Fault Location Scheme of Smart Grid Based on Wireless Sensor Networks

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Abstract. The paper develops a fault location scheme for Smart Grid based on wireless sensor networks. Some fault location and detection principles are illustrated based on wireless sensor networks. The scheme is designed according to the requirements of end—to—end delay, reliability, and synchronization in power distribution system and simulation results indicate that it is feasible to implement the Smart Grid fault location based on wireless sensor networks.

Keywords: Smart Grid, Wireless Sensor Networks, Fault Location.

1 Introduction

Nowadays, the development of power sector is faced up with many challenges such as low investment efficiency and reliability of power supply, weak flexibility and adaptability, serious environmental damage and so on. The developed countries like USA and EU all believe that to construct a Smart Grid based on brand-new technological architecture is the best way to solve the problems. Once the Smart Grid is put forward, it immediately becomes popular and booms all around the world, which turns into the trend of the next generation power grid.

Smart Grid based on integrated and high-speed two-way communication networks performs well for the power grid. Through advanced sensor, measurement techniques, the control method and decision support system, it guarantees the power grid can operate in a reliable, safe, economic, efficient and economically friendly way.

With the rapid development of MEMS(Micro-Electro-Mechanism System), SOC(System on Chip), wireless communication and low-power embedded technologies, WSN (Wireless Sensor Networks) comes into being and brings a revolution of information perception owing to its low power consumption and cost, distributed and self-organizing features. WSN is a multi-hop and self-organized network formed from a large amount of cheap mini sensor nodes. It has a wide application in multiple targets, short distance communication, and also plays significant roles in the construction of Smart Grid.

Based on the fault handling automatic technology in power distribution system, the paper employs the signal injection method to locate the fault sector based on the wireless sensor network, thus offers a new idea for the construction of Smart Grid.

In order to have a systematic and clear understanding about the fault process of power distribution system, we divide the process into three stages [1].

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①Faults switch and remove when faults occur. The stage can finish in milliseconds using high voltage breaker combination with relay protection automatic device. If the relay protection quickly breaks, the duration is commonly 100ms around.

②Fault sector's isolation and normal sector's power restoration. The duration generally lasts seconds to minutes.

③Fault location and remove. It usually needs ten minutes to several hours

In the three stages above, problems concerned are not the same. The paper mainly considers the third stage, aims to improving the repairing efficiency and lowering the cost.

2 Current Research Situation

At present, most of the power distribution system can’t carry out monitoring over all distribution circuits, even in main lines with a switch subsection. The system can only isolate limited segments, so it’s inevitable to consume large manpower and material resources to locate the faults.

The power distribution network covers a wide range included the urban area, rural area and mountainous area, so it suffers from wind and rain all year ,plus the unpredictable man-made factors, which lead to the short-circuit accidents occur- red frequently.

Once the fault occurs, if it can’t be rapidly located, the efficiency is very low. Especially when single-phase-to-ground fault occurs in the power distribution network with neutral point not grounded, the voltage is square root of three times the normal voltage although no large short-circuit current exists, so if we can’t promptly remove the ground fault, it can trigger a new short-circuit fault. It’s more difficult to locate the fault in the single-phase-to-ground system.

For a long time, it is a technical difficulty when it comes to single-phase-to-ground fault’s line selection and location in the low current grounding system. Choosing grounding lines accurately and locating the single-phase-to-ground sector can avoid the unnecessary switching operation on non-fault lines so as to maintain the power continuity, therefore, researchers at home and abroad focus on the issue, and many corresponding products are already used in power grid.

The fundamental principle of single-phase-to-ground fault detection is the same as single-phase–to-ground line selection. Basically, the methods to detect single-phase-to-ground fault are as follows, five times harmonic method, current mutations hair method, the first half wave method, the zero sequence current method and signal injection method[2-4]. Except signal injection method, the rest detection methods are passive detections, which rely on the change of the parameters before and after single-phase-to-ground fault. Owing to the complexity of distribution network’s topology structure and the varied operation mode, also plus the electromagnetic interference and harmonic pollution, the signal would be distorted when single-phase-to-ground fault occurs, therefore, the accuracy of the signal can’t be guaranteed.

