Leakage Current and Discharge Phenomenon of Outdoor Insulators

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Abstract: This paper descirbes leakage current characters and discharge phenomenon of outdoor insulators both in the lab and in the field. The results are hoped to be used for online monitoring of the contamination levels. The following contents are introduced in the paper: leakage current monitoring systems, relationships between leakage current and discharge phenomenon, flashover prediction methods and its applications in the field. The leakage current monitoring system is introduced firstly. Then the relationships between leakage current and discharge phenomenon for both suspension insulators and post insulators are presented based on the laboratory tests. A new parameter (I^*) that accounted for maximum leakage current (I_h) and different insulator shapes is introduced to estimate the flashover voltage for different kinds of pollutant layers when they are saturated with moisture. Meanwhile, the relationships between relative humdity (RH) and maximum leakage curren, altitude and maximum leakage current are investigated. With these results a flashover prediction method is developed. I_h measured in different relative humidity is converted to I^* for the same contaminate layer when it is saturated with moisture. Then the flashover voltage is estimated by I^*. Furthermore, an online leakage current monitoring results are analyzed. The relationships between leakage current characters in the field and ambient relative humidity are analyzed. The results show that although there are some differences between the leakage current in the field and in the lab because of some especially serve atmospheric conditions, the relationships are similar. Meanwhile, leakage current waveforms in different weather conditions are investigated. The waveforms of leakage current in the field are similar with those in the lab. The leakage current waveform that accounted for strong arc is found in the field. Finally, the contamination level of the field insulator is evaluated. The results corresponds well with the local condition.
Key words: Flashover, Leakage currents, Insulator contamination, relative humdity.

1. Introduction

Outdoor insulators can become heavily coated with dirt and chemicals by environmental pollution. In severe atmospheric conditions such as fog, dew or drizzle, the contaminant will partially be dissolved, forming a conductive layer. Leakage current that flows along the surface will increase and may eventually cause flashover [1, 2].

ESDD is widely used in China and several other countries to qualify pollution levels on insulators. The ESDD level of the insulators is easy to measure, but has some disadvantages. Firstly, it is difficult to online monitor the ESDD levels in the field. Secondly, many studies show that the flashover voltages on artificially polluted insulators do not agree well with those on naturally contaminated insulators with the same ESDD, since the natural contaminants are much more complex than that of the artificial contaminants. Several studies have shown that factors such as the composition of the conductive components, the level of NSDD and the distribution of the contaminants would affect the flashover voltage [3-5].

Advanced statistical processing of the leakage current envelope gave reliable predictions of flashover voltage on single disc insulators. A lot of research has been carried out to study the relationship between leakage current and flashover voltage. However, to use the results for the online monitoring and evaluation of the insulators in the field, three problems should be solved.

Firstly, most of the researchers focused their interests on the leakage current at pre flashover stage. However, the voltage applied on the insulator in that situation is usually higher than the operating voltage of the insulators in the field. So the leakage current is also different from that of the insulators in the field.

Secondly, nature pollution is more complex than artificial pollution. Thus, it is necessary to study whether the relationship between leakage current and flashover voltage is related to the kinds of pollutant layers.

Thirdly, laboratory tests always carried out in the fog chamber with the pollutant layers of the tested insulators saturated with moisture. But in the field, factors such as relative humidity and air pressure can also affect the flashover voltage. Thus, effects of these environmental factors to leakage current must be studied.

A lot of online leakage current monitoring systems have been installed. However, it is still difficult to assess the contamination levels by online leakage current monitoring results because of above problems. Therefore, in this paper, a multi channel leakage current monitoring system is introduced first. Then, not the leakage current at pre flashover stage, but the leakage current at the phase to ground voltage of 110kV transmission lines (8kV/disc) was studied with different kinds of pollutant layer. The discharge phenomenon during the tests is observed. The relationships between maximum leakage current at service voltage and flashover voltage are studied, a new parameter I^* is used to assess the contamination level by maximum leakage current. Meanwhile, relationships between leakage current and altitude, leakage current and relative humidity are investigated. Furthermore, a flashover prediction method is developed. In addition, the leakage current acquired by online monitoring system is analyzed. Relationship between leakage current and climate in the field is studied. Finally, the contamination level in the field is assessed using above study results.

