TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.7, July 2014, pp. 4963 ~ 4972
DOI: 10.11591/telkomnika.v12i7.5467

Research on Zigbee Network Temperature Sensor in Intelligent High-voltage Switch Cabinet

Huang Xin-bo, **Zhao Yang***, **Zhao Xiao-hui, Liao Zhi-jun**
College of Electronics and Information, Xi'an Polytechnic University,
Xi'an 710048, Shaanxi Province, China
*Corresponding author, e-mail: 951801764@qq.com

Abstract

The contacts of high-voltage switchgear will heat and cause safety hazards due to poor contact while running. A Zigbee-based wireless network sensor was designed by the authors of this paper for real-time monitoring of high voltage switchgear when contact temperature rises. This paper first gives a brief introduction to the Zigbee protocol, the protocol stack and the network topology, and then makes an elaboration on the system framework, hardware and software designs of the Zigbee wireless sensor and the design of high-voltage bootstrap power supply. In the end, the field application and analysis proves that based on the Zigbee technology, the online monitoring system of the temperature rise for high-voltage switchgear is stable and capable of real-time reporting the true temperature of the contact. Therefore, the design has the characteristics of high stability, low power consumption, low cost, as well as high flexibility and scalability.

Keywords: *Zigbee, Zigbee protocol, high-voltage switchgear, wireless network sensor, contact temperature rise*

1. Introduction

The monitoring of safe operation of the high-voltage switchgear has been one of the major concerns of the safe operation of the power system. However, it still has not been solved as the monitoring of contact temperature is constantly influenced by high pressure, measuring point and the interference of strong electric field. Nowadays, temperature measurement system mainly includes three kinds of communication programs: ordinary cables, optical fibers and wireless communication, among which the ordinary cables will bring about safety hidden dangers by affecting electrical isolation of the switchgear. Optical fiber temperature online monitoring device is impervious to high pressure and environment by using the optical fiber to transmit signals [1-3]. However, as the optical fiber can be broken off easily, cannot stand the high temperature, and can be difficult to wire etc., it is difficult to meet the requirements of on-line monitoring of the high-voltage switchgear. In contrast, as Zigbee wireless network has the merits of low cost, unlicensed frequency band, low power consumption, no wiring, no impact on the characteristics of electricity [4-5] and so on, it is in full compliance with the requirements of the switchboard online monitoring.

2. Introduction of Zigbee Technology and the Feasibility Analysis of Application to Switchgear Communication

2.1. Zigbee Protocol Overview and Protocol Stack

Zigbee, the standard that stipulates a series of short-distance wireless network communication protocol for transmission rate of data, is mainly applied in short-distance wireless data transmission. The network standards of Zigbee, formulated by 802.15.4 working group established by the IEEE, are based on IEEE802.15.4 protocol and employ the free global communication frequency band to communicate. On the whole, it defines three frequency bands: 2.4GHz, 915MHz and 868MHz [6-7]. And the number of the frequency band channels has been set when they are stipulated by the working group. For example, the 2.4GHz band could offer a total of 16 channels (channels 11-26) [8-9], whose data transfer rate is the fastest-250kbps; the 915 MHz band could offer a total of 10 channels (channels 1-10), whose data

Received December 23, 2013; Revised February 28, 2014; Accepted March 16, 2014

transfer rate is 40kbps; while the 868MHz can only offer one channel (channel 0), and its data transmission rate is 20kbps [10]. Hence, the higher the communication band is, the greater the transmission data rate is. However, due to the delay in the actual data transfer process, the transfer rate will be slightly smaller than the specified.

The Zigbee stack consists of four layers, and from the top down, they are the application layer, the MAC layer, the network layer and the physical layer respectively. The upper layer can acquire services and relative data from its lower layer. The physical layer is responsible for the setting of the three working frequency bands and their data transmission rate; the function of the MAC layer is to make sure that a set of wireless communication devices working in the same space can share the frequency band without producing signal conflicts; the application layer can be divided into three parts: the device object (ZDO), the application support sub-layer (APS), and the application objects. Its protocol stack is shown in Figure 1.