Considering the features of the low current grounding system, this paper employs signal injection method for fault location. When single-phase-to-ground fault occurs, the source from the transformer substation will spontaneously inject a special signal into the bus bar, which will pass around the loop circuit composed of the source and the ground point. Once the power sensor detects the signal, it sends the fault information.

Signal injection method is free from the effect of the system operating mode, topology structure, the method of grounding the neutrals, and random fault and so on. There is no need to set threshold for fault indicator. Moreover, the method of detecting single-phase-to-ground fault is far more accurate than other methods.

3 Principle

This system uses a signal injection method for fault location. Firstly, locate the fault sector through distribution terminal, and then improve the location accuracy by WSN.

The system employs three layers of wireless communication networks, which is composed of base stations, FTU (feedback terminal unit), CT (current sensor), PDA, source, GPRS networks and WSN, as shown in Fig.1. between sensor nodes and PDA using without the routing protocol 470MHz short-range wireless communication; besides sensor nodes and between sensor nodes and FTU using ZigBee Pro protocol stack based on WSN communication, which is the 2.4GHz Mesh network; between FTU and base station using the GPRS network.

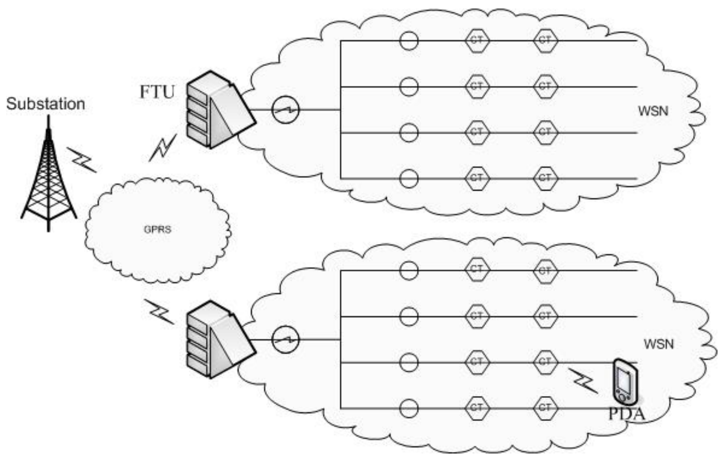

Fig. 1. the structure of system

There installs a dynamic-impedance load source device in the transformer substation, so when single-phase-to-ground fault occurs, in a period of time, offset voltage can be detected by the controller at neutral point, meanwhile the source device will automatically work for a few seconds and then exit. The system with extinction coil which has a delay for the source input is designed to let the ground-fault point automatically extinguish arc and eliminate the fault consequently. As is known, grounds points only exist in the fault lines, which can form a loop circuit combined with the source, it's no doubt that there is a current flow in the circuit. In order to detect the current of each phase-line, sensors for current detection are scattered around each phase-line in the transformer substation's coil out or the branch of the distribution circuit. If the indicator in some line can demodulate the current, it illustrates that the line is the fault line. The method can also be used to detect short-circuit fault, we can see clearly in Fig.2.