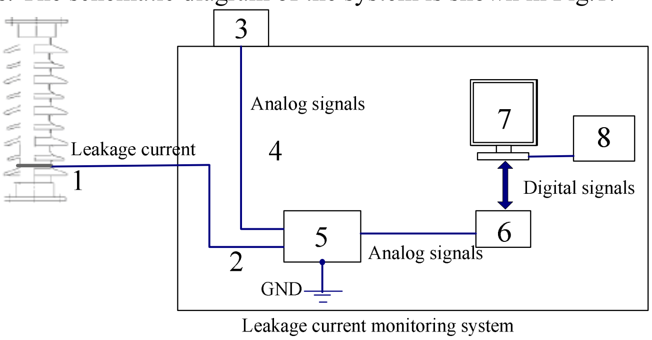
2. Leakage current monitoring system

A kind of high precision leakage current monitoring system is used in the laboratory tests and online monitoring, so accurate leakage current information can be obtained for further research. The parameters of the system are shown in Table 1.

Table 1 Parameters of leakage current monitoring system

Measuring range	Sampling rate	Number of Chanel
0.5 mA~2 A	20 kHz	8

The leakage current monitoring system is combined with the following four main components: Leakage current sensor, data acquisition hardware, personal computer and protective devices. The schematic diagram of the system is shown in Fig.1.



1 Copper ring, 2 Copper wire, 3 relative humidity and temperature sensor, 4 Double shielded cable, 5 leakage current sensor, 6 data acquisition hardware, 7 Personal computer, 8 Source protection device.

Fig.1. A schematic diagram of the leakage current monitoring system

Leakage current is collected by a copper ring fixed at the low potential end of the insulators and flows into ground through the leakage current sensor. Meanwhile, relative humidity and temperature near the insulator are also measured. A high speed data acquisition hardware is used to convert the analog signals to digital signals. Then the signals are transmitted into the personal computer, where the signals are converted into real leakage current value and analyzed by the specially designed software. The computer is connected with a protective device to prevent it from being destructed by the voltage surge caused by flashover of the insulators.

Leakage current sensor is the key component of the system. In order to prevent the leakage current signals from being distorted, A circuit mainly consists of resistors is designed. Their resistances are accurate and wouldn’t change by temperature variation. By using resistors as a sensor, not only the leakage current of the AC system, but also the leakage current of DC system, can easily be measured by the same leakage current sensor.

Fig.2 is the schematic diagram of the leakage current sensor. The sensor is combined with two resistors: R_{s1} has higher resistance and converts low amplitude leakage current signals signal into voltage signals; R_{s2} have lower resistance and convert high amplitude leakage current signals to voltage signals. With this method the input voltages of the Data acquisition hardware is kept in a high level. The precision of the sensor is increased.

The input of data acquisition hardware must be lower than 10V or it would be destroyed. Therefore, some protection devices are used in the leakage current sensor. Both of the resistors are paralleled with switches whose response time is about 10 ns. They are used as the first level protection. Piezo-resistors whose response time is about 50 ns are used as the second level protection. Meanwhile, a surge arrestor is paralleled between the high voltage end of the sensor and the ground for third level protection.

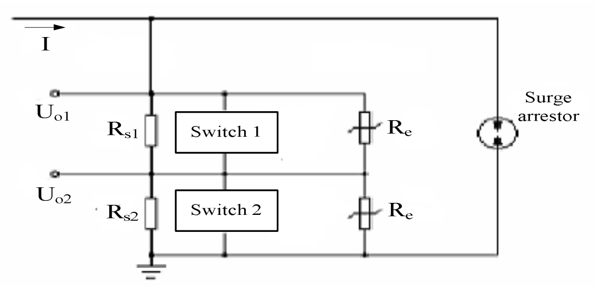
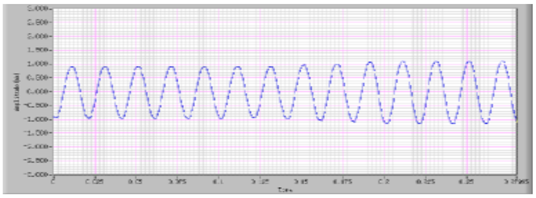


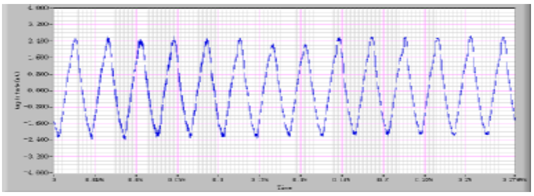
Fig.2. A schematic diagram of the leakage current sensor

In the software, the signals from the leakage current sensor are combined together to form the actual leakage current waveform. Leakage current characters such as the peak values, the number of the leakage current pulses are taken from the leakage current waveform and recorded. Meanwhile, the waveform of leakage current can also be saved as files in the computer both in the lab and in the field. So the information of the leakage current can be saved completely for further research.

