Research on residual current detection system of substation alternating current power supply

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Abstract—Residual current monitoring of substation is essential to prevent electrical fire and plays an important role in the safety of substation. This paper studied residual current detection technology of substation AC power supply, and proposed a residual current detection system composed of three devices: sensing terminal, management terminal and monitoring terminal. The design could solve some difficult problems such as the secondary line caused by equipment installation, fault wave recording, fault location analysis, and early warning based on analysis of big data. The study could improve the intelligent level and maintenance efficiency of residual current monitoring in substation.

1. Introduction
Residual current is also leakage current which is the electric current between the cable and the ground because the insulation of the cable or load device to the ground has broken [1]. Leakage current due to insulation damage of electrical lines or equipment probably cause electrical fire and electric shock accidents [2-3]. At present, residual current monitoring technology has been widely used in power system [4-9]. Residual current monitoring is essential for substation and other important facilities of power system, which can effectively prevent electrical fire, electric shock and other accidents, and plays an important role in the safety and stability of substation [10-11].

In May 2019, a fire accident occurred in 500KV Zhangjiaba Substation. After investigation and analysis, it was found that the incident was a typical electrical fire accident caused by cable fire, which ignited the control cable mixed in the same ditch and led to the trip of equipment. Through analysis, the cause of the fire was found that the insulation of power cable was weak which was from the AC central distribution panel to the relay protection cell in the station, and the relative armored layer was short-circuited and discharged, and the AC molded case circuit breaker in the circuit failed to jump off in time. There were some problems exposed in the accident that the lack of insulation monitoring means for low-voltage AC cables used in the station and the lack of sensitivity of low-voltage AC circuit breakers, make it impossible to find and remove metal grounding and high-resistance grounding faults in time. The monitoring technology of substation AC power system based on residual current has a good prevention effect on the cable initial fire caused by high resistance grounding.

The paper proposed residual current detection scheme for substation AC power system and developed the devices which were with the function of fault detection and protection for a substation low-voltage AC cable insulation. The system can on-line monitor the insulation status and running status of cable and load equipment online in real time. It could effectively realize the early warning of
substation fire, timely find out fire hazards in substation, reduce the risk of fire, improve the efficiency of maintenance and reduce the cost of maintenance.

2. System architecture
The residual current monitoring system adopts three-layer architecture design, including data acquisition layer, collection management layer and edge calculation layer. The three-layer architecture is composed of three devices: sensing terminal, management terminal and monitoring terminal. The overall architecture of the system is shown in Figure 1.

Fig. 1 Overall architecture design of the system

The design ideas of the system are introduced as follows:

(1) Sensing terminal can acquire residual current value, ambient temperature and humidity of each feeder branch of the AC power system.

(2) Management terminal can collect the data from multi-channel sensing terminal, be used for steady data record, leakage current alarm monitoring and fault alarm transient data record.

(3) Monitoring terminal can integrate various monitoring data of the sensing terminals in all systems and realize residual current monitoring, early warning, strong graphic display functions and human-machine interaction based on big data analysis.

(4) Communication between system devices, can support wireless communication such as LORA and RS-485. Wireless communication can effectively solve the problems such as secondary lines, the difficulty and low efficiency due to installation and maintenance of communication lines between the devices. RS-485 is compatible with existing equipment to meet the needs of wired communication.

3. Design of terminals

3.1. Sensing terminal
Based on the investigation and analysis of the existing residual current monitoring equipment in the market, this paper proposed the integrated design of the sensing terminal, which had functions residual current monitoring, inductive power-taking, wireless communication, temperature monitoring and humidity monitoring.

The design of sensing terminal is introduced as follows. The schematic diagram is shown in Figure 2.

(1) The power module composed of inductive power taking module, power conversion module and power function module can provide stable power for other functional hardware modules.

(2) Residual current sensor and signal processing modules, can support residual current values acquisition and A/D sampling and processing.

(3) The T/H sensor hardware directly transmits IO signals to the processor for data transmission.

(4) Processor unit can support local calculation of residual current, temperature and humidity data.