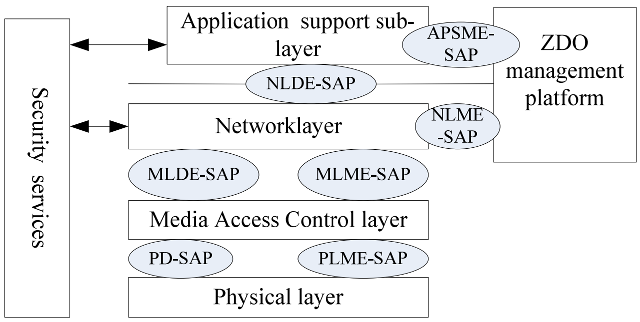

Figure 1. Zigbee Stack

2.2. Zigbee Network Topology [11]

IEEE802.15.4 provides three types of effective network structures (cluster type, mesh, and star shape) and three kinds of device operating modes (coordinators, full function devices, and reduced function devices). The reduced function device can only be used as the terminal sensor node; the full function device can be taken as a terminal sensor node as well as a routing node; the coordinator can only serve as a routing node. Thus, Zigbee-based wireless sensor networks can roughly form three basic topologies, as shown in Figure 2:

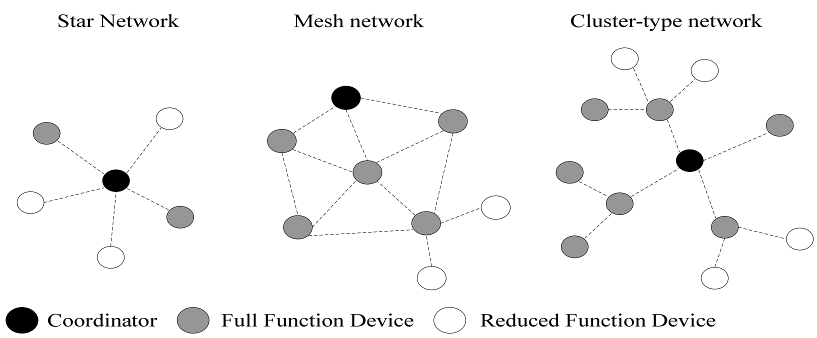

Figure 2. Zigbee Network Topology Diagram

(1) The star-shape-based topology has a natural distributed processing capability and the routing node of the star shape is the distributed processing center, i.e. it possesses the capability of data processing and integration as well as a routing function. Each wireless terminal sensor node will transfer the data to the routing node of the same topology, where the data integration will be completed in a simple and effective way and then the processed data will be transmitted. This kind of network topology is adopted by this program.

(2) The mesh-based topology, whose wireless sensor nodes are connected into a net, can transmit data through several routing channels simultaneously, which could maintain high transmission reliability. The network of this topology is so powerful and elastic that network separation won't happen when several links and sensor nodes fail to work.

(3) The cluster-type-based topology, whose sensor nodes are connected in one or more chains and the end of each chain is connected with the terminal sensor node. In this program some terminal nodes will lose connection if intermediate nodes lose effects.

2.3. Feasibility of Zigbee Wireless Network Application in Switchgear Online Monitoring

By employing 2.4GHz band, Zigbee can fully meet the demand for online monitoring of the switchgear. At first the dielectric properties of the material of the high-voltage switchgear and its semi-closed structure make it equivalent to the waveguide in the high frequency so that high-frequency wireless signals in the switch cabinet can be better transmitted. Secondly, the size of the Zigbee wave length is much smaller than the obstacles which impede its spread. The wireless signals can be regarded as the integral result of the direct light, diffraction and reflection, which occur in the space where light is prevented from spreading. The spread of UHF band signals in the switchgear cabinet have more advantages over that of the VHF or lower band signals.

Besides, although the 2.4GHz band signals can not be compared with 500 ~ 1000MHz radio signals in fading performance, the internal distance of switchgear space is so short that the propagation loss of the signals is within the acceptable range. Meanwhile, given that the 2.4GHz band is a free frequency band without application, and the power consumption of the high-band chip, the size of the antenna and the volume of the wireless data module are all very small, it is very suitable to use the Zigbee of the 2.4GHz band as the working frequency band of the wireless data transmission in the present system.