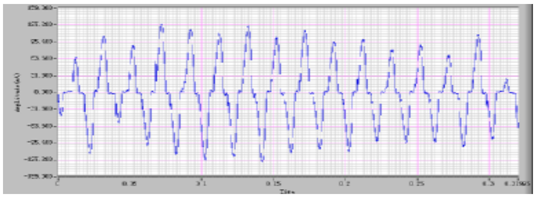
Flashover tests were carried out with this leakage current monitoring system in the lab for thousands of times, the system is still working well. Fig 3 shows typical leakage current waveforms when increasing the voltage applied on the insulator until flashover occur.



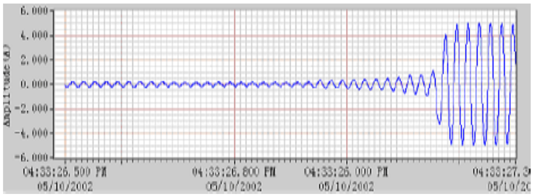
(a)



(b)



(c)



(d)

Fig. 3. Leakage current waveforms

Fig 3 (a) is the leakage current when no discharge appear on the insulators. The waveform is sinuoidal. Fig 3 (b) is the leakage current when weak discharge appear on the insulator surface. The waveform is distorted. Fig 3 (c) is the waveform when strong arc appears. The amplitudes can be several hundreds of milliampere. Fig 3 (d) is the leakage current when flashover occurs. Leakage current increases quickly before flashover. When flashover happens, short current is monitored.

3. Laboratory tests

3. 1 Experimental setup and test procedure

Three kinds of widely used suspension insulators (Fig. 4) were tested. Typical parameters are shown in Table 2. XWP-70 and XP-70 were porcelain insulators and LXY-70 was glass insulator.

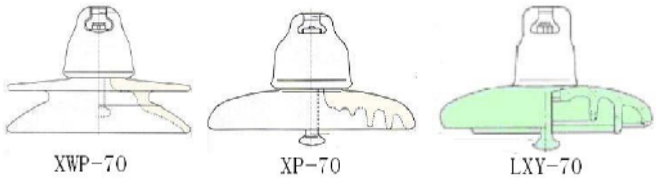


Fig. 4. Insulator profiles.

Table2 Insulator Geometric Parameters

Type	Diameter (mm)	Leakage Distance（mm）	Surface areas (mm^2)
XWP-70	255	408	2068
XP-70	255	290	1490
LXY-70	255	335	1668

Three kinds of tests were carried out in the lab. The first kind is design to study the relationship between leakage current, SDD and flashover voltage when the contaminated surface is saturated with moisture. The second kind is designed to study the relationship between leakage current and altitude. The third kind is designed to study the relationship between leakage current and relative humidity.

The first kind of experiments was carried out in the laboratory of the Yunnan electric power test and research institute. This lab is located in Yunnan Province, in southeast China at an altitude of about 2000 m. For the first kind of the tests, a string consisting of 8 pieces of the same type of insulators was suspended in the fog chamber. The chamber was then filled with fog while a voltage of 63.5 kV was applied on the insulator string. The voltage and the fog were maintained for 30 minutes. Then the applied voltage was increased until flashover occurred. The flashover voltage and the leakage current during the whole process were recorded by the monitoring system. To improve the experimental results, for each kind of pollutant layer, 10 groups of the specimens were tested with the average results presented in the discussion.

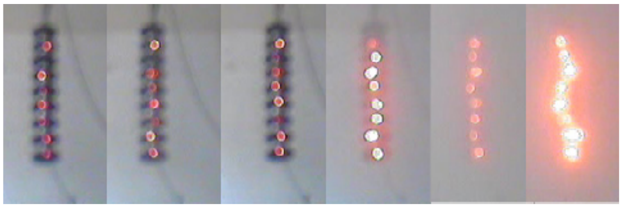
The second kind of experiments was carried out in an air pressure controllable chamber in the laboratory in China Electric Power Research Institute in Beijing, China. Two kinds of insulators, XWP-70 and LXY-70, are tested at altitudes from 0 m to 3000 m. The test steps are the same as the first kind.

