Instrument for insulation conditions detection of roof insulator on high-speed-train

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Abstract: With the rapid development of high-speed-railway, environment around high voltage device on train roof becomes very complicated. Most train accidents happened due to occurrence of flashover on roof insulator, but the insulation condition estimation of insulator in such environment is much difficult. To ensure the insulation property of electric equipment, and guarantee the operation safety of high-speed-train, here established an instrument with high reliability which can on-line monitor insulation condition of roof insulator and give out advanced alarm before the incipient insulator flashover. The instrument consists of three parts, Data Acquisition & Sensor, Data Processing and Back Processing. Anti-interference and protection methods are processed to Rogowski coil sensor for better leakage current signal. To avoid the fluctuation from railway power supply, four modules are set to filter the power supply waveform. Through laboratory measurement, it is shown that the leakage current and the impedance angle can be detected by the instrument accurately. From the comparison of leakage current and impedance angle results under different moisture condition and the alarm operation when leakage current value reached threshold, this instrument can give out enough information for staff to understand the insulation condition of insulator.

Key words: High-speed-train, Insulator, Insulation condition detection, Leakage current, Impedance Angle

1 Introduction

High speed (350km/h), punctuality and advancement in safety, has made high-speed-railway popular in Chinese mainland recently. Until 2013, mileage of high-speed-railway had reached 10,000 kilometers. Up to 2015, the mileage of high-speed-railway would reach 18,000 kilometers based on programmed guideline. But the actual operation period of high-speed-railway in China is not more than 6 years. There isn't enough knowledge or guideline to understand the insulation property of high voltage equipment upon high-speed-train, which includes the contamination principle of roof insulator and its flashover characteristics. During the period of starting off, passing neutral-section or slowing down, overvoltage will be generated when pantograph lifting up and down. This made flashover occur frequently at roof insulator or even worse in foggy, sand dust or snow weather conditions [1-2]. These are severe accidents to high-speed-train operation, which can lead to half-power work, even make train be late or stop. For example, Luzhou-Beijing high-speed -railway in 2011 and Zhengzhou-Xi'an high-speed -railway in 2012 occurred insulator flashover accidents successively. Investigation reveals that they were all because of flashover happened on polluted insulator in foggy day coincided with pantograph lifting up or down.

1.1 Airflow distribution on Roof Insulator [1-2]

According to the high speed operation of train, the relative movement between roof insulator and airflow can reach 100m/s, which will lead to obvious change on airflow pressure and airflow speed distribution around insulator.

Figure 1 shows the airflow pressure distribution around insulator while train speed reaches 100m/s. The pressure at windward side is 1.14 times of standard atmospheric pressure, but pressure at lateral side is only 0.87 times.

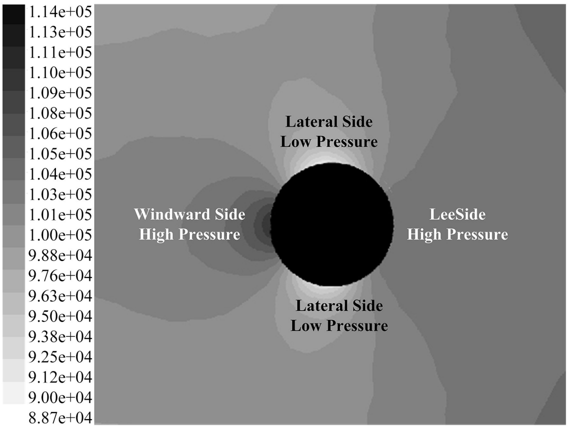

Fig. 1 Air Pressure around insulator in high speed airflow

Figure 2 shows the airflow speed distribution around insulator when train speed reaches 100m/s. The highest airflow speed at lateral side reaches 1.5 times, but the airflow speed at leeside is only 0.75 times. This means high speed operation of train decrease airflow speed at windward side and leeside, while increase speed at lateral side. In the meantime, there is a boundary layer with zero speed vectors around insulator.

