Research on Smart Substation Equipment Condition Monitoring System Based on Wireless Sensor Networks

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Abstract. Reference to characteristics of wireless sensor networks (WSNs) technology and the three-tier architecture of smart substation, the paper designs an on-line condition monitoring system of smart substation equipment based on WSNs. The system is designed as a hierarchical distributed structure and is divided into perception level, convergence level and application level. Then the paper proposed some of the key issues resolved in the design of monitoring system. These key issues include sensor node design, network topology, error handling, information management, network security, time-synchronized, integrating with substation communication network. It provides a new solution for improvement and optimization of substation equipment monitoring system and contributes to improving the running speed and flexibility.

Keywords: wireless sensor networks, smart substation, on-line condition monitoring, hierarchical distributed architecture, key issues.

1 Introduction

Currently, Smart grid [1-2] becomes an international hot point on the development of the future grid. As an integral part of power transformer link in smart grid, smart substation [3] has also been concerned and researched in the power industry. With the development of related technologies and smart devices in substation and with the growing capabilities of self-describing and self-diagnostic, the on-line condition monitoring system of power equipment in substation will better reflect these advantages. Collection of equipment condition information in substation is the basis of condition assessment, risk assessment, development of maintenance strategy and so on [4]. Traditional substation equipment monitoring system is typically realized through wired communication. However, the wired monitoring system requires expensive communication cables to be installed and regularly maintained, and thus, it is not widely implemented today because of its high cost [5]. Hence, there is an urgent need for cost-effective wireless monitoring system that improves system reliability and efficiency by optimizing the management of smart substation.

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Wireless Sensor Networks is a new type of information acquisition and processing system. It is the combination of computer technology, sensor technology, MEMS manufacturing technology and network communication technology, involves multidisciplinary fields such as micro-sensors and micro-machinery, communications, automatic control and artificial intelligence. With the development of WSNs technology, it can not only collect, transmit and process simple scalar data, but also can obtain sounds, images and other multimedia data containing massive information. Thus, WSNs realize fine-grained information monitoring and comprehensive monitoring of the perception area. The application of WSNs has been extended by the military to anti-terrorism, explosion prevention, environmental monitoring, health care, home dwelling, commercial, industrial and other fields [6-8].

Compared with the traditional substation equipment condition monitoring system, the advantages of using WSNs include followings:

(1) Nodes in WSNs highly integrated data acquisition, data processing and communications functions. It greatly simplifies equipments and achieves multi-parameters and comprehensive monitoring of smart substation equipment.

(2) Because wireless communication mode does not require complex circuit wiring, it makes WSNs more cost-effective.

(3) WSNs has self-organized, large-scale and dynamic characteristics. These make WSNs more suitable for distributed processing, increases the scalability of monitoring system and build the protection platform rapidly without the need to add more facilities.

(4) WSNs can quickly build an application platform based on different programs. It can be configured with appropriate sensor nodes and sensed multiple types of data for different substation environment.

Therefore, low-cost and low-power wireless sensor networks will likely become the solution of substation equipment on-line monitoring [9-11].

Combined with smart substation three-tier architecture and in the analysis of characteristics of WSNs, the paper proposes an on-line condition monitoring system of smart substation equipment based on WSNs and designs the hierarchical distributed architecture. Finally, some of the key issues that achieve reliable operation of the monitoring system are researched.

2 WSNs Characteristics and Communication Protocols

2.1 WSNs Technical Characteristics

WSNs are usually composed of nodes by self-organizing way. These nodes include embedded processors, sensors and wireless transmitters and receivers. WSNs use these nodes to work together to collect and process network coverage area of the target information. Figure 1 is often cited as a typical network deployment of WSNs [12].