The third kind of experiments was carried out in the laboratory in Graduate School at Shenzhen, Tsinghua University, where the altitude is about 0m. For the second kinds of tests, a piece of the insulators was placed in an artificial climate chamber. Then the relative humidity of the chamber was adjusted to the proposed level. The relative humidity was kept in the same level for adequate time to make the insulator sufficiently moist. Then operating voltage of 8 kV was applied on the insulators for 10 minutes, because the discharge on the insulator surface would be weak enough after 10 minutes. Five levels of the relative humidity were tested in the experiment, respectively 85%, 90%, 95%, 99% and 100%. This experiment procedure simulated the wettest surface conditions of the proposed relative humidity levels. It was equal to the condition when the surface was rapidly wetted. To improve the experimental results, for each SDD level and each relative humidity, three groups of the insulators were tested.

3. 2 Results and Discussion

3. 2. 1 Discharge phenomenon

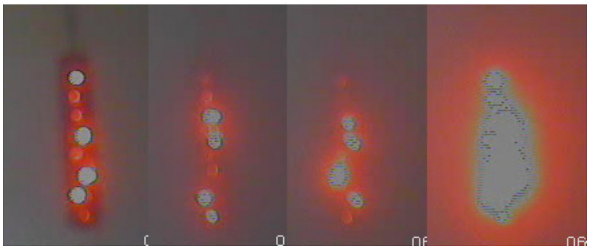
Fig.5 and Fig.6 are typical discharge phenomenon in the laboratory tests. Fig.5 shows the discharge phenomenon of insulators being lightly polluted. Fig.6 shows the discharge phenomenon of the insulators being heavily polluted.



1’16”	1’28”	3’22”	11’17”	21’26”	29’42”
16mA	50mA	106mA	162 mA	210 mA	641 mA

Fig .5. Discharge phenomenon in the test.

(XP-70, SDD=0.1mg/cm^2, SDD of top surface/SDD of bottom surface=1/5)



4’09”	15’47”	29’42”	31’58”
278mA	646mA	748mA	Flashover

Fig .6. Discharge phenomenon in the test.

(XWP-70, SDD=0.25mg/cm^2)

When the pollution level is low, in the first few minutes, discharge appears in each piece of the insulator. While the pollutant layer absorbs more vapour, the discharge glows stronger and the amplitude of leakage current becomes higher. However, the arcs between the insulators wouldn’t connect together before flashover.

When the pollution level is high, strong discharge occurs in each insulator in the first few minutes, and leakage current of high amplitude appear. While the pollutant layer absorbs more vapour, the arcs of nearby insulators connect together, forming stronger arcs cross the insulator string, the amplitude of the leakage current glows even higher. When all the arcs on the insulator connect together, flashover occurs. The amplitude of leakage current is much higher in Fig.6 than that in Fig.5. The discharge phenomenon and leakage current is strongly relative.

Table 3 shows the correlations between maximum leakage current and the discharge phenomenon for XP-70 type insulators. Similar relationship is found for XWP-70 and some other kinds suspension and post insulators. Using these relationships, the discharge phenomenon in the field can be evaluated by the online leakage current monitoring results.

Table 3. Correlations between I_h and the discharge phenomenon for XP-70

I_h(mA)	Discharge phenomenon
<2	No obvious discharge phenomenon
5	Purple sparks near the cap and pin
10~20	purple arcs near the cap, and purple brush discharge near the pin
50	Orange short electric arcs
70~100	Arcs in the bottom surface reach to 1/3 distance of the diameter.
200	One or more bright arcs appear at both sides of the insulator surface.
200~400	Bright main arcs nearly reach the edge of the surface. Massive of saffron small arcs appear around the cap and in the grooves in the bottom surface.
400~900	The arcs nearly breakthrough the surface of insulators. The discharges are strong and have long last time.
900~1500	Red arcs appear, the specimen would flashover at any time

3. 2. 2 Relationship between I_h and flashover voltage

Fig.7 shows the relationship between maximum leakage current and SDD in standard pollutant layers. The standard pollutant layers in this paper are NaCl as the conductive component, Kaolin with an NSDD of 1.0 mg/cm^2 as the non soluble component, with the contaminant uniformly brushed onto the insulators. I_h increases linearly with SDD.