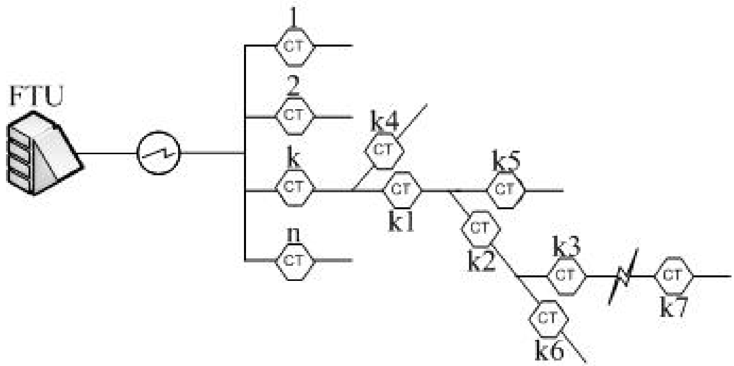

Fig. 2. The principle of system

(1) Single-phase ground fault occurs. Source substation operation automatic after a few seconds delay, stop running after 10s; The sensor node which is installed in the substation outlet indicates the fault outlet(k No sensor action); selecting device automatically display and record the fault outlet, and reported to the FTU by WSN, The sensor node k installed on the fault line sending fault information the it child node k1 and k4, the sensor node k4 installed on the normal line send back normal information, the sensor node k1 installed on the fault line send fault information back and send this message to it son node k2 and k5, Information will dissemination by this principle, until the sensor node k3 installed on the fault line receive feedback information by it child nodes are all normal message, it can be determined that a fault point is between the k3 and it's child node k7.

(2) Phase short circuit fault occurs. Signal source does not move, the other procedures were the same as (1).

4 Simulation

Electric power fault detection system has established rules for system communication [5]. Some crucial criteria are as follows. Transmission time for fault information is within 4ms and maximal transmission time for fault information between substations is commonly 8 ~ 12ms. For a breaker, its controlling signal's maximal transmission time is commonly 2 ~ 8ms, while sending a signal to the adjacent area needs 8 ~ 12ms. Also, time synchronization should be less than 1ms. In reliability, transmission error should be immune to environmental noise, and when a fault occurs, the system can detect and deliver the fault timely and accurately to regional management node unit for further processing.

4.1 Reliability

To ensure data information from low-layer sensor node can reliably transmit to regional management node, we model the system in the network simulation software OMNeT++ as seen in Fig.3. The degree of redundancy for each line is 1, data transmission rate is set to 150kb/s, packet transmission rate is 50 per second, packet length is 28 bytes. Besides every second intervals, the link error that is caused by environmental interference obeys Poisson distribution which parameters λ is 0.5.

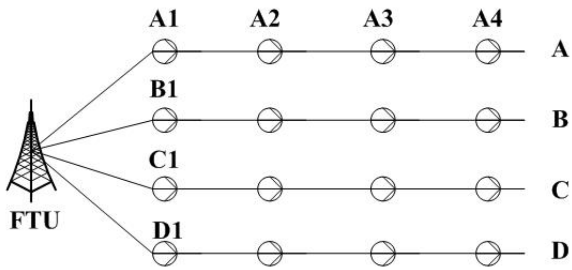

Fig. 3. Topology of a simulation network

MAC layer use CSMA/CA protocol. All communications employ ACK mechanism, if no ACK frame received, the system retransmit data. It can be seen in Fig.4, for regional management node, the probability for successfully receiving data from line nodes is 97.83% and 98.62%. When the maximal retransmission number is set to be R≥4, regional management nodes can successful receive all packets. A packet RTT (round-trip time) is defined as the time difference between the sending and receiving the corresponding confirmation, then RTO (retransmission timeout) can be evaluated as follows:

$$RTO=\beta\times RTT \quad (1)$$

Where β is larger than 1, so RTO should be slightly larger than RTT, namely, the much closer to1, the timelier for retransmission. But if the packet is not lost, retransmission may even heavy network burden just for a slight time delay, so, in the simulation β is set to 1.5. According to the requirements, we have RTT bigger than 1.5ms, thus RTO is bigger than 2.25ms. Obviously, the delay of successfully sent is greatly increased with each retransmission. But the power protection system has a high demand for data transmission delay, usually less than 4ms[5]. Generally, the packet loss rate is high in wireless sensor networks so to ensure the reliability of data transmission more retransmissions are inevitable, which contradicts with the maximal delay. In order to solve this problem, this paper develops a kind of reliable transmission mechanism oriented to events.