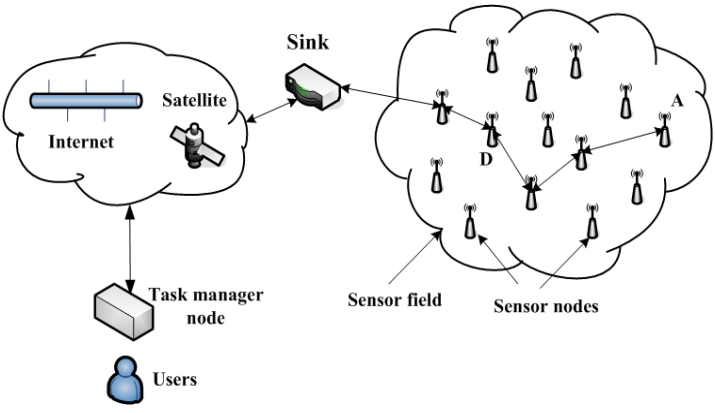

Fig. 1. WSNs network deployment

It can be seen from the WSNs deployment figure that it is a large-scale self-organization network centered with data and related to applications. It is a kind of specific Ad hoc network. Although WSNs and Ad hoc self-organizing networks have some similarities, there are also some different features between them [13]: ①The number of nodes in WSNs is much more and intensively deployed than Ad hoc. ② WSNs need higher requirement of fault-tolerance for it is often deployed in dangerous or unprotected area. ③WSNs nodes are generally relative static, while Ad hoc are strong mobility. The transforms of WSNs topology are mainly on account of electricity drained, parts fault, captured factors, but shift of node position. ④WSNs are also exposed to some limitation including processing power, storage and communication ability. The various solutions for WSNs are contented with as low complexity and power consumption as possible. ⑤Sensor nodes usually are not charging, and are fragile to failure for energy exhausted and environmental impact. The request of the quality of service (QoS) is not too high. In contract, improving the network service quality is its primary goal in Ad hoc; ⑥According to WSNs application characteristics, it often uses multicast or radio communication mode, and its data correlation is larger, so it is adapt to data-centric design; Rather, communication mode in Ad hoc is primarily point-to-point. It is suitable to the node centered design which can provide distributed applications with interconnection and processing power. ⑦WSNs often belong to an institution. Some global parameters or individual information in operation process can be pre-allocated before deployment.

As we know from the above, WSNs cannot effectively utilize in communication protocols which are suitable to conventional wireless networks and Ad hoc networks. Thus, WSNs need to formulate corresponding routing and MAC protocols.

2.2 Routing Protocol

The main objective of WSNs routing protocol is: seeking for power-efficient routing method and reliable data transmission method for WSNs, balancing the entire

network power consumption to maximize the network life cycle. Thus the conventional wireless network routing protocols may be not suitable to WSNs.

Many different routing protocols have been proposed for different WSNs applications. According to different communication ways which nodes participate in, routing protocols can be divided into Location-based protocol, Flat-based routing and Hierarchical-based routing. From the specific application of WSNs, according to the different degree of sensitivity which applications of WSNs caused, routing protocols can be divided into energy-aware routing, query-driven routing, geographical aware routing, reliable routing and IP-based routing; According to the network topology structure, it can be divided into flat routing protocols and cluster-based routing protocols [14-15]. So far, there is no complete and clear routing protocol classification. To sum up, above classification of routing protocols have the characteristics of energy priority, local topology information-based, data-centric and application related. Therefore, when designing the routing mechanism in the specific application, it should satisfy the WSNs routing mechanism requirements that include energy efficient, expansibility, robustness, load balance and fast convergence.

2.3 MAC Protocol

WSNs MAC protocol is used to build the understratum infrastructure of sensor networks system and solve nodes using what kind of rules to share media in order to obtain satisfactory network performance. MAC protocol used in WSNs directly affects the network throughput, delay and other performance. In the design for MAC protocols, the following aspects need take into consideration: saving energy consumption, expansibility, network efficiency (fairness, real-time, throughput rate and bandwidth utilization ratio) and QoS The MAC protocol design should have the following attributes: energy efficiency, scalable to node density, frame synchronization, fairness, bandwidth utilization, flow control, and error control for data communication, especially considering saving energy consumption as a key factors.