3. The Design of Temperature Monitoring System for High Voltage Switchgear

3.1. System Framework

The communication between the high-voltage switchgear contact and the host computer of station level can be achieved by means of Zigbee wireless network, IEC61850 protocol [12-13] and the RS-485 bus [14], as shown in Figure 3.

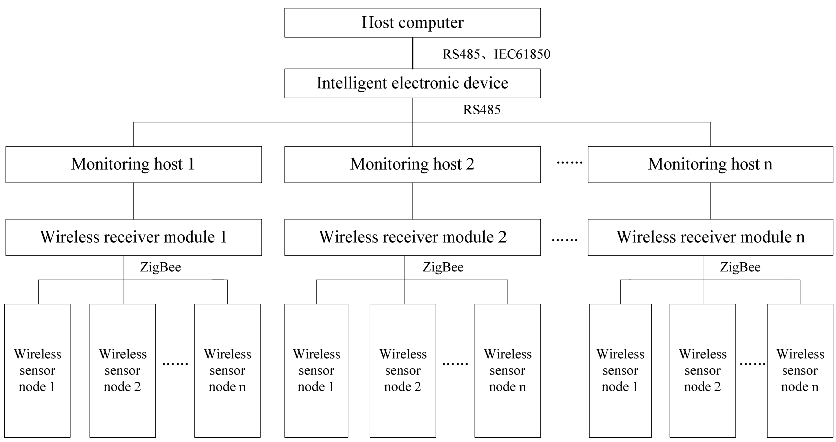

Figure 3. System Framework

Wireless temperature measurement system consists of the following five parts, namely, wireless sensor nodes, wireless receiver module, the monitoring host, intelligent electronic device and the host computer of the station level, as shown in Figure 3.

(1) Wireless sensor nodes: As wireless sensor nodes are set on the contact arm and temperature sensors and the contact arm are in good contact, the real-time temperature data of contacts can be gathered and sent out through Zigbee network.

(2) Wireless receiver module: Installed in the back of the monitoring host, it's responsible for collecting the data of temperature sent by wireless sensor nodes and uploading them to the monitoring host.

(3) The monitoring host: It's responsible for setting the operating parameters of data receiving terminal, receiving, saving, analyzing and managing the temperature data uploaded from each Zigbee network coordinator etc. It can also upload the data to IED through the RS-485 bus.

(4) The intelligent electronic device: The intelligent electronic device receives the data collection instructions sent by the host computer at a fixed time and then distributes corresponding collection instructions to each monitoring host through the RS-485 bus. After the monitoring host uploads the temperature parameter of each contact to the intelligent electronic device, the data will be analyzed and processed by the intelligent electronic device, and following the IEC61850 agreement, these thermal state parameters as well as the pre-warning and warning messages will be sent back to the host computer of the station level to achieve the remote monitoring.

(5) The host computer: installed in the control room of the station level, it is in charge of storage and display of online monitoring data.

3.2. Hardware Design of Zigbee Sensor Nodes

Wireless communication module takes the control chip MC9S08QG8 and RF chip MC13192 [15-16] as its main components. The control chip MC9S08QG8 in this module can calculate the temperature of switchgear contact by 1-wire digital thermometer DS18B20, and through SPI communicate with RF chip MC13192, which can send out the wireless messages through antenna. MC13192 in wireless receiver module can receive the data through antenna and send out them through SPI to MC9S08QG8, which can send data to the monitoring host through a serial port. The wireless communication module is composed of a wireless sending module and a wireless receiver module, whose hardware designs are the same, but different in programming. Its block diagram is shown in Figure 4:

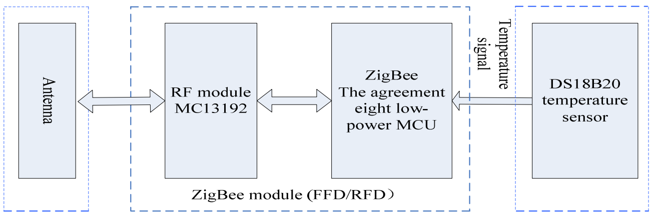

Figure 4. Internal Structures of Zigbee Wireless Sensor Nodes

The MCU (MC9S08QG8) and MC13192 can achieve the exchange of information through SPI. The principle of the wireless communication module is illustrated in Figure 5.

