

Research on ON-LINE Insulation Monitoring Instrument of IT Power System in the Down Hole Mine

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Abstract. Base on The characteristics of IT power distribution system in metal mine downhole, on the basis of the analysis and comparison of existing insulation monitoring methods, with the low-frequency power injection method, the online insulation monitoring instrument of the IT power distribution system is designed in the metal mine down hole. By injecting the low-frequency power in the IT power distribution system, urge Low frequency signal source and insulation resistance and ground make up of circuit, Real-time detect voltage and current in the circuit. Sampling signals filtered By means of hardware and software filter, extracting low-frequency voltage and current in the circuit, implement ON-LINE insulation monitoring of IT power distribution system. Proved by experiment, the instrument is highly accurate and can complete the insulation performance monitoring of the whole IT power system.

1. Introduction

IT power distribution system is an Isolated Neutral power distribution system. When the single-phase earth fault occurs, because of the detected leakage current too low, leakage protection cannot normally work, thus, power distribution system still run for a while, so the IT power distribution system is extensively applied in mine, Auxiliary Power System in Power Plant, the ship, the operating room etc. But during underground mining in the metal mine, due to lacking the underground mining working space which is long, narrow and continuous, and wet and dusty air, the tunnel and chamber may be containing drop of water in the metal mine[1-2]. The insulation level of cables and electrical equipment will gradually decrease, leading to falling of Insulation resistance, even partial discharge, thus single-phase leakage or single-phase grounding faults often occur in underground power distribution system. If the fault cannot be dealt in time, the fault will become interphase faults. So, underground workers are more likely to be shocked than normal [3].

In order to ensure the normal operation of underground production and protect the safety of underground worker, according to the article 5.4.2 of national standard (system grounding type and safety technical requirements (GB 14050-2008)), insulation monitoring instrument (IMD) [4] should be equipped in the IT power distribution system. But, the IMD used in the metal mine is still basically controlled by the foreign brands; there is no mature product in China. Thus, it is of great practical



significance to study the insulation monitoring instrument of underground IT distribution system in metal mines.

Back in the 1960s, developed countries in Europe and America Began to study on Insulation monitoring and fault diagnosis technology in the power system. With developing of MCU technology, on-line fault diagnosis technology is applied of insulation monitoring of the power system. In china, insulation fault diagnosis technology mainly started in the 1980s. Universities and power research institutes have carried out this research in the field [5].

At present, a large number of methods can be applied to the insulation monitoring of the power grid, the literature [6] propose that is a dc component method. Base on the "rectification effect" of water branches in cables, during the IT distribution network works normally, the deterioration of cable insulation can be diagnosed by detecting a weak dc component from the ac current flowing through the insulation layer of the cable. The method is simple, but, because of the weak dc component, the measurement is easy to get distracted, and the measurement error is also relatively high for the cable easily contaminated. The literature [7] propose a kind of Ac superposition method, the method is to superposition the ac voltage signal to the shielding layer of the cable. The frequency of ac voltage signal is two times +1Hz Power Frequency. Then, according to detecting the leakage current which frequency is 1Hz, the state of cable insulation can be judged. This method will not be affected by the insulation resistance of the shield layer and the interference caused by the damp or dirty of the cable, and easy to install. But, it hard to detect the weak current signal (nanoampere level). Thus, the method is still in the theoretical research stage. In addition, in the field of IT power distribution system insulation monitoring, On-Line $\tan\delta$, dc superposition method and the low-frequency power injection are also applied. The literature [8-16] provide the basic principle of On-Line $\tan\delta$ and the practical effect in various environments. By detecting voltage and current in the cable used voltage transformer and current transformer, dielectric loss factor is monitored compared with the phase of voltage and current monitoring of the cable. The flaws of the method are obvious, which only detect the overall insulation performance of the IT power distribution system. If the leakage of some parts of IT power distribution system are serious, it's not going to cause a significant change in $\tan\delta$. So the method can monitor the overall insulation of the IT power distribution system, and is difficult to monitor the local insulation state. The literature [17] provide the principle of dc superposition method. The method is to inject dc signal into the neutral point of the transformer in the IT power distribution system first. Then, the insulation of the IT power distribution system is judged by detecting dc current on a cable connected with a neutral point. The method is simple and easy to implement, so it has been widely used in practice. This method is better in dc distribution system. Thus it is always used in the operating room of the hospital. But compared with the effect in dc distribution system, the detection accuracy of the method is low in ac distribution system for the load capacitance, and is unable to reflect the change of the equivalent ground capacitance in the IT distribution system. The low-frequency power injection method can overcome these defects by injecting low frequency ac signals. Therefore, a comprehensive survey of the above methods, the low-frequency power injection method is especially suitable for on-line monitoring of the insulation state of IT power distribution system in the metal mine.

