Development of on-line monitoring system for insulation of high voltage electrical equipment

Hang Li¹, Yaoyao Luo¹*, Yang He¹, Fangying Li¹, Ting Wu¹
¹Chengdu University of Technology, Chengdu 610059, China

* Corresponding author and e-mail: Yaoyao Luo, 280460115@qq.com

Abstract. The development of on-line monitoring technology for high-voltage electrical equipment insulation, the working principle of online monitoring device, and the problems in operation were comprehensively expounded. The on-site verification technology of high-voltage electrical equipment insulation online monitoring system was studied, and online monitoring was analyzed. Management and technical issues with the device were found. On this basis, the on-site calibration device for the on-line monitoring system of high-voltage electrical equipment insulation was developed. The results of on-site non-power-off verification of high-voltage electrical equipment insulation online monitoring system produced by several manufacturers were introduced. Analysis and elaboration of its key technologies.

1. Introduction
The aging and failure of high-voltage electrical equipment insulation is a slowly developing latent fault. The traditional preventive experiment has a long experimental period, and the equipment cannot be found to deteriorate in a short period of time. The experimental voltage is much lower than the normal operating voltage of the equipment, and it is susceptible to temperature and humidity. Many defects such as strong electromagnetic field interference and influence cannot be discovered. Moreover, the sudden development cannot be discovered in time, which has serious consequences for power supply and production. Online monitoring of power equipment insulation is an important technical means to ensure safe power generation and power supply, to detect hidden dangers in time, to reduce power outages and repairs, and to improve power supply reliability. On-line monitoring system for power equipment insulation can continuously monitor the leakage current, dielectric loss, equivalent capacitance, operating voltage, ambient temperature and humidity of high-voltage electrical insulation equipment, and collect data and automatic analysis by computer, make equipment final evaluation of normal work can improve the early prevention of insulation damage of high voltage electrical equipment. At present, the advanced and reliable equipment of domestic substation equipment is generally low, and the reserve factor of equipment is also low, which cannot guarantee the safe operation of power equipment. Therefore, it is of great practical significance to develop and promote the online monitoring technology of insulation.
2. Status of online monitoring of domestic high voltage electrical equipment insulation

The development and application of on-line monitoring technology for power equipment insulation in China has been carried out for decades. This work has played a positive role in improving the operation and maintenance level of power equipment, detecting hidden troubles in time, and reducing the occurrence of power outages. But there are still many problems. According to the survey results of 57 sets of centralized online insulation monitoring systems installed by the China Electric Power Research Institute in 1998 in some provinces and municipalities, it is only 30% of normal or relatively normal, and it is determined that it cannot operate normally or is in a state of paralysis. It accounts for 35% of the total. The main performance is that the insulation online monitoring system is not reliable, for the following reasons:

At present, some online monitoring systems adopt a centralized signal processing method, that is, after a signal is extracted by a sensor placed near the field device, the weak signal to be measured is directly introduced into a computer placed in the main control room through a large number of cables, and the host pair Field devices perform tour detection and data processing. Other detection systems use a centralized processing method of partitioning, which is, dividing the device under test into several regions according to the distribution of equipment in the substation, respectively performing aggregation and signal strobing, and passing the gated analog signal through a special multi-core shielded cable. It is sent to the host of the main control room, and the host performs tour detection and data processing. Although the second method reduces the amount of cable used, it still cannot solve the distortion problem caused by the analog signal after long-distance transmission, and both of these methods have the characteristics of large on-site installation workload and difficult maintenance.

The sensor's ability to resist environmental temperature, humidity changes and electromagnetic interference is relatively poor, resulting in sensor failure, damage, voltage signal distortion, causing media measurement is not accurate enough, stability, repeatability is poor, and measurement error is large.

In the traditional insulation online monitoring system, communication is carried out through analog signals, so the system communication anti-interference ability is poor, the signal is easily distorted, the data transmission and processing part is faulty, and data loss occurs.