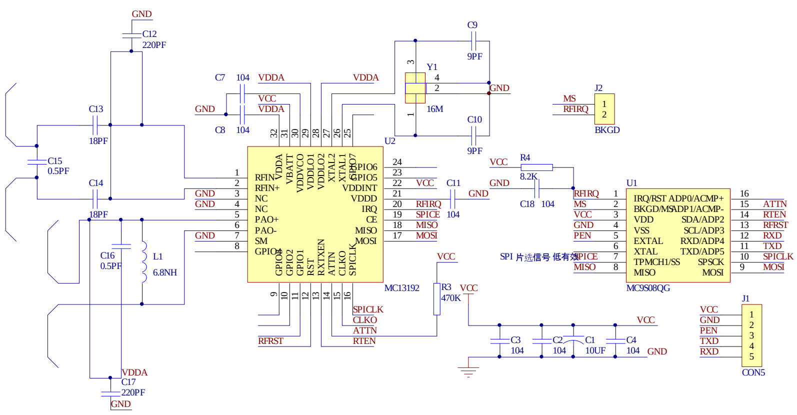

Figure 5. Schematic Diagram of a Wireless Communication Module

3.3. Zigbee Wireless Communication Module Software Process Design

In order to reduce the power consumption of the wireless communication module, this program adopts a more simplified Zigbee protocol stack and a communication protocol. The temperature of the internal measuring point within the switchgear can be collected by wireless sending module once every 10 seconds, sent out wirelessly and uploaded to the monitoring host MCU through the serial port by the receiving module. The communication protocol has a total of 5 parts: start bit (FE), the address high (1 byte), the address low (1 byte), the temperature value (1 byte) and the CRC parity bits (1 byte). The flow chart of the wireless sending module is demonstrated in Figure 6, and the flow chart of wireless receiver module is displayed in Figure 7.

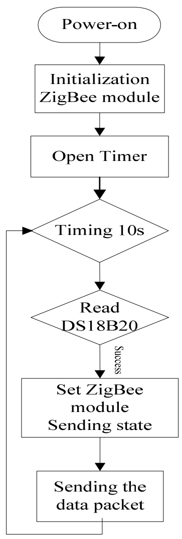

Figure 6. The Flow Chart of Temperature Collection of the Wireless Sending Module

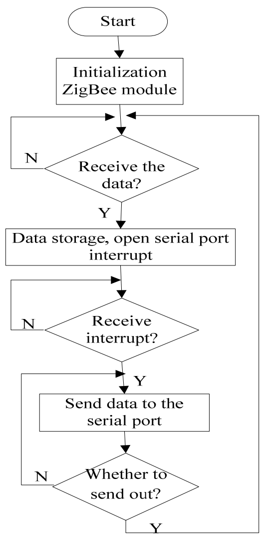

Figure 7. The Software Flow Chart of the Wireless Receiver Module

3.4. Design of High-voltage Bootstrap Power Supply

The power supply design is a crucial part of this program. Wireless sensor networks can adopt two power source modes: battery power or bootstrap power [17]. As the power failure of high-voltage switchgear won't occur during operation and it is impossible to exchange the battery, the battery power can't guarantee the long-term work of nodes. Therefore, this program adopts the bootstrap power supply, which means a small current obtained from the contact according to the electromagnetic theory will go through the front-end impact protection module, rectifier filter module, over-voltage and over-current protection module, step-down module, and DC/DC module, whose system block diagram is shown in Figure 8. Since cast and packaged in epoxy resin and then set around the contact arm, the bootstrap power supply module is safe and reliable.