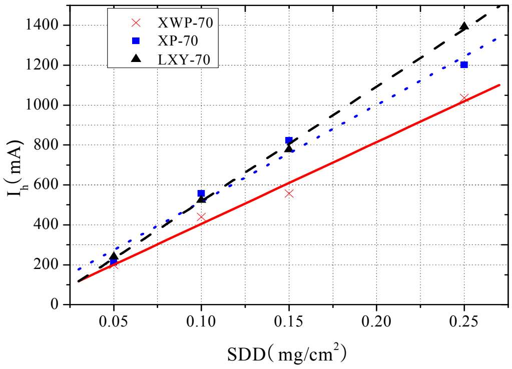


Fig.7. Variation of leakage current with SDD for the standard pollutant layers.

Fig.8 compares the relationships between I_h and U_{FO} for the standard pollutant layers and pollutant layers with different composition of the conductive components, different level of NSDD and different distribution for the XWP-70 type insulators. The two curves are quite close, which means that the relationship between I_h and U_{FO} is nearly the same for the different pollutant layers. Therefore, the two curves can be combined into one. The relationships between I_h and U_{FO} can be expressed by a negative power function

$$U_{FO} = aI_h^{-b} \tag{1}$$

Where a and b are both positive numbers. This relationship does not change for different pollutant layers.

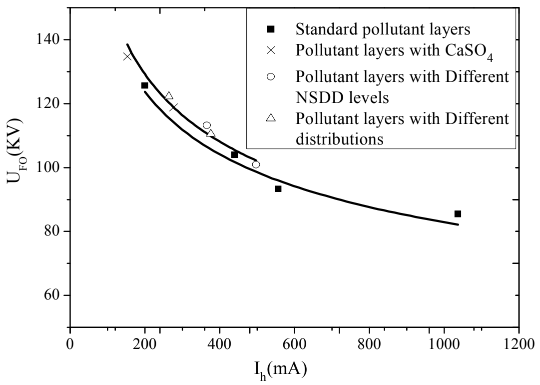


Fig. 8. Flashover characteristics for various kinds of pollutant layers (XWP-70).

For different kinds of insulator, their flashover characteristics are different. These differences are caused by the differences of their profiles and leakage distances. These two factors can be combined into a new parameter.

$$I^* = I_h fL \tag{2}$$

Where f is the form factor

$$f = \frac{1}{\pi}\int_0^L \frac{dl}{D(l)} \tag{3}$$

Where dl is a differential element along the leakage distance, $D(l)$ is the insulator diameter at distance l and L is the leakage distance on the insulator.

The relationship between I^* and E_f is illustrated in Fig. 9. The differences between the three types of insulators are so small that they can be neglected, so the relationship between E_f and I^* can be expressed by one curve:

$$E_f = 66.7 I^{*-0.238} \tag{4}$$

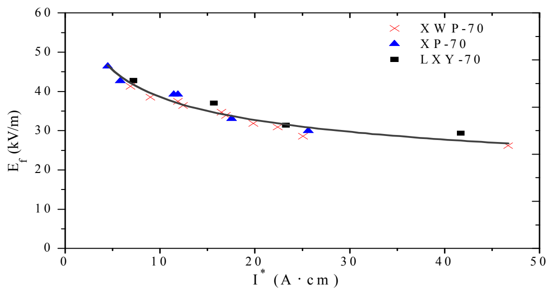


Fig. 9 Variations of the flashover gradient for the suspension insulators

This equation can be used to estimate the flashover voltage for all three kinds of insulators with different kinds of pollutant layers.

For insulators working at different service voltage, the parameters must be converted to the experimental conditions first by the following equations.

$$I^* = I_h L^* f^* \tag{5}$$

$$L^* = \frac{8\sqrt{3}nL}{U_y} \tag{6}$$

$$f^* = \frac{8\sqrt{3}nf}{U_y} \tag{7}$$

Where L^* and f^* are effective leakage distance and effective form factor, U_y is the service voltage.

