required to measure the phase angle of fault current. To avoid external synchronous clock and simplify the design of distributed intelligence, it can use the time instant when fault signal appears to synchronize the phase angle measurement. For the length of the distribution feeder is much shorter, it can ignore the delay of the current transmission along the distribution feeder. If the sampling frequency of FTU is high enough (say higher than 64 samples per cycle), the time synchronization accuracy shall be able to meet the application requirement.

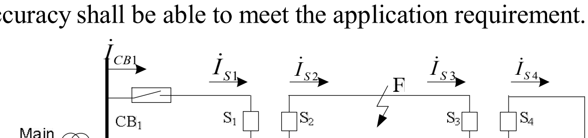

Fig. 3 A closed loop cable circuit

Take a fault in section 2 of the circuit as shown in Fig. 3 as an example. The current $\dot{I}_{CB1}$ and current $\dot{I}_{S1}$ at both ends of the first section are provided by the main system and will exceed over-current setting. Then the phase angle difference between $\dot{I}_{CB1}$ and $\dot{I}_{S1}$ is examined. The section is identified as a healthy one as the phase angle difference is about zero. For cable section 2, the upstream current $\dot{I}_{S2}$ is provided by the main system and will exceed overcurrent setting. If $\dot{I}_{S3}$ also exceeds overcurrent setting, the section is identified as a faulted one by comparing the phase angle difference between $\dot{I}_{S2}$ and $\dot{I}_{S3}$ which approaches to 180^0.

Considering the fact that various factors, such as the error of current transformer, may affect the actual measured phase angle of fault current, a phase angle φ_m is introduced to give more tolerance to measurement error. The actual fault location criterion is:

For faulty section: $180^0 + \varphi_m > \varphi > 180^0 - \varphi_m$

For healthy section: $\varphi_m > \varphi > -\varphi_m$

There, φ represents the phase angle difference of upstream and downstream currents; φ_m is the maximum phase angle error allowed which can be set as 70º in practical application.

The above fault location criterion is illustrated in Fig.4.

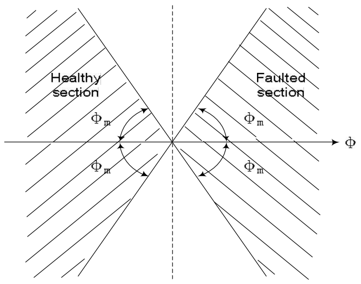

Fig. 4 The actual fault location criteria

TEST RESULTS

Tests of the self-healing system for open-loop cable circuit

The algorithm is tested by the fault data from a static physical simulation system in the laboratory. The fault in the distribution circuit as shown in Fig.1 is simulated in the laboratory. When short-circuit fault occurs, the relay detects fault and cuts off short-circuit current, and FTUs of the RMU that feels the fault acquire the fault information of the RMU itself and the adjacent ones to start self-healing algorithm to realize fault isolation and service restoration.

For the simulated faults shown in Fig.1, the calculated result of three times tests of the fault isolation and service restoration is listed in Table 2, there millisecond is the unit of time.

Table 2 The test results

Fault	Action	Seq.	Relay trip time	Fault isolation time	Relay reclose time	Tie close time
F_1	CB_1 trip; S_{12},S_{21} trip; CB_1,S_{22} close	1	231	563	744	1246
		2	158	496	720	1429
		3	203	569	752	1262
F_2	CB_1 trip; S_{11},S_{12} trip; S_{22} close	1	229	472	\	1394
		2	179	531	\	1310
		3	165	554	\	1404

Tests proved the system is effective for all kinds of faults in the circuit. It can isolate the fault within 600ms and restore service within 1.5s. The system has been put into trial operation in an open loop cable circuit of Xiamen Power Bureau, Fujian, China, as shown in Fig.5.

Fig.5 Field test

Tests of the self-healing system for closed-loop cable circuit

The simulated 10kV cable circuit is as shown in Fig.3 where the downstream fault current is also provided by main system. A three phase short-circuit fault is placed at the middle point of section 2. The fault data is acquired using a fault recorder whose sampling frequency is 64 samples per cycle.