3. Working principle of high-voltage electrical equipment insulation online monitoring system tester

High-voltage electrical equipment insulation online monitoring system High-voltage standard tester is an electrical device that can change the dielectric loss with power. The device under test can work under the system voltage. The change of dielectric loss is known and tested by standard. The high-voltage standard tester is mainly composed of a high-voltage non-destructive standard capacitor, a low-voltage adjustable non-inductive standard resistor, and a switching device. The high-voltage standard capacitor has a capacitance of 1 000 pF, and the low-voltage non-inductive standard resistor is combined with different values to form a high-voltage standard loss tester with a dielectric loss of 0.33 to 1.337 and a total of 7 stops. The high-voltage standard loss tester can be used in the device under test. Adjust the gear of the standard loss tester with the operating voltage always applied. The sensor of the insulated online monitoring system is connected to the low voltage side of the high voltage standard tester. The schematic diagram of the comparison test of the high-voltage standard tester for the insulation online monitoring system is shown in Fig. 1. The checker is mainly composed of AC filter power supply, 30 kVA voltage regulator (B1), 80 kV cascade test transformer (B2, B3), high voltage standard capacitor (C), 100 kV/100 V standard voltage mutual inductance. Device (B4) composed with discharge tube (P-350), standard non-inductive resistor and other components. High-voltage electrical equipment insulation online monitoring system standard tester generated by the current IN (current sampling sensor is also called I / U converter converted into voltage signal UIN) and standard voltage signal UN (taken from the voltage transformer secondary) input Data processing to the insulation online monitoring system. From this, the dielectric loss tan δ, capacitance C and leakage current IN can be measured.
When the high-voltage standard tester performs the comparison test on the on-line monitoring system in the field, there are many devices used, and sometimes the detection is inconvenient. For this reason, the ZJB-I type low-voltage standard loss device with variable dielectric loss value is developed. The low-voltage standard tester that can change the dielectric loss value consists of a filter power supply (external), a voltage regulator, an isolation transformer, CN1, CN2, CN3 standard capacitors, standard non-inductive resistors R1 to R21, a voltmeter, an ammeter, and a switch. The working principle of the comparison test on the insulation online monitoring system is shown in Fig. 2.

According to the sampling sensor current of the insulation online monitoring system, select the loss selection 1 ~ 3. The low-voltage standard tester is also equipped with a full-current and resistive current test circuit for the zinc oxide surge arrester.

4. Edge online monitoring system hardware design
Insulation online monitoring system should be able to accurately and accurately reflect the insulation of high voltage equipment. The hardware circuit used to obtain the required signal must have high monitoring sensitivity and good anti-interference ability. Due to the required signals and various interferences in the power system, in order to carry out accurate on-line monitoring of insulation, the pre-hardware circuit must be sensitive to capture the required voltage and current signals, and within the precision range allowed by the project. The resulting signal is pre-processed to reduce or suppress interference, and is subjected to analog-to-digital conversion to a digital signal that can be processed by the computer. Since the tgδ value is small, the performance requirements for the hardware circuit are also relatively high. In order to improve the accuracy and accuracy of the measurement, the hardware circuit to be used has high sensitivity, low temperature drift, and high common mode rejection ratio. At the same time, this paper samples the software analysis method based on FFT. The hardware circuit is relatively simple. Some integrated circuit chips and circuits with better performance can be used to eliminate the interference and prevent the signal from being distorted. In the insulation online monitoring system studied in this paper, the front circuit part realizes the functions of signal conversion, amplification, filtering and sampling. This chapter will introduce the working principle of each part from the selection of sensors, the amplifying circuit, the design of the filter circuit, and the analog-to-digital conversion.
When $\tan \delta$ is very small:

$$tg \delta = \frac{R_s}{\omega C_i} = \frac{1}{\omega C_i}$$

So:

$$P = \frac{U^2 \omega C_i \sin \delta}{\sqrt{1 + (\tan \delta)^2}} = \frac{U^2 \omega C_i \cos \Phi}{\sqrt{1 + (\omega R_s C_i)^2}} = \frac{U^2 \omega C_i \sin \delta}{\sqrt{1 + (\omega R_s C_i)^2}}$$

A medium or a device, whether represented by a series circuit or by a parallel circuit, flowing the same voltage.