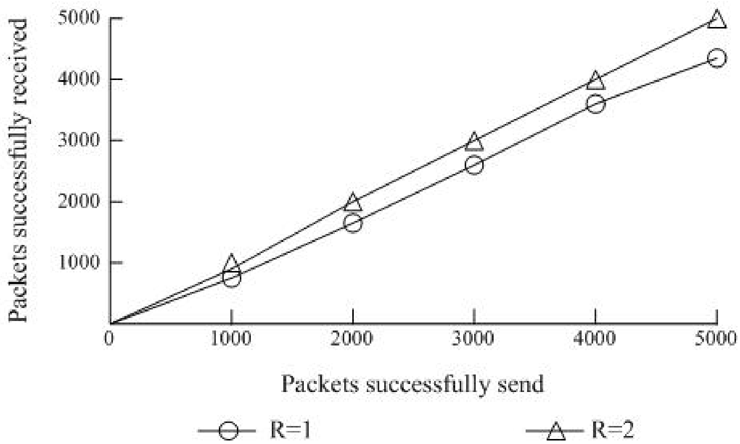

Fig. 4. Probability of packets successfully received

One important feature of wireless sensor networks is its node's redundancy which makes the system blessed with the ability of strong tolerance. Induced by the redundancy properties, event-oriented reliable transmission mechanism comes into being. We define event-oriented reliability as the packets set required in fault detection during a time interval t, denoted by P.

In our simulation network model, each perception object (A phase, B phase, C phase, D phase) has four wireless sensor nodes for data collection. Suppose in Fig.3, single-phase-to-ground fault happens at A phase, according to the fault detection model[6], the current data at A, B and C and D phase should be first obtained. Let Sa, Sb, Sc and Sd denote the current data at A, B and C and D phase, respectively, then we have:

$$P = \{Sa, Sb, Sc, Sd\} \quad (2)$$

Sa can not only be obtained by the node Node_A1, but also by A phase's other nodes. i.e., during t time, at least one node of A phase can successfully transmit its sampling data to regional management node. For Sb, Sc and Sd , it's the same case.

Event-oriented reliable transmission mechanism can be briefly described as follows:

(1) In each regional management node unit, save the transmission link-state of all the nodes involved in the unit, and each node's link-state can be seen as the transmission reliability of the nodes before it;

(2) Compared with redundant nodes, the node with a higher reliability possesses a better transmission priority;

(3) When a node send a request, regional management node inquires the information whether it has been received or not. If so, the node won't send the data information.

Fig.5 gives the number of transmission packets of different redundancy, based on event-oriented reliable mechanism under the same reliability condition. It can be seen in Fig.4 that the reliability of data collection is increased with the redundancy, but when redundancy exceeds 4, redundancy has little effect on the reliability. Moreover, the larger the redundancy, the higher the installation cost of wireless sensor network. So we should take comprehensive consideration of the node's redundancy.

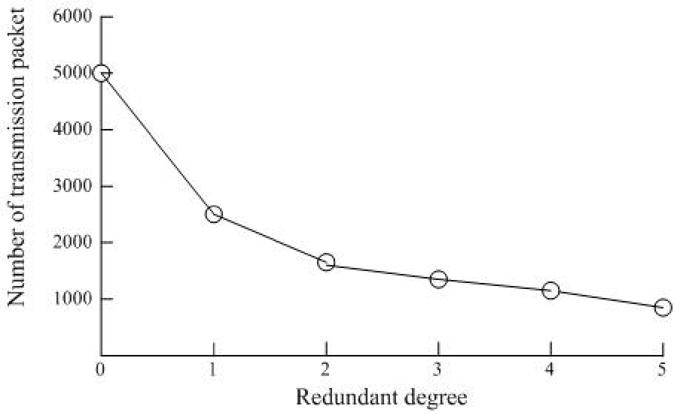

Fig. 5. Number of transmission packets versus redundant degree

4.2 Delay

Above, we have known that the power protection system has a high demand for data transmission delay, usually less than 4ms[5]. So the data gathering delay should be paid great attention when making the feasibility analysis.