The current MAC protocols for WSNs include four types. They are protocol based on scheduling algorithm, non-collision protocol, protocol based on competition and hybrid MAC protocol. In MAC protocol based on scheduling, the time interval which sensor nodes send data is decided by a scheduling algorithm. Such type of protocols contains SMACS [16], DE-MAC [17] and EMACS [18]. The non-collision MAC protocol has completely avoided the generation of confliction theoretically, including IP-MAC [19], TRAMA [20] and MMF-MAC [21], etc. MAC protocol based on competition is to acquire channel access in a competitive way when nodes need to send data. The typical protocols include S-MAC [22], T-MAC [23] and B-MAC [24]. The hybrid MAC Protocol combines multiple mechanisms to get a compromise between their strengths and weaknesses, such protocols include Physical Layer Driven Protocol [25], Hybrid TDM-FDM MAC [26] and CAT-MAC [27]. At present time, it is generally accepted that TDMA is more suitable for wireless sensor networks.

3 Monitoring System Design of Smart Substation Equipment Condition Based on WSNs

In general, equipment condition monitoring in smart substation has two different ways, on-line monitoring and off-line monitoring. The on-line monitoring uses the measurement system and technology which is installed directly on the equipment and record the characteristic quantity of equipment operating condition in real time. The off-line monitoring includes essential tests and technologies which can obtain the operation condition data through indirect contact with the equipment such as infrared monitoring. This way is an important complement of the on-line monitoring technology [28]. Nowadays, the most researches of condition monitoring are focused on the on-line monitoring. Its model is developing to hierarchical and distributed comprehensive on-line monitoring system. Based on the diversity of smart substation equipment and the complex characteristic of equipment condition information, the paper provides general hierarchical and distributed on-line monitoring system architecture based on WSNs.

3.1 Smart Substation Architecture

Deployment of WSNs must be designed according to the needs of the object. Like digital substation architecture, the architecture of smart substation is divided into three levels in State Grid Corporation of China's latest technology guidelines. They are process level, bay level and station level. As shown in Figure 2.

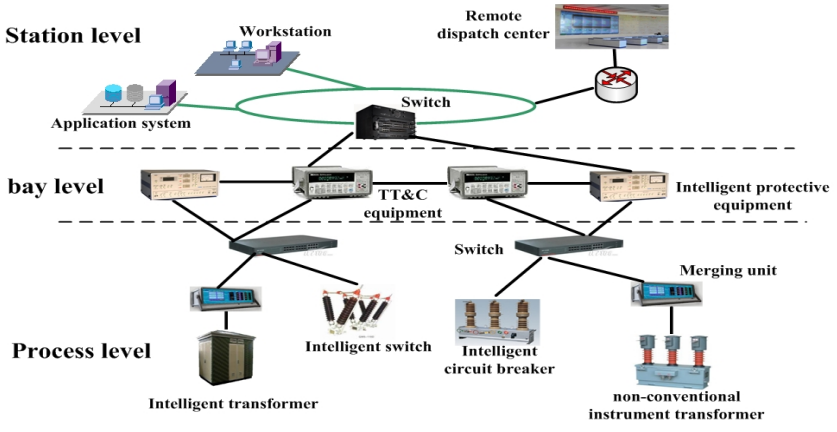

Fig. 2. Smart substation three-tier architecture

3.2 Monitoring Parameter of Smart Substation Equipment

As shown in figure 2, smart substation is a whole that requires harmonization work together of multiple equipments. Usually separated power equipments include intelligent transformer and circuit breaker, non-conventional instrument transformer,

switchgear, reactor, type arrester and so on. Therefore, it needs to monitor more parameters including followings:

Intelligent transformer: partial discharge, grounded neutral current, dissolved gas analysis, moisture content, winging deformation, oil chromatogram, oil temperature

Intelligent circuit breaker: mechanical behavior, temperature, leakage current of exterior insulation, breaking time, current of opening and closing coil

GIS: partial discharge, air pressure, SF6 characteristic

Type arrester: phase current, capacitive current, resistive current, struck number

Capacitive equipment: dielectric loss, leakage current, equivalence condenser

Switchgear: temperature rise of bus contract points, partial discharge, temperature and humidity

In addition to these parameters, it also includes power quality on-line monitoring.

Sensors are the main equipments in distributed on-line monitoring system and there are many types, such as pulse current sensor, gas temperature and pressure sensor, hall sensor, photoelectric sensor. Here, the paper simply divides them into two types of data sensor and image sensor.