2. The principle of low frequency power injection method

The low-frequency power injection method is used to inject low frequency ac signals between the neutral point and ground of the IT power distribution system. Then the method cans real-time monitor the insulation state of the IT power distribution system, by on-line monitoring the voltage and current between the signal and the ground. Its principle structure is shown in figure 1.

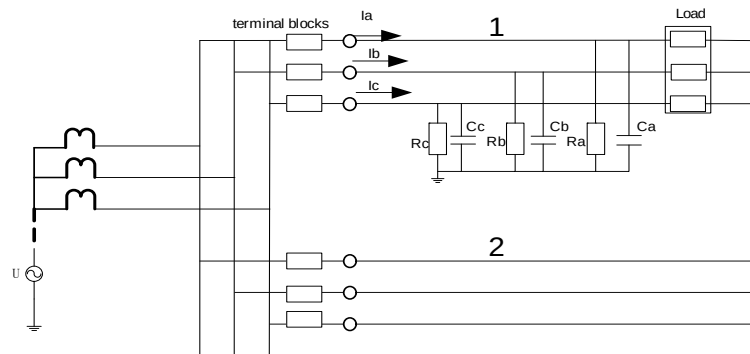


Figure 1. Low-frequency power injection scheme

According to Fig 1, the low frequency power with a particular frequency is injected into the neutral point of the low-voltage side of the isolation transformer. Assuming that R_a , R_b and R_c are insulation resistance, and I_a , I_b and I_c are the current generated by the low frequency power in the three-phase of the part 1 of the circuit, another part will not be analyzed in the current state. Before insulation of the IT power distribution system falling, R_a , R_b , R_c which is the Insulation resistance from the phase A, B and C, are far greater than load resistance, So the current on the insulation resistance is very weak. Meanwhile, for the three-phase load great symmetry of underground distribution network, there is no electric potential difference between the neutral point of the low-voltage side and the load neutral point of the insulated transformer, moreover, the load neutral point of is not grounded. Thus, there is no form a circuit between the low-frequency power and the load, the low frequency power is not considered to generate current on the load. Therefore, the equivalent circuit of part 1 in figure 1 can be simplified to figure 2 and further simplified to figure 3.

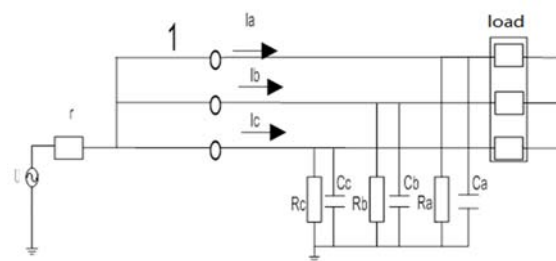


Figure 2. Figure 1 shows a simplified diagram

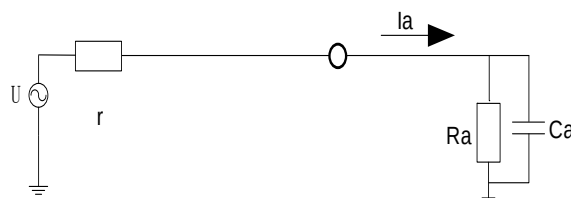


Figure 3. Figure 2 shows a simplified diagram

In the Fig2 and Fig3, r is the sum of the equivalent internal resistance of the low-frequency power and the equivalent resistance of the low voltage side of the isolation transformer. Therefore, the calculation formula of R_a and C_a parallel impedance Z_a is obtained:

$$Z_a = \frac{\dot{U}}{\dot{I}_a} - r \quad (1)$$

During the insulation of the IT power distribution system is badly damaged, assumed that R_a is lower than the load resistance, and R_b and R_c are much larger than the load resistance. At present, the current which contain I_b and I_c , flows through the load to Z_a from the phase b and c. so:

$$Z_a = \left| \frac{\dot{U}}{I_a + I_b + I_c} \right| - r \quad (2)$$

Obviously, according to formula (1), the calculation result is larger than the correct result. However, the insulation resistance has been reduced to low at this time, and I_b and I_c is lower than I_a for flowing through the load resistance. Therefore, when the insulation performance of IT power distribution system drops below the set value, it can also send alarm signal in time. At the same time, the result of calculating the equivalent insulation impedance of phase b or c used formula 1 show that the insulation of the phase b or c circuit has been damaged. But the insulation of the phase b or c circuit is still normal. Thus the method cannot determine which phase of the line is insulated.