The flow should be the same, i.e., the total impedance represented by the series loop and the total impedance represented by the parallel loop should be equal. At the same time, under the same conditions the loss and $\tan \delta$ should also be equal. Therefore:

$$P = U i \cos \Phi = U i R = U i C \tan \delta = U^2 \omega C_p \tan \delta$$

$$tg \delta = \frac{R_p}{\omega C_p} = \frac{1}{\omega R_p C_p}$$

Since the monitor uses sensors, and the accuracy of the measurement results largely depends on the sensor, in view of the importance of the sensor, an overview of the sensor principle, selection, etc. is made. The sensor is a device that converts the information of various physical quantities reflecting the state of the device into the same or other kinds of output according to a certain law, and is the primary link for realizing online monitoring, which directly affects the development of the monitoring technology. The accuracy of the monitoring system has a lot to do with the accuracy of the sensor. If the sensor’s monitoring parameters cannot be accurately and reliably measured, no matter how accurate and reliable the hardware circuit design is, how accurate the software analysis is, the measured data is inaccurate or even useless, so it is necessary to accurately perform online monitoring and select the sensor as the primary condition. When the insulation monitors the $\tan \delta$ value of the high-voltage equipment online, the value of the dielectric loss current is generally small, and the minimum level of micro-ampere is required to accurately obtain the signal. At the same time, the insulation online monitoring system and the monitored system are required to have no electrical connection to ensure the safety of the monitoring system and monitoring personnel will not affect the normal operation of the monitored system due to the failure of the monitoring system. This puts higher demands on the sensor used to acquire the signal. For the sensor used, it should be considered from several aspects: 1, In order to accurately measure the parameters, and take into account the convenience of monitoring system installation, commissioning and normal operation, the sensor installation position must be properly selected; 2, According to the power system requirements, technically based Different devices and different measurements are selected to select reasonable sensors, and their peripheral circuits are reasonably designed. 3, From an economic point of view, the sensor requires good performance, economical and durable, convenient for commissioning and maintenance. In view of the importance of the sensor, the following technical requirements are
imposed on the sensor for the specific parameters to be monitored. 1. It can detect the feature quantity reflecting the state of the device, and has good static characteristics (including linearity, sensitivity, resolution, accuracy, stability and hysteresis) and dynamic characteristics (including step response, sinusoidal response and dynamic response). 2. No impact or weakness on the device under test, the energy absorbed by the system to be tested is small, and the subsequent units can be well matched. 3. Good reliability and long life.

Since the voltage and current signals are taken from the grounding line of the transformer's last screen, the signal is very weak after the sensor (generally mA level), which contains a large number of common mode interference such as power frequency, static electricity and coupling, and must be accurately amplified by a certain multiple. It can meet the signal requirements of the measurement system. The preamplifier circuit is designed to have a high input impedance to reduce the effects of on-resistance. Usually to improve the accuracy of the amplifier circuit, the integrated amplifier is generally used to design the preamplifier. The integrated op amp has a high open-loop amplification factor (generally up to 410) and a high degree of integration. When it forms a negative feedback amplifying circuit, its voltage amplification factor depends only on the ratio of the external resistor, independent of the op amp parameters. Therefore, the preamplifier consisting of the integrated op amp as the main component is characterized by high gain and common mode rejection ratio, while the offset voltage and offset current, temperature drift, and noise are small, which is a versatility and strong amplifier. Since the amplifier circuit composed of the integrated operational amplifier has a high common mode rejection ratio and input impedance, low noise and low offset voltage, the resistance in the circuit should be carefully selected so that the circuit satisfies the symmetry requirement, and the resistance value due to process variations, it is difficult to select. If the circuit can't reach symmetry, it will have a great impact on the performance of the circuit. This is not only difficult to debug, but also inconvenient to manufacture. To this end, this article directly uses an integrated amplifier to design the preamplifier system. Among the many integrated amplifiers, we chose OP07 high-precision amplifier with high input impedance, low offset voltage, low noise, and large open-loop amplification. This was according to the performance and usage of the amplifier.