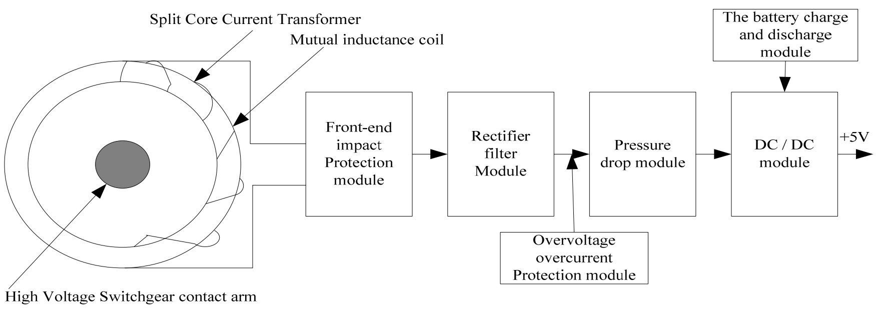

Figure 8. High-pressure self with the power system block diagram

(1) The Hardware Design of the Current Transformer

The overall design consists of three parts: the current transformer, the post-processing protective circuit and the battery charge and discharge module. Its block diagram is shown in Figure 8. In the design of the current transformer, amorphous material is chosen for the iron core, which is retractable. The current transformer is installed in the primary side of high pressure, and the current produced by the mutual inductance would go through the front-end impact protection module, the rectifier filter module, the over-voltage and over-current protection module, the antihypertensive module and the DC/DC module. When the current through the primary side of high pressure is so small that the induced voltage cannot meet the requirement of the operating voltage of the monitoring equipment, the design of the circuit will automatically switch into the battery power to meet the demands; while the current through the primary side of high pressure is so big that the induced voltage is more than the operating voltage of the monitoring equipment, the stable and safe operation of the monitoring equipment can be maintained by the over-voltage and over-current protection module, i.e., it can charge and store power for the battery with the charge and discharge module so that it can be used when the induced power is not adequate enough. If short circuiting occurs in the primary side, transient current may reach tens of kA and inrush current will be produced in the current transformer, but with multiple protection of front impact protection circuit as well as the following circuits, DC voltage of 5V can be output completely and stably.

The structural design of the rear stage protection portion is shown in Figure 9. The rear stage processing module is connected to the current transformer and the rear stage protection portion consists of a front-end impact protection module, the rectifier filter module, the over-voltage over-current protection module, the buck module and DC/DC module. The front-impact protection module comprises the capacitor C1 and the TVS tube D1 and D2; the rectifier filter module is made up of the rectifier bridge by diode D3, D4, D5 and D6, and electrolytic capacitors C2 and C3 to achieve the AC-to-DC conversion; the buck module, formed by the voltage conversion chips and resistors R1 and R2, makes the conversion from voltage 6V-75V to 5V; the DC/DC module, composed of the capacitor C4, C5, diode D7 and electrolytic capacitor C8, can stably output DC voltage of 5V; the over-voltage and over-current protection module, connected to the output terminal of the rectifier bridge and the output terminal of the DC/DC module, provides the protection for itself and the monitoring equipment. The over-voltage and over-current protection module is made up of diode D8-D13, resistors R3-R12, capacitors C7 and C8, the MOS tube T1, operational amplifier U1 and U2 to achieve over-voltage and over-current protection.

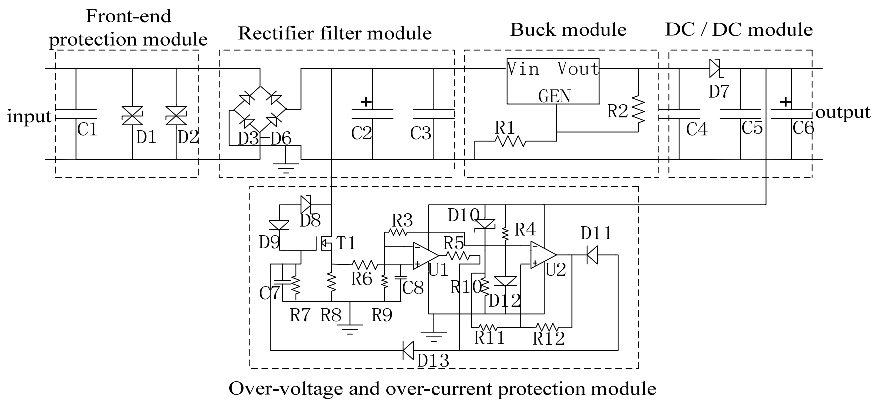

Figure 9. Backstage Protection Circuit

4. Testing of System Performance

4.1. Experiments and Data Analysis of High-voltage Bootstrap Power

The physical map of obtaining power from the current transformer is shown in Figure 10, in which the sensors and high-voltage bootstrap power package is cast and packaged in epoxy resin and then set around the contact arm. Amorphous material is chosen for the iron core, whose circular units are 61/70/10, and the diameter of enameled wire is 0.23mm.