1. Single-hop link data gathering delay

See in Fig.3. Gathering delay mainly investigates the average delay and the maximal delay of the multi-nodes sending data which are gathered at regional management node. Gathering delay mainly includes:

(1) Internal data processing delay Tp;
(2) Waiting for sending delay Tw;
(3) The transmission delay from the sending node to gathering node Tt;
(4) Processing data delay at regional management node Tr.

The delay simulation results based on the network structure in Fig.3.are shown in Table.1:

Table 1. Delay of the delivery packets

	communication traffic / Network capacity / (%)		
	4%	10%	15%
average delay / ms	1.46	1.62	1.87
maximal delay / ms	2.83	3.07	3.42

It can be seen that data gathering delay has a sharp increase along with the increased network communication.

2. Multi-hop link data gathering delay

In WSN the maximal delay for fault data determines the maximal coverage area for regional management node to collect data. Simulation results show that multi-hop link data gathering delay increases with the hop numbers. As in Fig.3, if the traffic/network capacity is 4%, then the average gathering delay is 3.72ms, and the maximal delay is 7.83ms, which is far more than allowed maximal transmission delay 4ms.

4.3 Synchronization

The fault monitoring system based on wireless sensor network is a typical distributed system that requires multi-nodes cooperation. And the cooperation work needs time synchronization.

The synchronization precision between the wireless sensor nodes is 0.05 ~ 0.1ms[5]. The network architecture in Fig.3 is based on the platform of Mica2 node[7], its clock is 7.3728 Mhz, which employs RBS (Reference Broadcast Synchronization)[8] and TPSN(Timing-sync Protocol for Sensor Networks)[9], where the synchronization precision of RBS is 0.027ms, TPSN's is 0.016ms. They all meet the requirements.

As the hop increases, the network synchronization precision increases. Take TPSN as an example, the simulation results is shown in Fig.6.

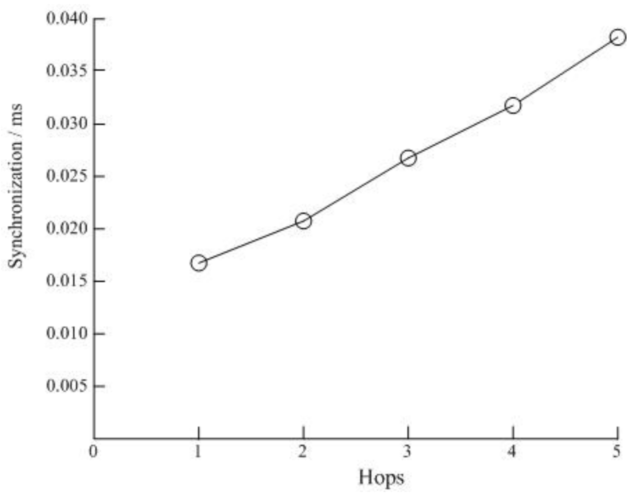

Fig. 6. Multi-hop synchronization analysis of TPSN

5 Conclusion

Through analysis, we can see that the fault detection for power system based on WSN meets the requirements in reliability, delay and synchronization precision.

As the processing capacity and distributed collaborative ability of WSN improve, WSN has laid the foundation of the new relay protection in power system.

For instance, Crossbow company launch an Imote2 wireless sensor node which has integrated PXA271 X Scale processor and 14 A/D conversions, compatible with IEEE802.15.4 RF chip. Its transmission rate reaches 250Kb/s and offers a variety of I/O interfaces.

Simulation results show that, for single-hop data gathering based on wireless sensor network, its maximal delay doesn't exceed 4ms, which satisfies power protection system's requirements on communication.

Especially for distributed bus bar protection and short-circuit protection, which has small coverage area of protection unit. Owing to its many outgoing lines, adopting conventional protection device will lead to complicated connection and high cost. In such an environment, it's more suitable and effective to use WSN to realize protection.

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