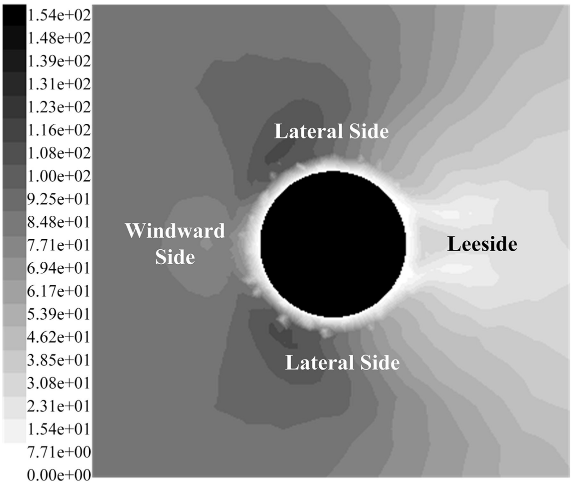

Fig. 2 Airflow distribution of insulator

Boundary layer effect and big blasting power caused by high speed airflow will change the common discharge property [3-4]. Insulator umbrella deformation caused by high speed airflow will lead to electric field distortion and insulator flashover.

1.2 Electrical Distribution of Roof Insulator

With regard to the contamination of roof insulator on high speed train, the relative movement between insulator and air can accelerate the deposition of contamination and make its distribution uniform[1]. From the simulation result [5-6], windward side and leeside had heavier contamination than lateral wind side.

Comparing the uniform distribution and non-uniform distribution of contamination, the electrical distribution of insulator are shown in Fig.3 [7]. According to the uniform distribution of contamination, electrical distribution is also uniform. But to the non-uniform distribution of contamination, lower electrical conductivity at lateral side will cause electrical concentration. Based on previous experiments, flashover of roof insulator always occurred near the interface between leeside and lateral side[2-3].

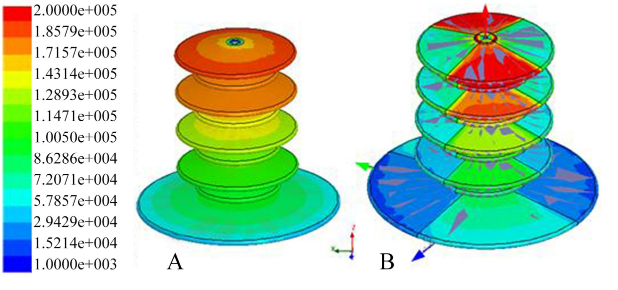

Fig. 3 Electrical distribution of polluted insulator

1.3 Characteristics of Chinese Railway

Chinese railway is long and filled with severe contamination. There are strong relations between electric railway environment and insulator flashover[8-9].

(1) Except normal air dust, there are various contaminations can deposit at the surface of insulator.

Contamination along the railway had acidity and high conductivity, especially in tunnel, where the pollution is hard to spread. Because of the acidity, it is easy to cause flashover on insulator surface.

(2) Compared with developed countries,

chinese railway travels so long that it has to face various weather condition. Therefore, it is difficult to govern the pollution degree and give out precautionary measurement.

(3) According to the railway operation condition, variation of railway load will bring harmonic wave to power supply. Moreover, the instability of pantograph-catenary relationship will lead to impulse and electromagnetism interference to measurement on leakage current and other conductive parameters. As a result, anti-interference methods need to be applied to insulation detection of roof insulator compared with traditional ways.

1.4 Specificity of Detection on Roof Insulator

In view of the traditional detections and experiments, it has been confirmed that there is much difference between good insulator and degraded insulator in electrical capability, partial discharge and temperature distribution, etc. [10-12]. According to the flashover of roof insulator, there are many new impact factors including the distortion pressure, non-uniform contamination distribution and electrical distribution [1-2]. Based on the understanding of the structure and operation character of high-speed-train, contamination principle and flashover characteristics of insulator during high speed operation, it can be concluded that the traditional method used for power system insulator may not be suitable to high voltage devices on high-speed-train. To ensure the insulation property of electric equipment, and guarantee the operation safety of high-speed-train, it is necessary to establish an instrument with high reliability for insulation condition detection of roof insulator and give out advanced alarm before the incipient insulator flashover.