5. Software design of insulation online monitoring system

The purpose of online monitoring is to obtain a true description of the operation of the equipment by analyzing and processing various raw data reflecting the condition of the operation of the electrical equipment. Therefore, online monitoring software design is particularly important. The hardware circuit part of the online monitoring is used to complete various functions such as voltage and current signal conversion, transmission amplification, filtering, and sampling/holding. After the original data is obtained, it has not been analyzed, calculated and displayed. It is not possible to visually describe the operating state of the power equipment. The software must be used to analyze and process the data in detail, and complete the functions of data storage, result analysis and fault diagnosis. System operators provide an intuitive, simple human-machine interface.

After power-on, the monitor begins to execute the application software that is cured at the EPROM address 0000H. Through the assignment statement command: (1) Set AT8051 internal memory 5FH-7FH is the stack area for calling subroutine and field protection when responding to interrupt. (2) Set the special function registers TMOD and TCON, and the state of the interrupt control enable register IE to determine the control and operation of the timer.

6. Anti-interference problem of insulated online monitoring system

Differential mode interference refers to the interference voltage that acts on the instrument after being superimposed in series with the effective signal, mainly from the space electromagnetic field generated by the high-voltage line and the power line laid parallel to the signal line. Therefore, differential mode interference is usually caused by electromagnetic coupling. The source of the interference is electromagnetically and electrostatically coupled to the signal line to an induced voltage of up to millivolts. In addition to the signal line, the inherent drift, ripple and noise of the signal source,
as well as the poor shielding and voltage-stabilizing filtering effect of the power supply introduce differential mode interference. Common mode interference refers to the interference voltage common to the two inputs of the input channel. Because there is often a certain potential difference VC between the references ground point of the signal under test and the reference ground point of the instrument. The amplitude of this interference is generally high, depending on the environmental conditions in which the interference occurs in the field and the grounding of the instrument. Common mode interference is more common, and the main hazard is the insulation damage of the instrument and the safety of the operator. Common mode interference can also be converted to differential mode interference when the common mode voltages on the two signal lines are not equal, or when the resistance of the two signal lines to ground is unbalanced. Interference caused by capacitive coupling is generally common mode interference. Suppressing common mode interference is related to whether the device can be used in the field.

Table 1. The test result compartment

| Range | Standard Value | Dielectric loss Test Value | Capacitance Test Value |
|-------|----------------|---------------------------|-----------------------|
|       |                |                           |                       |
| 0     | 0.313          | 0.53                      | 979                   |
| 1     | 0.426          | 0.59                      | 973                   |
| 2     | 0.541          | 0.73                      | 973                   |
| 3     | 0.770          | 0.97                      | 972                   |
| 4     | 0.887          | 1.10                      | 972                   |
| 5     | 1.111          | 1.33                      | 973                   |
| 6     | 1.384          | 1.62                      | 967                   |