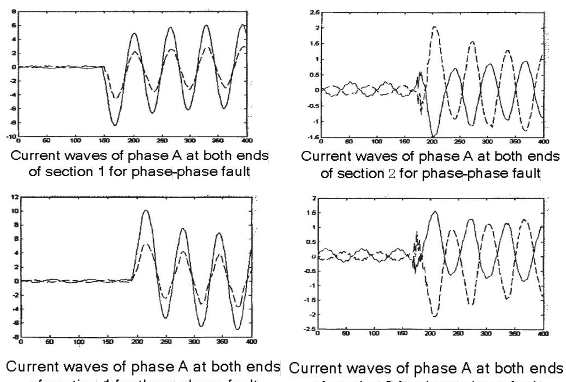

Fig. 6 Current waves of phase A

Fig.6 shows the current waves of the phase A at both end of section 1 and section 2 when three-phase or phase-phase short circuit fault occurs at point F. The phase angle difference is calculated from the recorded data, as shown in Table 3. The faulted section can be identified correctly using the proposed fault location method.

Table 3: The measured phase angle differnces for various fault tests

Fault type	*Sequence of fault tests*	*Phase angle difference between fault currents of section 1*	*Phase angle difference between fault currents of section 2*
Phase-phase fault	1	1^0	180^0
	2	-1^0	181^0
Three-phase fault	1	-2^0	178^0
	2	-2^0	180^0

The test results proved that the system can isolate the fault in 150ms without causing any interruption to the load in the circuit.

CONCLUSIONS

The self-healing technology based on the distributed intelligence can further reduce the number and duration of interruptions caused by fault in an open loop MV circuit. The distributed intelligence can also be applied to the closed loop cable circuit to achieve seamless self-healing. The faulted section of closed loop circuit can be identified reliably by measuring the phase angle difference between fault currents at both ends of the section. The measurement of phase angle difference is synchronized by the fault signal, and the fault signal is detected by examining whether the current deviation exceeds a threshold. The proposed technology provides a reliable and cost-effective self-healing solution for the fault in MV network.

Acknowledgments

The authors wish to thank Mr. Yong Chang, Mr. Jinghua Wang, Mr. Guanglin Lv of Kehui Ltd., Shandong, China, for their help in the implementation of the self-healing system.

REFERENCES

[1] Jian Liu, Jianli Ni, Yu Du, 1999, "A Unified Matrix Algorithm for Fault Section Detection and Isolation in Distribution System", *Automation of Electric Power Systems.* Vol. 23, 31-33.

[2] Wei Liu, Zhizhong Guo, 2002, "A New Matrix Algorithm for Fault Section Detection in Distribution System", *Automation of Electric Power Systems.* Vol. 26, 21-24.

[3] Yijun Yu, Jianming Zhang, Zhou Ye, etc, 2001, "Distribution Fault Processing and Practical Application", *Automation of Electric Power Systems.* Vol. 25, 63-64.

[4] Juancarlo Depablos, 2003, Internet Peer-to-Peer Communication Based Distribution Loop Control System, Virginia Tech Polytechnic Institute, USA.

[5] Qincheng Yuan, 2007, Automation Technology for Fault Handing in Distribution System, China Electrical Power Press, Beijing, China.

[6] Jian Liu, Baoji Yun, Qi Cui, etc, 2010, "A Distribution Intelligent Feeder Automation System with Fast Self-healing Performance", *Automation of Electric Power Systems.* Vol. 34, 62-66.

[7] Bingyin Xu, Tianyou Li, 2010, "Investigation to Some Distribution Automation Issues", *Automation of Electric Power Systems.* Vol. 34, 81-86.

[8] Bingyin Xu, Tianyou Li, Yongduan Xue, 2009, "Smart Distribution Grid and Distribution Automation" *Automation of Electric Power Systems.* Vol. 33, 38-41,55.

BIOGRAPHY

Mengyou Gao was born in 1983 and awarded Bachelor degree of electrical engineering by Shandong University, China, in June, 2007. He is now a Ph.D candidate of electrical engineering of Shandong University. His research area is smart distribution grid.

Bingyin XU was awarded Ph.D of electrical engineering by Xi'an Jiaotong University, China, in 1991. He studied in The City University, UK, from Oct. 1989 to Oct., 1990 as part of split-Ph.D training program. He is now a registered professor of Shandong University of Technology and Chairman of the board of Kehui Power Automation Co. Ltd., China. His research interests are fault location and monitoring of power networks and distribution automation.