3.3 Monitoring System Design Requirements

⑴ Flexibility in topology

According to the different design, the scale of smart substation is also different, and there are many intelligent electrical devices. In addition, line fault that may occur in the process of signal transmission must be considered. To ensure normal operation of equipment condition monitoring system, deployment of wireless sensor nodes need to be designed the net distribution and network architecture need to support flexible topology. So when happened a line fault, data can be transmitted from another line.

⑵ Support multiple data types transmission

Based on the various reasons for equipment failure, monitoring data can be divided into two categories. One is scalar data type, such as operating voltages and load currents for transformer, GIS and circuit breaker, ambient temperatures. Another is image type, such as surface's texture images for transformer bushing and insulation situation of current transformer. Therefore, monitoring nodes must be required to have heterogeneity and include both traditional scalar sensor nodes and image sensor nodes. These nodes can also support a variety of data transmission and have higher transmission bandwidth.

With the development of WSNs technology, it can not only collect, transmit and process simple scalar data, but also can obtain sounds, images and other multimedia data containing massive information. Thus, WSNs realizes fine-grained information monitoring and comprehensive monitoring of the perception area.

3.4 Monitoring System Design

The on-line condition monitoring system of smart substation equipment adopts a distributed hierarchical architecture. It has been divided into substation-level monitoring system and dispatch center-level monitoring system as a whole. As shown in figure 3.

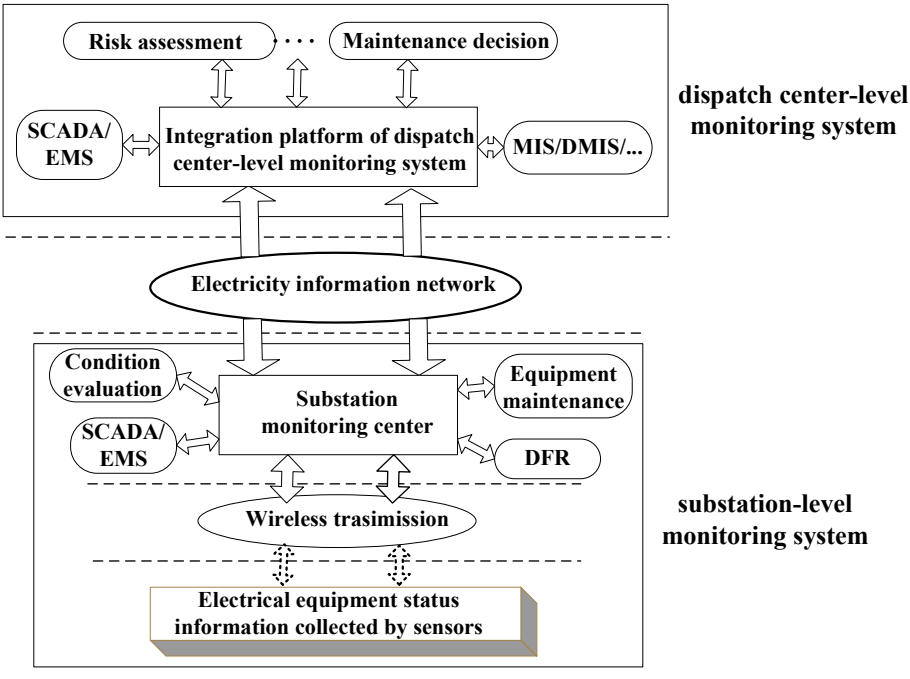

Fig. 3. Overall design of equipment condition monitoring system

Within smart substation, according to substation three-levels, the on-line condition monitoring system has been logically divided into three levels based on WSNs. The perception level is responsible for processing data and forming message. The convergence level is responsible for processing message and forming information. The application level is responsible for processing information and forming interaction. Clustered network topology and hierarchical routing protocol [29] is considered using in the monitoring system. As shown in figure 4.

Perception level mainly composed of sensor nodes that monitor a variety of electrical equipments. Besides traditional data sensors, it also adds image sensors that can realize equipment condition visualization. The first of deployment of sensor nodes logically divides substation equipments into different monitoring intervals according to different types. Inside the interval, sensor nodes have been divided into different cluster base on data sensors and image sensors. Each cluster is equivalent to a relatively fixed wireless network. So, the range of monitoring system is determined by actual situation of network coverage.