In this paper, an instrument is introduced to estimate insulation condition of roof insulator upon high-speed-train, which is based on the leakage current and the impedance angle. Comparing with traditional methods, a lot of methods are proceeded to improve the sensitivity and anti-interference. From the laboratory measurement, this instrument for roof insulator condition detection can give enough information for insulator condition estimation.

2 Instrument for Insulation Condition Detection of Roof Insulator

2.1 Structure and Main Function

The instrument for insulation condition detection of roof insulator consists of three parts, Data Acquisition & Sensor, Data Processing and Back Processing. The structure chart is as shown in Fig. 4.

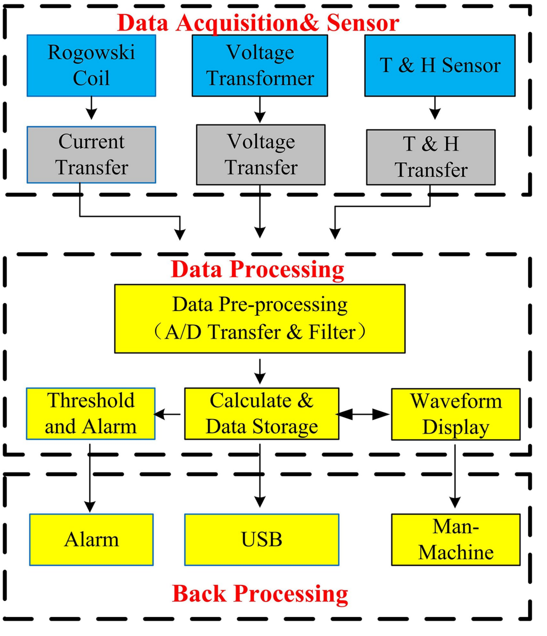

Fig. 4 Instrument structure chart

In Data Acquisition & Sensor part, as the effective data for insulator insulation condition estimation, leakage current and insulator potential are obtained. To estimate the insulator condition with more valid information, the environment temperature and humidity are also acquainted.

The above four signals are put into Data Processing part. After analog to digital conversion, data is primary filtered and processed. The purpose is to avoid interference of overvoltage from catenary, which including lighting overvoltage, overvoltage occurred when passing neutral section and other transient signals during train's operation. Although the sampling rate is 1kHz, magnitude of transient signal has be damped a lot. Fourier decomposition of the current and voltage waveforms was used for a further filtering process on data.

All the data in each operation period can be stored in memory. Any data which exceeds threshold would switch alarm with sound and light. Simultaneously, all the information can be displayed in screen, which include main interface, curve display and data browse. These above three modules constitute Back Processing part.

2.2 Key Technology of Data Acquisition

(1) Sensor Installation

To satisfy the structure of train roof, sensors installation at the train roof is shown in Fig.5. Leakage current sensor is set surrounded at the insulator base. Voltage transformer is set upon train's roof, whose prime terminal connected with metallic support to get power from catenary. Temperature and humidity sensor are fixed near insulator. All the signals from sensor are transmitted by double shielded cable to Data Processing part.