In practical, it is often difficult to determine the value of r which is internal resistance. So we need to simplify the formula further. According to the literature [20], When the value of insulation resistance of IT power system is below 30 k Ω , it can be considered that the IT power distribution system has single-phase grounding fault. When the setting value is set to 30 k Ω , because the r value is too small, the effect of r is negligible. Finally, the formula of insulation monitoring can be further simplified:

$$Z_a = \frac{\dot{U}}{I} \quad (3)$$

Then by the equation of parallel equivalent impedance,

$$Z_a = \frac{R_a}{1 + \omega^2 R_a^2 C_a^2} - j \frac{\omega R_a^2 C_a}{1 + \omega^2 R_a^2 C_a^2} \quad (4)$$

The equivalent insulation resistance can be calculated, in summary, the principle of insulation monitoring is that the insulation alarm signal will be sent, when any phase current in the phase a, b and c of a certain branch of IT power distribution system is satisfied formula 5,

$$R_a < \text{Reset} \quad (5)$$

In the above equation, Reset is the alarm setting value for insulation resistance. For not grounding the neutral point of the IT power distribution system, there is no neutral line. So the insulation monitoring instrument can directly inject the low-frequency ac signals into any phase of the IT power distribution system. The concrete structure is shown in Fig 4:

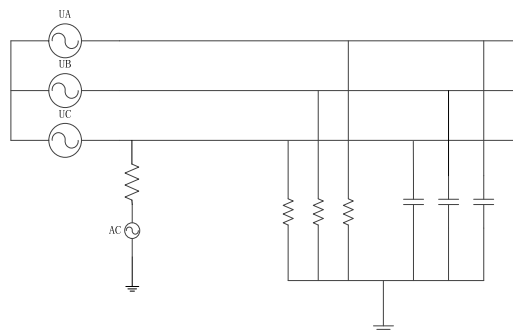


Figure 4. The actual system wiring diagram of insulation monitoring device

As is shown in fig4, the current generated by the low-frequency power on each phase is no longer measured. Instead, the current is detected directly at the output of the low-frequency power. In fact, the current is actually equivalent to the sum of $I_a + I_b + I_c$. Therefore, according to formula (4) and (6), the

equivalent impedance and insulation resistance of the IT power distribution system can be calculated. When the value of the equivalent insulation resistance is less than $30\text{ k}\Omega$, the insulation monitoring device need to immediately alarm.

3. System hardware design

The hardware of the insulation monitoring instrument mainly includes the low-frequency signal ac power, detection and signal processing circuit, MCU circuit, communication interface circuit and display setting circuit. The principle block diagram is shown in figure 5.