Convergence level's main task is to integrate these by cluster head node when equipment condition data and images through analog-to-digital conversion. Then the processed information is been sent to coordinator with GPRS modem. Through wireless gateway and GPRS network docking 100M/1000M Ethernet of station level, information arrives in substation monitoring center.

In order to ensure reliable transmission of substation equipment condition information, it has been considered node redundancy when cluster head node deployment. In each cluster, information is processed separately by data and image cluster head nodes. These cluster head nodes will fusion process collected data and image by sensor nodes under the jurisdiction of them, send information to the nearest coordination and can broadcast collected data packets from coordinator to jurisdiction of cluster at the same time. Cluster head node is located in a more central position where the cluster. It makes each node and cluster head node have the roughly same transmission distance and node power consumption of uniform distribution. Thus excessive energy consumption of some nodes has been avoided because of far transmission distance. Coordinator with GPRS modern is mainly responsible for cooperative building network. When designing the coordinator, because of taking in to account the possible connection failure between coordinator and wireless gateway, it can communicate between adjacent coordinators. Thus data and image of sensor nodes can be ensured the normal transmission through multi-hop path when a path failure.

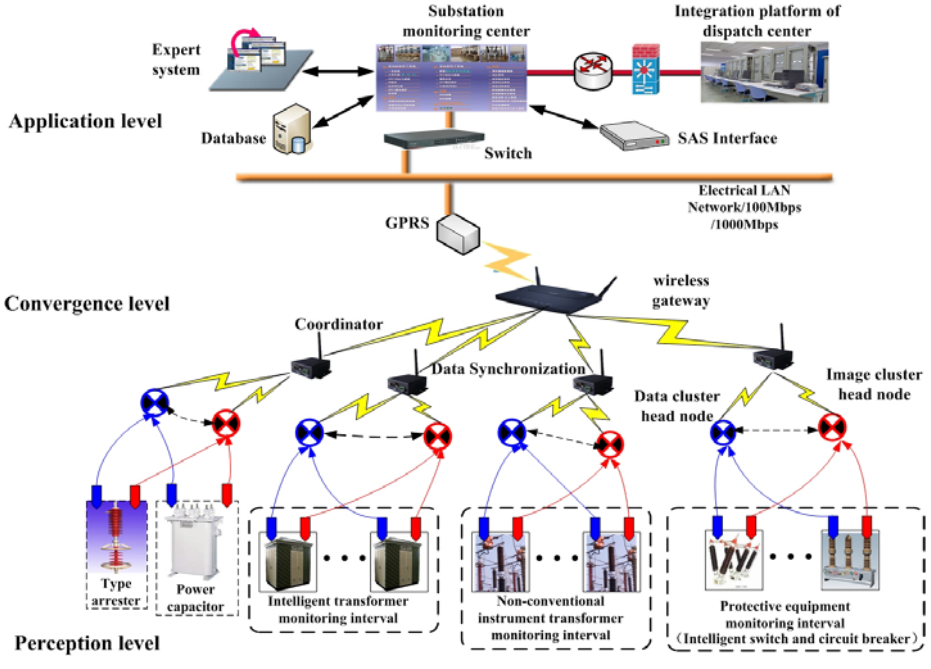

Fig. 4. Architecture of on-line condition monitoring system of smart substation equipment

Application level includes monitoring center, expert system, servers and so on. It is responsible for storage and analysis of equipment condition information. Then, monitoring center server completes the operation of general monitoring parameters with database and expert system, predicts the condition of equipment operation and finally provides the basis for maintenance decision system. Besides, equipment

condition information can transmit to dispatch center-level monitoring system through the router via electricity information network.

4 Key Issues for WSNs Application in Smart Substation

The key issues for WSNs application in smart substation concerns sensor node, network topology, error handling, information management, network security, time-synchronized, integrating with substation communication network.

4.1 WSNs Node Design

Since the development of MEMS technology, low-power analog and digital circuit technology, low-power radio frequency technology and sensor technology, WSNs can consider the intelligent sensor in smart substation. As shown in figure 5. Processor unit, wireless transmission technology and chip are more important parts of node design.