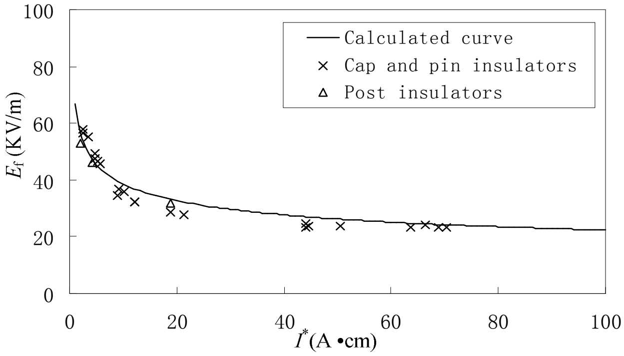


Fig.10. Comparisons between the experimental results and calculated results.

The experimental data for suspension insulators and post insulators in different service voltage are used to verify above equations, the results are shown in Fig 10. I^* and E_f obtained in the tests fit well with the curve calculated by equation (4), which proves is the effectiveness of equation (5)~(7) is certified.

3. 2. 3 Relationship between leakage current and altitude

The relationships between maximum leakage current and altitude are shown in Fig. 11. In same SDD, I_h increases when altitude increases. I_h(mA)

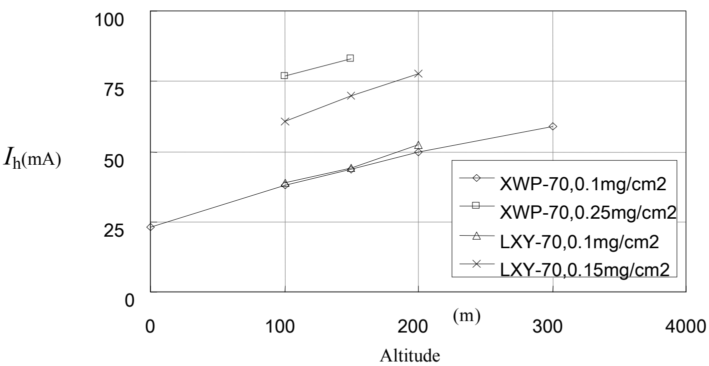


Fig. 11. Variations of the I_h with altitudes

The relationship between I^* and E_f in different altitudes are shown in Fig.12. The test results fit well with equations (4), which means no matter how altitude changes, E_f wouldn't change if I^* doesn't change. So the effect of air pressure can be neglected when I^* is used to estimate the flashover voltage.

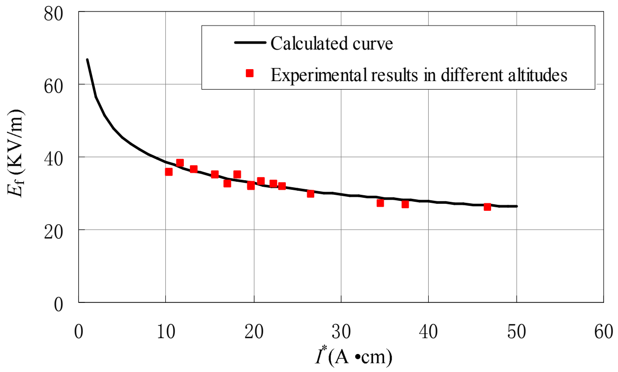


Fig.12. The relationship between I^* and E_f for different altitudes

3. 2. 4 Relationship between I_h and relative humidity

Fig.13 is the relationship between the maximum leakage currents and relative humidity. I_h increase when relative humidity increases. The variation can be divided into two stages.

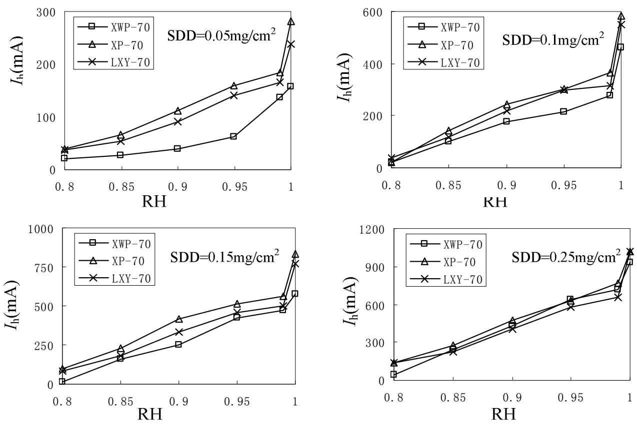


Fig.13. Relationships between I_h and relative humidity

Stage 1 is from 85% to 99% (critical saturation). The rates of increase of both the surface conductivity and the maximum value of leakage current are lesser at higher relative humidity.