The primary side current of the intelligent substation is so unstable that current may vary from dozens of amps to thousands of amps. In order to make the wireless network sensors work properly with the small current and prevent the damage to the wireless network sensors because of the high voltage of the secondary side current, the testing has been carried out on the secondary side current voltage in mutual inductance in the laboratory, to make sure whether the wireless network temperature sensor can still work stably and reliably when the primary side current reaches 40A-1500A. The experimental site of mutual inductance is shown in Figure 11.

Figure 10. Physical Map of the Current Field

Figure 11. Mutual Inductance Electrical Transformer

After a period of experimental observation, it is found that with the gradual increase of the primary side current, the mutual inductance coil tends to be saturated. Hence, it can be inferred that, when the primary side current is too big, the temperature sensor of the wireless network will not be damaged. It proves that the wireless network temperature sensor can work stably and reliably when the intelligent substation takes power with the mutual inductance module. System performance testing of power-taking with mutual inductance can be is illustrated in Table 1.

Table 1. Mutual Inductance Electrical Testing Data

Primary current（A/AC）	Secondary side current (mA/AC)	Secondary side voltage (V/AC)	Remark
20	45.2	1.44	The secondary side of the 30 ohm resistor in series
60	110.25	2.98	
100	136.85	3.23	
150	172.5	3.67	
200	189.2	3.85	
300	223.25	4.36	
400	242.76	4.74	
500	264.3	4.98	
600	279.63	5.28	
700	300.26	5.52	
800	314.51	5.74	
900	330.34	6.01	
1000	342.43	6.20	
1100	351.58	6.35	
1200	358.8	6.49	
1300	361.35	6.57	
1400	365.13	6.72	
1500	367.26	6.79	

4.2. Wireless Temperature Sensor Temperature Measurement Accuracy Experiments

In order to achieve the coverage of the measurement points of the primary equipment of the entire high-voltage switchgear, the wireless temperature sensor accuracy testing must be carried out.

In the experiment, three wireless temperature sensor modules (employed in the temperature acquisition and transmission) and a sink node (used to receive 3-way temperature data and to send to the computer) are involved to network with a star topology to simulate a small wireless temperature sensor network, in which wireless temperature sensor can be put into the high and low temperature test chamber after taking power, and the temperature of the test chamber can be adjusted by the controller on it after 30 minutes for temperature stabilization and then the data of the wireless temperature sensor can be observed. Figure 12 shows the high and low temperature monitoring test chamber, and Figure 13 is Zigbee wireless receiver module, in which the temperature data acquired from the convergent note of a sink node and a USB circuit board can be sent to the USB serial board through the serial ports, the then the temperature data will be transmitted to the computer through a USB port. In this way, the quality of wireless temperature sensor as well as the accuracy of wireless temperature sensors will be tested by observing the operation of the Zigbee wireless receiver module.

Figure 12. High and Low Temperature Module

Figure 13. Zigbee Wireless Receiver Monitoring of the Test Chamber

Table 2 shows the temperature values uploaded by three wireless temperature sensors in the high and low temperature test chamber (No.1, No.2 and No.3). The temperature range of the high and low temperature is -50℃~120℃. With the calibration of the wireless network temperature sensor, it turns out to be precise and the measurement error is lower than 1°C.

Table 2. Temperature Measurement Data

Test Chamber Temperature (℃)	The 1st monitoring temperature (℃)	The 2nd Monitoring Temperature (℃)	The 3rd Monitoring Temperature (℃)
-40	-40.2	-39.8	-39.8
-20	-20.1	-19.9	-19.6
0	-0.4	0.3	0.2
20	19.9	20.0	20.4
40	40.1	40.6	40.5
60	60.2	59.4	60.8
80	80.3	79.8	79.6
100	100.2	100.5	100.7

4.3. Testing Experiments on Zigbee Wireless Network Transmission Packet Loss Rate

In order to measure the transmission distance of the wireless module accurately, the test on communication distance between points of wireless network temperature sensor, considering the influence of the external environmental factors, is conducted, whose experimental apparatus and process are the same as the test on the accuracy of wireless temperature sensor. The test shows that the packet loss rate is smaller than 2% within a distance of 100 meters. The results are shown in Table 3.