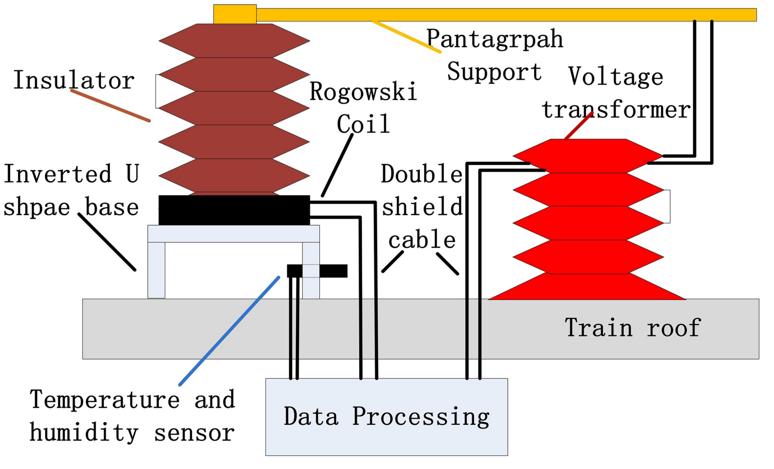

Fig. 5 Installation of sensors

(2) Rogowski Coil

Leakage current is inducted by Rogowski Coil, whose frequency band is 0 – 100kHz. Normally, leakage current is small with a few to tens mill-ampere range. When flashover occurs, leakage current can reach or exceed 1A. It is a little hard to collect leakage current in such a wide range. Accuracy of current sensor decides the instrument capability. To get a high sensitivity, the Rogowski coil should be as smooth and small as possible. In this instrument, the shape of coil is round and set surrounded at insulator base. In addition, a current sensor with an active circuit module is designed in this instrument. This active circuit module is connected to the output terminal of coil, whose function is filtering and amplifying the signal from coil.

(3) Voltage Transformer

Voltage transformer is set up at train roof to detect the condition of power supply. Signal is obtained from its secondary side. The rated input of voltage transformer is 25kV and output is 100V. Considering the fluctuation of catenary potential at different railway section, the actual secondary voltage could range from 72V to 124V. Another set-down transformer is connected to the output of the roof voltage transformer. Its output is set below 10V.

2.3 Main Parameters of Data preprocessing

(1) Leakage Current

Leakage current is an important parameter for on-site detection, which could reflect the development of discharge on insulator surface [13-5]. Therefore, leakage current root mean square (RMS) value was calculated, which is shown in equation (1). RMS voltage is given in equation (2), where time cycle was 20ms.

$$I = \sqrt{\frac{1}{T}\int_0^T i^2(t)\,dt} \tag{1}$$

$$V = \sqrt{\frac{1}{T}\int_0^T u^2(t)\,dt} \tag{2}$$

(2) Impedance Angle

Impedance angle is the phase difference between leakage current and insulator potential [16]. When approaching the flashover voltage of insulator, waveform of leakage current become distorted and have phase shift. So, the measurement of impedance angle can contribute to assist leakage current detection for staff to determine insulator state [12]. Measuring the zero time of leakage current and voltage, the impedance angle can be calculated by equation (3).

$$Angle = \frac{|t_{u0} - t_{i0}|}{T}360 \tag{3}$$

(3) Threshold for Alarm

Alarm starts to work until leakage current RMS value exceed threshold, which is defined by manual setting at the screen interface. To make the proper estimation of insulator insulation condition, threshold has to be given out accurately [11,17]. Usually, it needs laboratory measurement to give out a threshold database with various contamination conditions. Then, emendation should be processed based on on-site measurement results. According to previous experience on traction power supply insulator, flashover was obvious and might lead to penetrating discharge until the maximum value of leakage current exceed 500mA[1-2].

3 Anti-interference and Protection for Instrument

3.1 For Current Sensor

(1) Anti-interference

According to the terrible interference at the top of train, here gives out several anti-interference ways proceeded on current sensor.

a) The active current sensor is consists of Rogowski coil and active circuit. So it can be apart, and put away the circuit part into the instrument case. Coaxial cable is used to connect two parts for signal transmission.

b) Rogowski coil is embedded by epoxy resin, and the whole coil is put in an iron case for interference shielding.

c) In addition, coil plane and catenary plane should be set in parallel to weaken magnetic coupling interference.

(2) Protections

Flashover happened on insulator has two threaten to instrument.