(5) Communication unit has two-way data exchange with the processor unit and it can realize wireless communication and data transmission.
The main characteristics of sensing terminal are shown as follows:

1. Inductive power-taking. It can ensure power supply for the device and reduce greatly secondary cables compared with other forms of power-up. It can improve the efficiency of the installation, operation and maintenance for the low-voltage AC power system, because there are too many feeder in AC power system.

2. Wireless communication. Intelligent terminal with wireless communication is the development trend of power Internet of Things. And wireless communication can also effectively avoid using cable.

3. Acquisition of temperature and humidity. Ambient temperature and humidity are one of the important parameters for residual current analysis. The integration of ambient temperature, humidity and residual current monitoring can provide effective data support for the early warning analysis of residual current.

The key technical indicators are shown in the Table 1.

| Item | Residual current | Ambient temperature | Relative humidity |
|------|------------------|----------------------|------------------|
| Measurement range | 10mA~10000mA | -20℃ ~ +85℃ | 0-100% |
| Measurement accuracy | 0.5 level | ±1℃ | ±1% |

3.1.1. Power Module
The power module includes inductive power-taking module, power conversion module, and power function module. The induction power is obtained by current transformer (CT). According to the conventional load of substation AC power supply system, the starting current of CT is defined between 5A-500A. Considering the installation environment, the traditional high-voltage CT power-taking method is not appropriate, which will occupy a large space and cost too high. Therefore, use soft-power-taking method.

The design scheme is introduced. CT is used for power extraction, and super capacitor is equipped as backup power supply. In order to ensure that the capacity of super capacitor is fully utilized, DCDC is used as power conversion module. The key designed performance indexes are that maximum power is 1W and voltage output is 5V.

3.1.2. Residual current detection module
Residual current detection is based on the traditional electromagnetic induction principle. First, an ABCN line is used to pass through the magnetic loop coil for induction, then the acquisition circuit is used to signal transformation.

The key designed performance indexes are that residual current sampling accuracy should reach 0.2% and measurement range is 10mA-10A.
3.2. Management terminal
The management terminal can collect the residual current and other data from the sensing terminal, and to store and record steady-state recording and transient recording of fault alarm using wireless communication.

The fault wave-recording is for management terminal to record steady-recording of residual current and dynamic recording of the fault data in a specific time when the fault occurs. The function is used mainly to achieve data traceability and data backup, and to provide accurate and reliable data support for fault analysis. The leakage current, temperature and humidity. The leakage current, temperature and humidity are recorded for wave-recording.

The key technical indicators are as follows:
(1) Steady-state recording. The recording interval is 1s, and the recording time is over 6 months;
(2) Transient recording. The sampling frequency of recording is 4K Hz. It can record the transient waveform from 1s before leakage to 10s after leakage. A maximum of 500 transient recording waves can be recorded.

The design idea of the management terminal is to collect the residual current and other data from the sensing terminal, and to store and record steady-state recording and transient recording of fault alarm. Therefore, the hardware architecture of management terminal mainly includes processor unit, memory unit, display unit and communication unit. The main functions of the management terminal include wireless communication, fault alarm, fault wave-recording and management interface.

3.2.1. Wireless communication
When communicating with the sensing terminal, the management terminal acts as the host to realize one-to-many information interaction and mainly collects the remaining current, temperature and humidity data from sensing terminals. When communicating with the monitoring terminal, the management terminal acts as a slave and realizes many-to-one information interaction, and upload the collected data to the monitoring terminal.

In order to avoid mutual interference of wireless communications with sensing terminal and monitoring terminal, it is needed that two independent wireless communication modules are used for the management terminal.

(1) Because ultra-low power wireless communication is necessary for the communication between sensor, the wireless communication module in the 433MHz band is selected. Monitoring terminal can be connected to a maximum of 24 sensing terminals.

(2) For the communication between the management terminal and the monitoring terminal, it is necessary to consider the large amount of communication data and data security, the expansibility and universality. Lora is chosen for wireless communication module of management terminal and the encryption module of State Grid is applied to ensure the communication security.