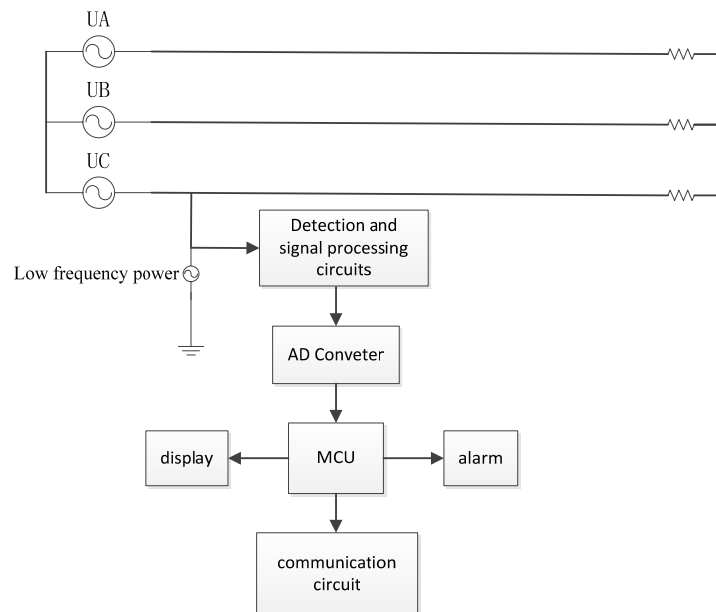


Figure 5. Hardware principle diagram

As is shown in fig5, when the low-frequency power signal is injected into the IT power distribution system, the low-frequency power and the insulation resistance of the cable and GND constitute circuit. Sampling the current by detecting resistance, then by filter and circuit filter, smoothing, amplification, extracting the low-frequency current signal related to the cable insulation resistance, converted to digital signal by A/D converter, finally by the MCU software for digital signal analysis and processing, the insulation resistance of the cable can be calculated, and the value of the insulation resistance are displayed in real time by LCD. When the insulation resistance drops to the set value, the sound light alarm is made. At the same time, the 485 communication interface is provided to communicate with the host computer.

Among them the low-frequency sinusoidal signal is generated by the tracing point method using MCU and DA chip. By the two stage amplifier, the signal voltage is amplified to 6V which is the peak voltage. Then used the push-pull circuit constituted by the power triode, the signal is injected into the IT power distribution system. By the detection resistance, the detection and signal processing circuit directly detect the voltage and current generated by the low-frequency power, but online monitoring, the detection circuit will have the power frequency high voltage signals from IT power distribution system and other frequency of the interference signals that are close to 50Hz to be combined with the low frequency signals, thus in the signal processing circuit, a bandstop filter is used to smooth or reduce most of the interference signals. The filter is composed of a double T - type notch circuit which don't include amplifier. Compared with the standard double T - type notch filter, the Stop band bandwidth of the circuit is wider. With the filter, most of the interference signals can be smoothed in the signal processing circuit. The specific circuit is shown in Fig 6.

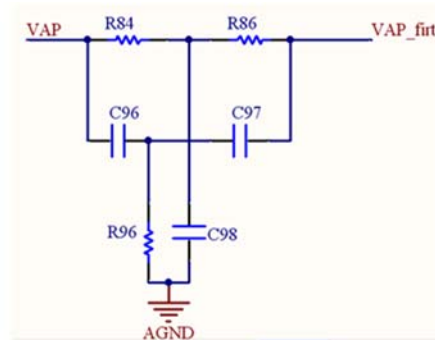


Figure 6. Double "T" filter

After filter, the signal is amplified by signal conditioning circuit. Then the voltage and current signals in the circuit are sampled by the AD embedded in MCU. In this system, MCU adopts STM32 chip from the STMicroelectronics NV. The main tasks of MCU contain the generation of the low-frequency signal source; thoroughly filter the interference of the industrial frequency signal in the sampling signal, by smoothing the sampling voltage and current; and the other Auxiliary functions which include the display, alarm and communication.

4. The software design

The main software function of online insulation monitoring instrument is to use a variety of digital filters to smooth the sampled data. According to the filter results, the value of insulation resistance is calculated, and the data is displayed in LCD and is transmitted to host computer by RS-485 bus. If the detection value exceeds the set alarm limit, the online insulation monitoring instrument will automatically provide sound and light alarm. The specific process is shown in Fig 7:

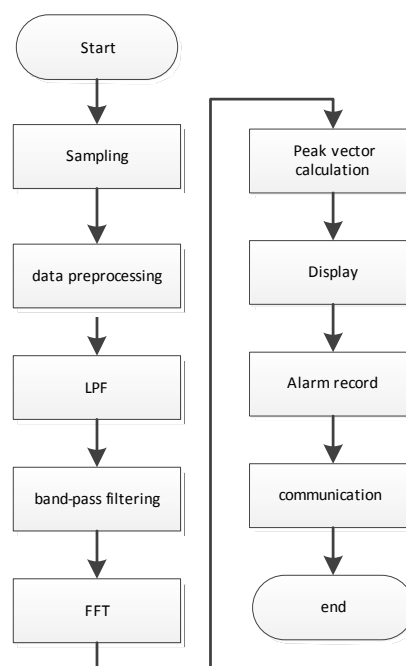


Figure 7. Software filtering logic diagram

Before sampling, the sampling frequency needs to be determined. In general, the higher the sampling frequency, the more accurate the sampling value is, but excessive high sampling frequency may cause

that MCU storage and computing power cannot satisfy the requirements of calculation. Thus the sampling frequency needs to be moderate. The sampling frequency is set to 600Hz in the insulation monitoring instrument, which can not only satisfy the requirements of the sampling of low-frequency signal, but also the requirement of MCU performance is not too high.