(a) One is the flashover arc spreading from insulator surface to current sensor case. Then, the case will connect with catenary, which could raise the case potential and cause a big threaten to system.

(b) The other is the transient impulse in induction current from Rogowski coil. This would give an overvoltage to system.

To guarantee data acquisition system and staff safe, it is necessary to solve these problems.

Usually, the case of sensor is made of high conductivity aluminum material for a good anti-interference from electromagnetic. To avoid the sensor case potential raise with catenary voltage, the current sensor case is set at the bottom of insulator and connects with insulator metallic base, which gives the case and insulator metallic base same potential. So, when arc spread to sensor case, case potential could be lowered through ground, which protects instrument successfully.

Current sensor is set around insulator base to induct the leakage current through insulator. When flashover happens, the maximum current through insulator could reach 15kA. As for the measuring range of current sensor is lower than 1A, a sudden increase of inducted current might destroy the backward electronic system. According to this problem, there connect TVS (the bidirectional transient suppression diodes) and piezoresistor in parallel between current sensor and active circuit module, as shown in Fig.6. TVS diode has a higher ability to withstand surge shock and can response in picosecond. It can keep the voltage on sampling resistance at a lower voltage even when inducted current of sensor increases suddenly. After the conduction of TVS, piezoresistor will become conducted in a lower response speed for further stabilizing of voltage. Through the double protection circuit, it could ensure the normal work of active circuit of current sensor and the whole instrument.

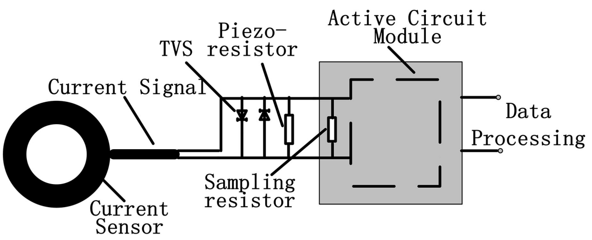

Fig. 6 Protection methods of Rogowski coil sensor

3.2 For Power Supply

Railway power supply has heavy fluctuation and many harmonic waves. This kind of power supply can affect the normal operation capability of electrical instruments on the train. So, it is important to design a stable power supply module for insulation detection instrument. Here set four stages for power supply to instrument, as shown in Fig. 7.

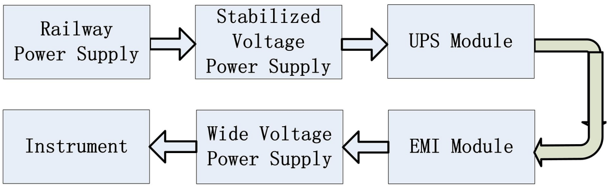

Fig. 7 Power supply modules

At first, stabilized voltage supply is used to stabilize voltage and avoid overvoltage. Then UPS power supply is used to avoid power off when passing neutral section. To avoid interference and ensure system normal operation, EMI module, a single-phase second-order filter with high insertion loss is used. It removes harmonics from switching power supply and data acquisition part. At last a wide range voltage switching power supply is used to satisfied railway power supply characteristics. After these four processing, the power supply will be much stable for normal work of instrument.

3.3 Others Anti-interference Ways

There are other anti-interference methods processed to the instrument.

a) All the transmission line use double shielded cable to avoid magnetic interference.

b) For higher anti-interference, iron material is not only used to the case of current sensor, but also the outer case of the instrument.

c) PLC module has been widely applied in complex industry site because of its high stability, adaptability and anti-interference characteristics. In the data processing part of this instrument, analog quantity input part, CPU part and digital quantity output part are all used PLC module.

4 Measurement and Results

4.1 Laboratory Measurement Circuit

To verify the performance of instrument, measurement was processed on insulator in laboratory. Measurement circuit is shown in Fig. 8.