Stage 2 is Form 99% to 100%(over saturation). I_h increase suddenly.

These two stages could be explained by different phenomena of the wetting of the insulator surface. Four phenomena are considered in the tests according to reference [6].

(a) Condensation;

(b) Collision of the water droplets with the insulator surface

(c) The hygroscopic behavior of the insulator surface deposit

(d) A chemical diffusion which develop between the NaCl solution on the insulator surface and the water molecules of the fog.

In stage 1, the major wetting factors are phenomena (c) and (d). But in stage 2, phenomena (b) plays an important role in the wetting process because the fog in the chamber is over saturated. As a result, much more moisture was absorbed by the contaminated surface, so the surface conductivity and the maximum value of leakage currents increase rapidly.

Fig.14 shows the relationship between I^* and E_f in different relative humidity. The experimental results fit well with the calculated curve, which means the relationship does not change for different relative humidity.

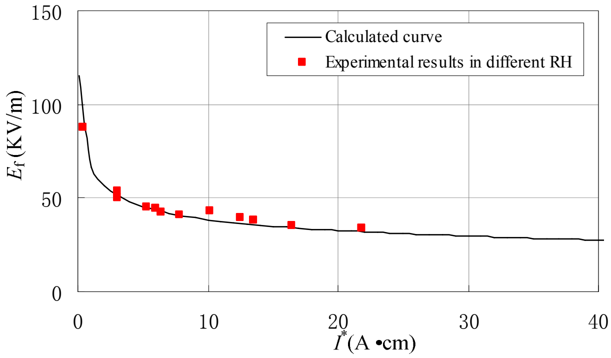


Fig.14. The relationship between I^* and E_f in different RH

3. 2. 5 Flashover Predition

Although flashover voltage in different relative humidity can be estimated by I^*, it is not the lowest flashover voltage for the contaminate layer. Because when relative humidity increases, the contaminate layer would absorb more moisture and the flashover voltage would be lower. In order to find out the lowest flashover voltage for a specific contaminate layer, the relationships between leakage currents in different relative humidity and leakage currents when the surfaces are saturated with moisture are needed.

The relationships between the leakage currents in different relative humidity and leakage currents when the surfaces are saturated with moisture are shown in Fig. 15. The relationships can be expressed by equation (8):

$$I_{h100}=aI_{hRH} \quad (8)$$

Where I_{h100} is the maximum leakage current when the contaminate layer is saturated with moisture, and I_{hRH} is the maximum leakage current of the same contaminate layer in different relative humidity. Similar principals are found in XWP-70 and LXY-70. For all the three kinds of insulators in the same relative humidity, the value a are similar. Following this equation, the I_h in different relative humidity can be converted to the I_h when the pollutant layers are saturated with moisture. Using equation (4) to (8), flashover voltage for insulators with their contaminate layer saturated with moisture can be estimated by maximum leakage currents monitored in different relative humidity.