As is shown in fig5, although most of the power frequency signal and other interference signal a can be smoothed by the double T - type notch circuit in the signal processing circuit, but still not enough, also need to design software filter for further smoothing.

For the white noise in the sampling process, therefore, the AD sample data is preprocessed to eliminate white noise (slide average filter algorithm). Then the power frequency signal is eliminated by chebyshev LPF. The cut-off frequency of the LPF is 10Hz. The parameters of chebyshev LPF are determined and verified by MATLAB simulation. The amplitude-frequency characteristics of the filter are shown in Fig 8.

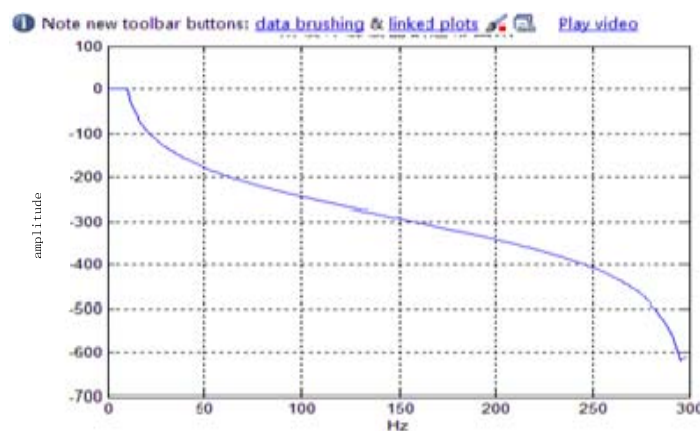


Figure 8. The low-pass filter amplitude-frequency characteristic diagram

After the sampling signal is filtered by the digital low-pass filter to eliminate the power frequency signal, it is combined with the low-frequency signal and the dc bias signal. The dc bias signal is designed to satisfy with stm32 chip sampling. For the unipolar AD of stm32. Thus, before sampling the dc bias signal must be superposed in the sampling signal to facilitate sampling. For detecting the insulation resistance, the desired signal is an low-frequency signal. So, after passes through the LPF the signal also needs a digital band-pass filter to eliminate the dc component in the sampling signal. The cut-off frequency of the band-pass filter is 1.1Hz and 1.4Hz respectively. The frequency of the low-frequency signal is between 1.1Hz-1.4Hz. The parameters of the filter are also confirmed and verified by MATLAB simulation software. Its amplitude frequency characteristic curve is shown in Fig 9.

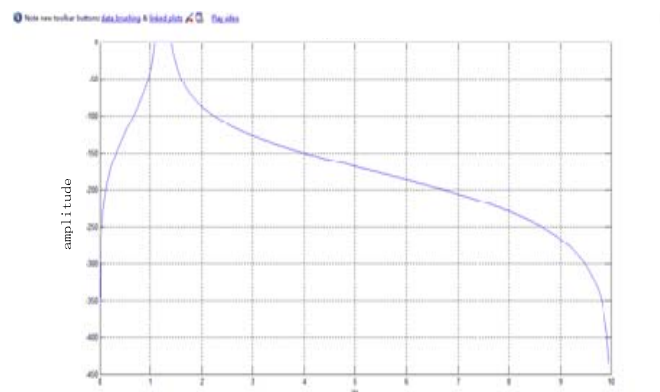


Figure 9. The band-pass filter amplitude-frequency characteristic diagram

Finally, after the sampling data are smoothed by the band-pass filter, the amplitude and phase of the voltage vector and current vector of the low-frequency signal in the IT power distribution system are obtained by the discrete Fourier transform. According to formula (4), the equivalent impedance, insulation resistance and equivalent capacitance are also calculated. If there are 5 continuous insulation resistance values below the threshold (it is usually set to 30k in the metal mine IT power distribution system), the online insulation monitoring instrument generates alarm.