Voltage regulator is connected to transformer primary side. Voltage is raised by transformer and applied to insulator. Ratio of transformer is 1:250. Capacitance of transformer is 5kVA. To avoid abrupt change of current and protect power supply, resistance 50KΩ is connected in series in the circuit. Insulator is set in an artificial climate chamber which can set different environmental conditions. Leakage current is obtained by current sensor set surround the grounding line. Insulator potential is got by voltage transformer. Temperature and humidity sensor is placed near insulator. All these signals are put into insulator condition detection instrument.

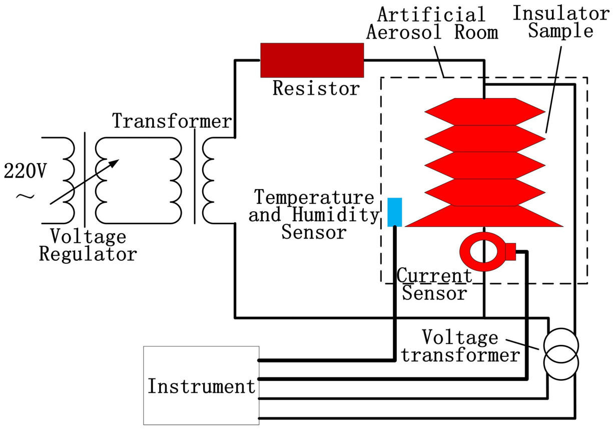

Fig. 8 Test circuit diagram

4.2 Sample and Contamination

Insulator flashover process includes four steps, insoluble contamination deposited on insulator surface, contamination absorb water under moisture condition, part of contamination layer becomes dried and flashover occurs, arc occurs until flashover forms from point to line [18,19]. The real action is related with water-soluble matter in contamination, which will make the electric conductivity enhance after it dissolved in water. For those experiments on insulator, usually the insulator was coated contamination artificially.

Based on GB/T4585-2004/IEC 60507: 1991, there are two kinds of materials:

a) Infusorial earth composition, which was composite by diatomite, high dispersion silicon dioxide (with 2um-20um size), water and some natural sodium chloride.

b) Kaolin composition, which was composite by kaolin, water and some natural sodium chloride.

In this experiment, to get the obvious value, ESDD was set 0.2mg/cm^2, severe degree. Before the test, insulator was cleaned first. After artificial contaminated, the insulator was stored 2 hours in normal temperature until its surface be dried entirely. The relative humidity of artificial climate chamber can be adjusted. Until the insulator surface was wet enough, apply voltage to insulator. Then record leakage current and observe where there happened flashover.

4.3 Measurement Results

Before the measurement, the response range and accuracy of Rogowski coil was confirmed, as shown in Fig. 9. It has perfect response accuracy from 1 mA to 1 A, where the most sensitivity is higher than 90%.

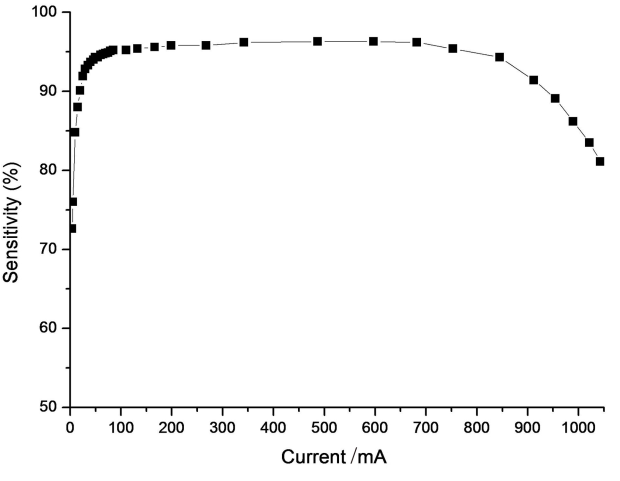

Fig. 9 Accuracy of Rogowski sensor

Then, leakage current and impedance angle were measured by this instrument. The results were exported from instrument for analysis. To confirm the capability of instrument, measurement was processed under two kind conditions, that moisture lower than 60% and moisture above 75%. In the meantime, measurements were all processed under continual moisture condition to keep the humidity of contamination on insulator surface. The temperature was set around 20℃. According to previous experiments, the threshold of alarm is set 500mA. Because of the limited capacitance of power supply system, applied voltage can only be increased to 45kV.