Table 3. Communication Distance Test Data

Test distance	Packet length	Send the package number	No. 1, packet loss rate	No. 2, packet loss rate	No. 3, packet loss rate
10	20Bytes	500	0%	0%	0%
30	20Bytes	500	0%	0%	0%
50	20Bytes	500	0%	0%	0%
70	20Bytes	500	0%	0%	0%
90	20Bytes	500	0.3%	0.2%	0.2%
110	20Bytes	500	0.4%	0.5%	0.5%

It can be drawn from the test of the accuracy and the transmission distance of the wireless temperature sensor that the wireless temperature sensor can accurately monitor the measured temperature state, and maintain a good and stable communication efficiency within a distance of 100 meters to meet the demands of the online temperature monitoring of the intelligent substation equipments for the accuracy and the stability of data communications.

5. Running Results and Data

This system has been successfully applied in Tang Shan Hongqiao substation, whose operation is stable and reliable. Its installation is shown in Figure 14 and Figure 15. Each switch cabinet layouts 9 Zigbee sensor nodes for testing the temperature of the joint connecting switch contact with busbar, and all the Zigbee sensor nodes in the distribution room form the Zigbee network. Zigbee sensor node is in the dormant state in most of the time, and it would be awake every 10 seconds (the interval can be set) to read the sensor temperature values and send them out. The wireless receiver module can receive and send out the data to the monitoring host through the serial port.

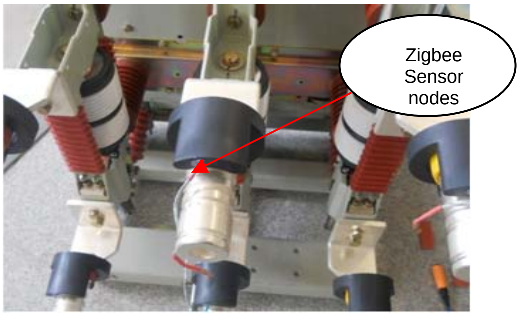

Figure 14. Zigbee Sensor Nodes Installation

Figure 15. Monitoring Host Installation

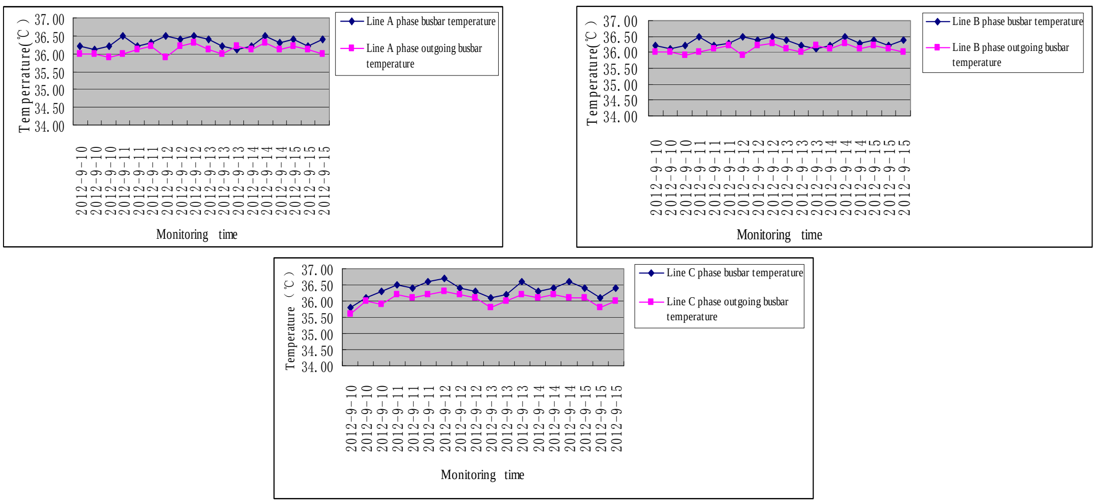

Figure 16. Three Temperature Data of Switchgear A, B, C

Running in more than one year, Zigbee wireless communication module can accurately transmit data; monitoring host can receive process and upload the data to the host computer; and the host computer expert software works properly. Figure 16 is the interface diagram of the recorded temperature rise curve.