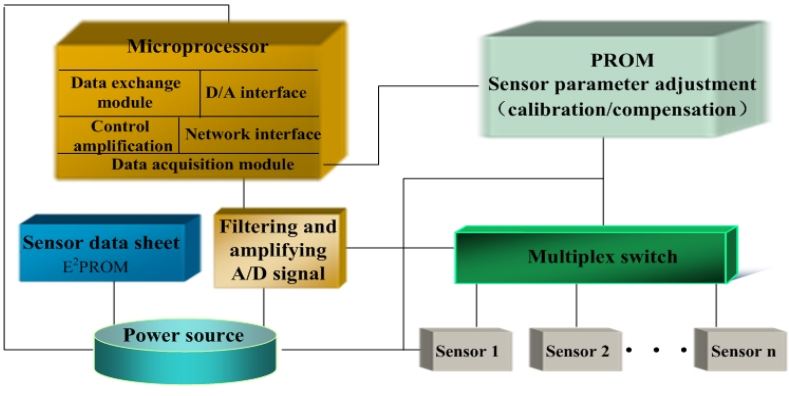

Fig. 5. Intelligent sensor structure

Sensor node processor that is responsible for collecting key equipment image and data can consider to using ARM processor. Because ARM processor has powerful processing capacity, it is suitable for application of high volume data services. Besides, it can also support energy saving policy such as DVS (Dynamic Voltage Scaling) or DFS (Dynamic Frequency Selection). Other sensor nodes can use low-performance microcontroller. Though processing power is week, energy consumption power is very small.

Commonly used in wireless communication technology typically include 802.11b, 802.15.4 (Zigbee), Bluetooth, UWB, RFID, IrDA and so on. Compared to other technologies, Zigbee technology is a short distance, low power, low-cost wireless communication technology [30] and its maximum bandwidth is 250kbit/s. It not only can meet temperature, sag and other needs of the scalar data transmission, but also can take into account image and other needs of mass data transmission in a small

network area. It has a complete protocol stack only 32K and can be embedded in a variety of devises, while supporting geographic targeting. So it can consider using Zigbee in monitoring system based on the above characteristics. Alternatively, it can also choose an ordinary radio chip because the chip may customize MAC and routing protocols. In smart substation, wireless sensors are used to complete a variety of electrical quantities, digital, analog and other monitoring and testing. Therefore, it must fully consider the characteristics of substation in the design of monitoring system based on WSNs. Design of WSNs that is able to operate stable and reliable in substation environment is the key issue of custom communication protocols to be considered.

4.2 Network Topology

Network topology is one of the reasons for transmission reliability of sensor network. Access node adopts star structure in the traditional point to multipoint network. When a node fails, especially the central node fails, it will affect the normal operation of the entire work. The current improved point-to-point communication network has been adopted a number of protective measures in order to improve network reliability such as backup ling configuration. This method is simple, but requires each path to need equipped with two separate links and a protection switching. It greatly reduces the efficiency and improves the cost.

Thus, monitoring system design uses a net structure. It gives the function of each network node to automatically select the path. So each node may use multiple paths to connection and can be greatly increased with the number of link. If one out of a failure of a link, node can automatically link access to other optional link so that network reliability has been greatly improved. Arrangement of nodes in the network topology must also consider the impact of distance. Wireless signal transmission distance is affected by transmission power, receiving sensitivity, antenna gain and other factors. It can refer to the following formula to calculate.

$$20\lg d = P_t + G_t + G_r - (L_t + L_r) - \Delta - 20\lg f - 32.45 .$$

Here, d is transmission distance. P_t is transmission power. G_t and G_r are transmitting antenna and receiving antenna gain. L_t and L_r are transmitting antenna and receiving antenna loss. Δ is a wireless link power margin and usually takes 15∼20. f is frequency.

4.3 Error Handling and Information Management

WSNs spread signal through the air as a transmission medium. Wireless transmission signals will be affected by signal waveform reflection, diffraction and scattering, node movement, path loss, attenuation and obstacle. So bit error rate than conventional wired systems are usually several orders of magnitude higher. Through error control can guarantee error-free communication in WSNs. There are some measures to handling error including packet loss handling, excluding original error and forward error correction (FRC) [31]. Considering the energy loss factor and data features in

WSNs of substation monitoring system, it is able to use FEC coding control techniques for processing network error.