Figure 10 showed the changes of leakage current and impedance angle with applied voltage.

Leakage current reflects the synthetical result of salt density, humidity and applied voltage. It means with the increase of applied voltage, leakage current would increase after insulator become enough damp. When the moisture was lower than 60%, the leakage current started about 0.2mA and increase slowly with the change of voltage. Even voltage was raised to 35kV, noise occurred but the leakage current only reached 10mA. Under this condition, flashover was hard to occur. When moisture condition was higher than 75%, leakage current was small at first. Until some flashover spark occurred at about 25kV, it increased fast. After the rated voltage, flashover was obvious and might join to penetrated discharge if the applied voltage continues to increase. Based on the threshold setting, the alarm did not work until the leakage current exceeded 500mA, where the applied voltage was around 40kV. The operation of alarm declared flashover occurrence on insulator and informed staff to take action.

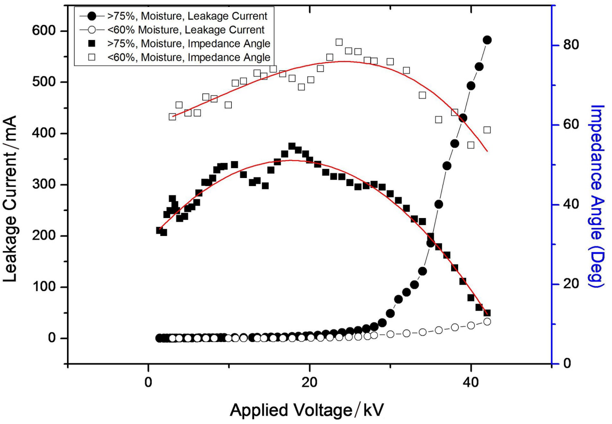

Fig. 10 Leakage current vs. applied voltage and Impedance angle vs. applied voltage

According to impedance angle, it was approximately 70 degrees when the moisture was lower than 60%. Until the discharge occurred when applied voltage was 35kV, impedance angle had little decrease. If the moisture condition was higher than 75%, impedance angle remained around 40 degrees at the beginning. As for the inductive effect of discharge will increase the inductance of the whole circuit [12], impedance angle decreased a lot when discharge occurred with the increase of applied voltage. So when applied voltage was 40kV, impedance angle was already 15 degrees. This decrease explained discharge occurrence on insulator surface.

As a result, based on the above measurement results, leakage current and impedance angle could be helpful to estimate the insulator condition and inform staff to take actions to any affairs. In addition, all the data was recorded in history of the detection system, which could be the backup to understand the location and magnitude of flashover occurred during the measurement. This instrument is on planning to be applied to real high-speed-train for field test.

5 Conclusion

With the rapid development of high-speed-railway, to ensure the insulation property of electric equipment, and guarantee the operation safety of high-speed-train, an instrument for insulation condition detection has been developed for roof insulator on high-speed-train.

1) The instrument consists of Data Acquisition & Sensor, Data Processing and Back Processing. Its function is to measure and display the leakage current, impedance angle etc. It will switch out the alarm when accidents happen to insulator.

2) To ensure the normal operation of instrument, there processed anti-interference and protection methods to Rogowski coil sensor. Four modules protections are made to avoid the heavy fluctuation and harmonic waves from railway power supply.

3) Laboratory measurement was processed on insulator by this instrument. Leakage current and impedance angle were got accurately, which reflect well about the insulation condition of insulator. Alarm operated when leakage current exceeded threshold.

For further application on high-speed-train, field test of instrument will be processed. Leakage current threshold will be defined well to satisfy the real operation of roof insulator.

Acknowledgement

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