There are many causes of interference, such as lightning, substation switch operation, corona, radio emissions, and so on. In short, all emitters of electromagnetic energy may become sources of interference, and those who receive this energy and affect their own performance become disturbed, such as monitoring devices placed at the substation site. Because the insulated in-line device is placed directly at the high-voltage equipment, and the electromagnetic environment there is extremely harsh, a simple analysis of the electromagnetic interference problem is made here. There are two types of ways in which electromagnetic interference propagates from the source to the affected equipment: radiation and conductance. Radiated interference is transmitted to the affected equipment through space; conducted interference is transmitted to the affected equipment through the circuit. When the distance S between the interference source and the monitoring device is large relative to the wavelength λ of the interference signal (i.e., $S > \lambda / (2\pi)$), the nature of the interference source appears as a source of radiation interference, and the nature of the field is expressed as radiation electromagnetic field. The radiated electromagnetic field belongs to the radiation field. This kind of interference is usually the interference with high frequency; when the distance S between the interference source and the monitoring device is small which was relative to the wavelength λ of the interference signal (i.e. $S < \lambda / (2\pi)$), The nature of the interference source is the source of conducted interference, and the nature of the field is mainly represented by the electric field or the main representation of the magnetic field. This interference frequency is generally low.

In the case where two circuits have a common wire (such as a power line, an input/output signal line, a ground line, etc.), the current flows of the two circuits pass through a common impedance, so that the current in one circuit is at the common impedance. The pressure drop constitutes interference with another loop. Zg in the figure below is the common impedance of loop 1 and loop 2.

There are always stray capacitances between different conductors in the medium. When two circuits are at different potentials, the charge of one circuit will be induced to the other. Generally, the circuit with large ground impedance is easily interfered by the electromagnetic field, so the ground
resistance is reduced, the stray capacitance between the two circuits is reduced, and the interference caused by the capacitive coupling can be reduced; The higher the frequency of the interference source, the easier it is. Other loops create capacitive coupling. There is a mutual inductance between the two circuits, and a change in current in one circuit can affect the other circuit through the flux linkage. The induced potential is proportional to the angular frequency of the interferer. It can be seen that the higher the frequency of the interference source, the greater the mutual inductance between the two circuits, and the greater the interference caused by the inductive coupling.

To suppress the interference source is to reduce the $du/dt$, $di/dt$ of the interference source as much as possible. This is the most important and most important principle in anti-jamming design in PCBs, and it often has a multiplier effect. Reducing the $du/dt$ of the interference source is mainly achieved by connecting capacitors across the interference source. Reducing the $di/dt$ of the interferer is achieved by placing the inductor or resistor in series with the source loop and adding a freewheeling diode. The main measure is to connect a high frequency capacitor of 0.01ìF~0.1ìF to each IC on the circuit board to reduce the impact of the IC on the power supply. Avoid 90-degree fold lines when wiring will reduce high-frequency noise emissions.

Pay attention to the crystal wiring. The crystal oscillator and the MCU pins are as close as possible, and the clock region is isolated by the ground wire. The crystal oscillator case is grounded and fixed. The board is reasonably partitioned, such as strong and weak signals, digital and analog signals. Keep interference sources (such as motors, relays) away from sensitive components (such as microcontrollers) as much as possible. Use a ground wire to isolate the digital zone from the analog zone and finally connect it to the power ground at one point.

Improving the anti-interference performance of sensitive devices refers to the method of minimizing the pickup of interference noise and recovering from an abnormal state as soon as possible from the sensitive device side. The measures to improve the anti-jamming performance of sensitive devices are as follows: Minimize the loop area during wiring to reduce the induced noise. When wiring, try to increase the power supply and ground wires. In addition to reducing the voltage drop, it is more important to reduce the coupling noise. For the idle I/O port of the MCU, it is grounded or connected to the power supply. On the idle side of other ICs, ground or power is connected without changing the system logic. The system uses the watchdog circuit MAX813L, which can greatly improve the anti-jamming performance of the entire circuit.

7. Conclusion
Through an on-line monitoring technology for parameters such as dielectric loss, leakage current, equivalent capacitance, and operating voltage of power equipment, an on-line monitoring system based on monitoring leakage current and dielectric loss angle of high-voltage equipment has been developed. Find hidden dangers in time, reduce power outages, and improve power supply reliability.

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