3.2.2. Fault Alarm
The management terminal provides the local alarm function. When the leakage current exceeds the threshold or the device status is abnormal, LED indicator or buzzer are used to notify user for the alarm status.

3.2.3. Fault wave-recording
Fault wave-recording is for management terminal to record steady-recording of residual current and dynamic recording of the fault data in a specific time when the fault occurs. The function is used mainly to achieve data traceability and data backup, and to provide accurate and reliable data support for fault analysis. The leakage current, temperature and humidity. The leakage current, temperature and humidity are recorded for wave-recording. The flow chart of wave recording function is shown in Figure 3.
Based on the effective value of leakage current, the management terminal can make real-time warning and alarm judgment. When the leakage current is greater than the threshold for a while, the wave-recording is started. The management terminal records the valid values of the current alarm branch within a fixed period and stores them until the alarm disappears or the recorded data exceeds the maximum range.

3.2.4. Management interface
(1) Real-time data display. The monitoring terminal obtains the leakage current and temperature and humidity values through wireless communication with sensing terminals of each branch and displays them on LCD.
(2) Configure parameter Settings. User can set the IP address, real-time time, and leakage current limit of the management terminal by pressing buttons.
(3) Data query. The management terminal can switch the interface menu by pressing buttons to query the data.

3.3. Monitoring terminal
The monitoring terminal is the core of data collection, calculation, and management for residual current monitoring system. There are the functions including data collection, data analysis and management interface.

3.3.1. Data collection
(1) Real-time data collection. The monitoring terminal can collect the leakage current, temperature and humidity and device status. The monitoring component can collect and display all the data and status information.
(2) History data collection. It includes historical alarm data and wave recording data. The history data is stored in the form of files in SD cards through the file system. User can view a maximum of 1000 pieces of historical data through the device interaction and copy data through to USB storage.
3.3.2. Data analysis

(1) Fault location. The monitoring terminal saves the sensor ID configured on the connected sensing terminal and identifies the specific branch ID. When the leakage current alarm exceeds the alarm threshold, the monitoring terminal determines the branch alarm to locate the specific branch.

(2) Fault warning. The thresholds are set for the monitoring terminal according to the real-time and history monitoring data values. Based the early-warning algorithm of big data analysis, it can analyze the trend change of leakage current, temperature, and humidity. When fault risks are found, the early warning is sent for user.

3.3.3. Management interface

(1) Operation monitoring. The monitoring terminal can monitor the operating status, communication status, semaphore, leakage current value, temperature and humidity value in real time. It can display the data value and alarm information on the interface.

(2) Operation and maintenance management. Device parameters can be set on the user interface, such as equipment number, alarm threshold through management interface.

(3) Remote control function. User can set the parameters of the sensing terminal through communication and manually control opening and closing through the remote-control function on the interface.

4. System testing

According to the system design scheme, three kinds of equipment products including sensing terminal, management terminal and monitoring terminal have been developed. The residual current monitoring system was tested in the laboratory simulation environment. The sensing terminals were installed on each feeder of the AC power supply. The management terminals were installed on the two AC distribution panels. And The monitoring terminal was installed in the transformer room.

When various leakage faults were simulated, the monitoring system was tested and the residual current values were measured electrical measuring instrument. Comparing the monitoring system with measurement values, The accuracy of residual current reached 1%. The monitoring system could trigger the alarm response time within 10 seconds and reflect timely and accurately the leakage situations. The test results were approved by experts from State Grid Corporation.

![Fig. 4 Schematic diagram of management terminal installation](image)

5. Conclusion

The research work has successfully designed the residual current monitoring scheme for substation AC power supply and developed three kinds of equipment including sensing terminal, management terminal and monitoring terminal. The system can solve the pain points and difficulties of secondary
line due to the equipment installing, fault wave-recording, fault location analysis and fault warning based on big data analysis. It can realize the real-time on-line monitoring the insulation state and running state of each cable in the substation AC power supply system, improve the operation and maintenance efficiency, and reduce the cost of maintenance. In the future, the algorithm for residual current monitoring and early warning will be optimized to improve the monitoring accuracy.

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