As large amount of monitoring data in the substation, different types of data requirements of different transmission quality and response time and the need to deal with different data, it requires the management of monitoring data and the use of hierarchical distributed processing mechanism. Only sensor combined with location information, its obtained information has practical meaning in substation. For example, only know exactly them specific location information, electrical quantum, switching value and other data can be effectively monitored and analyzed. Under the premise of satisfaction of substation positioning requirements, design a low overhead, low cost Distributed Location Algorithm is one of the key issues for WSNs applications in smart substation.

4.4 Security Problem

In the communication process, when the information of key equipments has been collected and transmitted in substation, it must guarantee their confidentiality, reliability and security to prevent data from being tapped or illegal user access. Network is vulnerable to tap and even to attack [32] because of characteristics of sensor node.

Security is determined by the openness of network deployment area and the broadcast nature of wireless networks in WSNs. It includes access control and confidentiality. Access control ensures that sensitive data is only accessed by authorized users. Confidentiality ensures that data transmitted is only received and processed by target. Therefore considered security threats must include conventional wire transmission with security threats and hidden troubles, transfer information without encryption or weak encryption, data theft and information tampered and inserted, which may lead to equipment malfunction and miss trip. The current measures to address security issues focuses on key management, identification, data encryption, attack detection and resist, secure routing and so on.

Now the main technology used in WSNs is symmetric encryption based on key pre-distribution and asymmetry encryption based on base station management key. But they have their own advantages and disadvantages, whereas using soft encryption is a feasible program.

Attack detection and resist is mainly to guarantee the normal operation of WSNs when sensor node has been hostile attacked such as interference service and node capture. "Method to find abnormal nodes by sending validation data to independent multi-path" is a solution [33]. This method proposed the “safe and flexible time-synchronized protocol”.

Routing protocols in WSNs have many security weaknesses and are vulnerable to attack. If injecting malicious routing information to WSNs, the network will be paralyzed. For routing security issues, it has been proposed some methods such as “A defense method using certification against malicious injection” [34], “Broadcast encryption scheme” [35] and “a method that radio base station random tests node whether can receive its broadcast” [36].

4.5 Time-Synchronized and Substation Communication Network Access

WSNs application in substation must guarantee time-synchronized [37]. The main reasons are as follows. It needs collaboration between the sensor to comprehensive determine and analysis the monitoring electric quantum information. It will need synchronization mechanism to guarantee synchronization of each sensor data collected. Synchronization is beneficial to extend network lifetime and ensures that data will not lost because of mutual interference in the communication process. Smart substation currently includes three methods of time-synchronized. GPS has high precision and low cost characteristics and its related technology has matured [38-39]. The accuracy of Simple Network Time Protocol (SNTP) time synchronization can be achieved 1ms and the accuracy of IEEE1588 protocol network time synchronization may be achieved sub-microsecond [40]. How to use these three methods to realize WSNs time-synchronized is also one of the key issues to be resolved.

Electrical quantum, switching value, analog and other data of sensor nodes collected need to upload to monitoring center of the station level by monitoring network for analysis and monitoring. Smart substation communication network is the connecting link of a variety of intelligent electrical equipment. It uses a uniform standard IEC 61850 and is used to store and transmit events, quantity of electricity, operation, fault recording and other data. Therefore, it requires that WSNs accesses to smart substation communication network to achieve data sharing and complementation and avoid information isolated island.

5 Conclusion

WSNs application in various fields becomes increasingly widespread. Especially in difficult or adverse environmental conditions, it has unparalleled advantages compared with traditional monitoring techniques. Take into account characteristics of WSNs technology and the three-tier architecture of smart substation, the paper proposes an on-line hierarchical distributed monitoring system of smart substation equipment condition based on WSNs. Then some of key issues resolved in the design are discussed in detail such as sensor node design, network topology, error handling, information management, network security, time-synchronized, integrating with substation communication network. The monitoring system based on WSNs will not only help to improve the running speed and flexibility, but also is of great significance for comprehensive assessment of substation equipment health condition, as well as eliminate equipment potential failure and improve equipment reliability.

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