According to the above analysis of the operating data, the application of Zigbee network sensors in the intelligent high-voltage switchgear can effectively solve the problems of switch cabinet data communication. It has the characteristics of thorough isolation, strong anti-interference ability, low cost, simple structure and strong stability etc. to achieve real-time monitoring of high-voltage switchgear contacts and inside temperature, and acquires the function of giving early warnings and alarms so as to upgrade the safe operation of the switchgear.

6. Conclusion

In view of the urgent demand of temperature monitoring of the high-voltage switchgear and the characteristics of the project field, a wireless temperature monitoring system based on Zigbee technology is presented in this paper to conduct the monitoring of key points in the switch cabinet so that the occurrence of major accidents can be prevented effectively. The system is of low cost, easy installation, low power consumption in the terminal node, stable operation, and strong engineering practicality and marketing value. In this program, Zigbee network communication works as the core of the wireless temperature sensor network and in combination with a star topology network structure, it provides the stable and reliable data transmission.

References

[1] L Balgard, L Lundin. Monitoring Primary Circuit Temperature and Breakers Condition in MV Substations. *ABB Review.* 1993; (3): 21-26.

[2] Zheng Daohong, Liu Nian, Zhou Longxiang. High voltage switchgear contacts optical fiber smart temperature. *High-voltage electrical appliances.* 1995; 31(4): 37-39.

[3] Cai Wei. Optical fiber Bragg grating temperature sensor technology research. Master Thesis. Wuhan. Wuhan University of Technology. 2004.

[4] Huang Xinbo. On-line monitoring and fault diagnosis of transmission line. First Edition. Beijing: China Electric Power Press. 2000: 5-15.

[5] Deng Lei-lei, Zhang Xian. Zigbee Technology in Intelligent Electric Leakage Protection System Applied Research. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(8): 4291-4295.

[6] HAN Li-na. Zigbee-based the mine personnel management system design. Master thesis. Shanghai. Tongji University. 2007.

[7] Xu Rende. Research and design of wireless video access control system based on Zigbee technology. Master thesis. Nanjing. Nanjing University. 2008.

[8] Wang Ran. Zigbee wireless networking technology to achieve. Master thesis, Jilin. Jilin University; 2007.

[9] Zhu Jianhua. Zigbee 2006 research and application of the protocol stack. Master Thesis .Shanghai. East China Normal University; 2007.

[10] Zhang Hongtao, Xulian Ming, Zhang Yi-wen. Key technologies and system applications of Internet of Things. First Edition. China Machine Press. 2011: 30-45.

[11] Liu Qing, Song Lijun. Study on Zigbee Wireless Sensor Net. *Computer Development and Application*. 2008; 44(6): 44-48.

[12] Yin Zhiliang, Liu Wan-shun Yang Qixun. *Process bus communication research based on IEC61850 standard.* Proceeding of the CSEE. 2005; 25(8): 84-89.

[13] Wu Zai-Jun, HU Min-qiang. Research on a substation automation system based on lEC 61850. *Power System Technology.* 2003; 27(10): 62-65.

[14] Wang Ran, Tang Dongyi. Achievement of Masterslave Communication Architecture Based on RS485. *Modern electronics Technique.* 2003; 24: 67-71.

[15] Wu Xiao ran. Design of Zigbee System Based on MC13192. *Industrial Control Computer.* 2007; 24 (4): 19-20.

[16] Zhenghua Xin, Hong Li, Liangyi Hu. The Research on CC2530 Nodes Communicating with Each Other Based on Wireless. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(1): 430-435.

[17] Sha Yuzhou, Qiu Honghui, Xiong Ying. Design of Self-supplying Power Sour cue Applied in High Voltage Electronic System. *High Voltage Apparatus.* 2007; 43(1): 21-24.