5. Experiment and Data analysis

5.1. Establishment of experimental platform

For simulate the operating environment of the IT power distribution system, the key is to use the appropriate method to simulate the equivalent resistance. Equivalent resistance to ground in any one phase of the IT power distribution system. In the experimental platform built for testing the performance of the device, the insulation resistance to ground of the IT power distribution system can be simulated by a high power adjustable resistor in series between a phase and earth wire in the IT distribution network. When the high power adjustable resistance changes, the insulation resistance to ground of the IT power distribution system will be changed. Meanwhile a three-phase transformer with 380v output voltage is selected as the power supply transformer of the IT power distribution system. Finally, a three-phase adjustable load box is used to simulate various resistivities, capacitive or inductive load in the IT power distribution system. In practice, the low-frequency signal source will inject the 1.25HZ ac signal into any one phase of the IT power distribution system, and the voltage and current between the low-frequency signal and ground in the IT power distribution system are sampled by the detection resistor and filter. The structure of the whole experimental platform is shown in Fig 10:

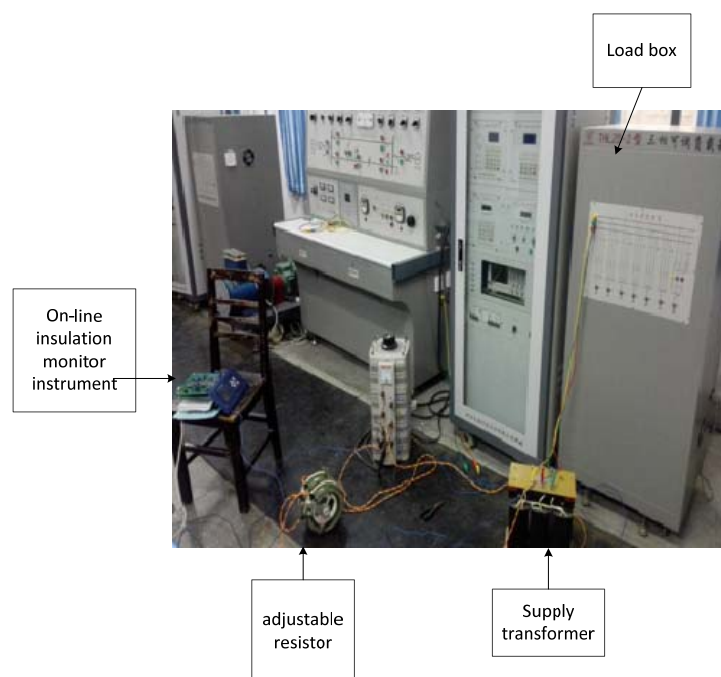


Figure 10. The experiment platform

As is shown in Fig10, when the injected low-frequency signal voltage is constant, the insulation state of the IT power distribution system is determined by the current of the low-frequency signal in the detection resistance. Therefore, in order to establish the relationship between the insulation resistance of the tested cable and the detected voltage and the current signal, by using the experimental platform, the variation of the insulation resistance of the cable is simulated by changing the adjustable resistor,

and the low-frequency voltage and current are sampled by MCU. Then the subsection linearization method is used to sample the voltage and the current value of the low-frequency signal corresponding to multiple resistance values. Finally using two adjacent data, the linear relation is constituted. The data between these two points can be calculated through this linear relationship.

5.2. Analysis of experimental results

The main purpose of the experiment is to obtain the relationship between the insulation resistance in different values and corresponding the low-frequency signal voltage and current, and to verify the accuracy. In the experiment, the insulation resistance of the IT power distribution system can be changed by the adjustable resistance, and the equivalent capacitance to ground is simulated with a Electrolytic capacitor. The value of the Electrolytic capacitor is $0.1\mu\text{F}$. In practice, for each simulation insulation resistance, the MCU will sample the voltage and the current of the low-frequency signal by the hardware filtering in real time. Then residual power frequency signal and other high-frequency harmonic signals superimposed on the low-frequency signal are eliminated using Software filtering algorithm. Finally the insulation resistance of the IT power distribution system is calculated and the insulation resistance is displayed in real time. The data relationship between the measured insulation resistance data and the adjustable resistance and the variation trend of the detection precision are shown in table 1 and Fig11. At the same time, compared with the effect of the low-frequency power injection method and dc superposition method, the same experiment scheme is applied to dc insulation monitoring device test, the measured data are shown in table 2.

As can be seen from table 1, with the insulation resistance continuous increasing, the measured insulation resistance is also increasing, and the trend of Variation on the measured insulation resistance is the same. As is shown in Fig11, The detection precision drop after the simulation resistance is over $30\text{k}\Omega$. The main reason is that the simulation resistance is too large, causing the current in the detection circuit to be too small. But overall, the worst accuracy is not more than 2%, and the detection precision of insulation resistance can meet the design requirements. It prove in this paper, the design of analog and digital filter can eliminate the power frequency and high frequency interference signals in the detection circuit, so the power frequency and other high frequency interference signals in the detection circuit do not affect the detection precision. Meanwhile, compared with the test results of table 1 and table 2, for not considered the influence of the equivalent capacitance to ground in dc superposition method, the measured value and the test data are obviously low. In fact, with the increasing of simulation insulation resistance, the current in the detection circuit becomes smaller which cause the detection precision of the two methods declining. However, the detection precision of dc superposition method will drop faster for ignored the effect of capacitance. Therefore, the detection precision of the low-frequency power injection method is obviously higher than dc superposition method.

It is proved by practice that the on-line insulation monitoring system can measure the insulation resistance of the IT power distribution system and meet the design requirements, which is superior to the insulation monitoring device base on dc superposition method.

Table 1. The comparison between simulation insulation resistance and measuring insulation resistance (The low-frequency power injection method)

The Simulation resistance($\text{k}\Omega$)	The measured resistance($\text{k}\Omega$)	The Simulation resistance($\text{k}\Omega$)	The measured resistance($\text{k}\Omega$)	The Simulation resistance($\text{k}\Omega$)	The measured resistance($\text{k}\Omega$)
0.98	0.974	10	10.1	50	50.85
1.5	1.49	15	15.12	100	96.46
2.3	2.287	18	17.85	300	291.49
3.1	3.15	30	30.58	660	698.42

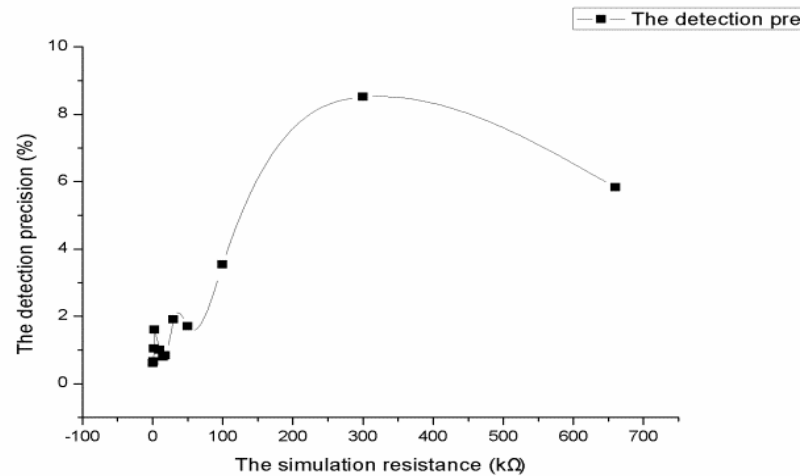


Figure 11. The change trend chart of resistance error

Table 2. The comparison between simulation insulation resistance and measuring insulation resistance (dc superposition method)

The Simulation resistance(kΩ)	The measured resistance(kΩ)	The Simulation resistance(kΩ)	The measured resistance(kΩ)	The Simulation resistance(kΩ)	The measured resistance(kΩ)
0.98	0.95	10	9.32	50	47.35
1.5	1.42	15	14.21	100	94.32
2.3	2.05	18	16.89	300	290.3
3.1	2.95	30	27.86	660	621.2

6. Conclusion

On the basis of analysis and comparison of common insulation detection methods, for the characteristics of neutral point in the IT power distribution system, by using the low-frequency power injection method to monitor the insulation state of the IT power distribution system, a insulation monitoring instrument based on MCU is designed and tested. The experiment results show that the reliability of the system can meet the requirements of on-line monitoring of cable insulation in industrial field, but the accuracy of On-line insulation monitoring instrument have certain disparity with similar kinds of foreign products.

Meanwhile the device can only find the overall insulation in the IT power distribution network, cannot determine which position in the IT power distribution network can cause a leakage. So the method is needed to locate the position which generates leakage.

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