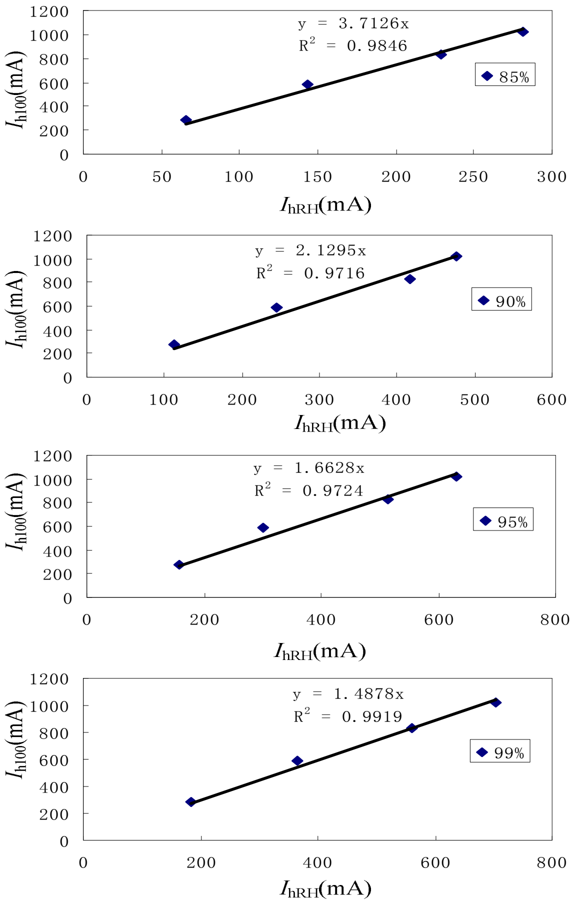


Fig.15. Relationship between I_{hRH} and I_{h100} （XP-70）

Table 4 is some typical insulation levels for XP-70 with 110kV/8 disc in different relative humidity. Insulation level K is calculated by equation (9) and (10)

$$U_w = nLE_f(1-3\sigma)k \tag{9}$$

$$K = U_w / U_{yh} \tag{10}$$

Where n is the unit number of the insulator string. σ is standard deviation. k is the coefficient of parallel strings. U_{yh} is the highest phase voltage that would be applied on the insulators.

Table 4. Some typical K value in different relative humidity

RH	I_h(mA)							
	10	20	50	80	100	150	200	250
85%	1.60	1.36	1.09	0.97	—	—	—	—
90%	1.27	1.21	1.10	1.02	0.98	—	—	—
95%	1.98	1.68	1.35	1.21	1.14	1.04	—	—
99%	2.03	1.72	1.39	1.24	1.18	1.07	1.00	0.94

4. Online Leakage current monitoring results

An online leakage current monitoring system is installed in Ha'nan Substation, which is in Harbin, Northeast China.

Fig.16. Photo from Ha'nan substation

The substation is surrounded with farm. Contamination level there is level II. The general climate in Harbin is as follows. Rainfall is focused between July and September. Form October to March it is dry. Snow is focused in March, with temperature above 0□ and relative humidity above 90%. So from February to March the insulators would threat by flashover most serious. ESDD in this area is 0.06 to 0.1mg/cm^2.

The leakage current monitoring system monitors two post insulators of the same type. Not only the leakage current characters, but also the leakage current waveforms whose amplitude is above 5mA are recorded.

4.1 General leakage current character in the field

Fig.17 is the leakage current character form October, 2006 to April, 2007 in Ha'nan Substation. Each point represents the maximum leakage current in 5 minutes. There are only a few pulses whose amplitudes are above 10 mA. Most of the high amplitude pulses occurred in February and March for both of the insulators, which corresponds well with the climate of the region.

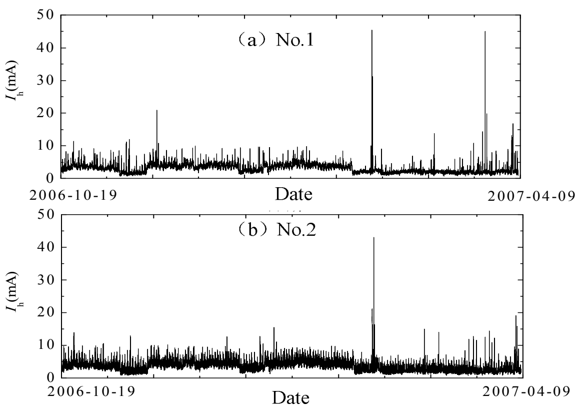


Fig.17 Leakage current in the substation.

There are a large number of leakage currents above 5mA. They appear in different relative. Therefore, it doesn't correspond well with the contaminate level and moist level. So it is not suitable for analysis. The leakage current pulses above 10mA are fewer. But they illustrate more serious discharge condition, so it must be tightly related to the contamination levels.

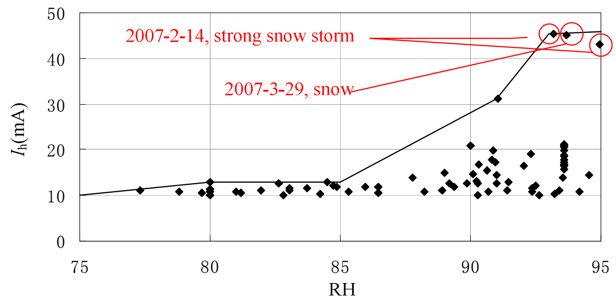


Fig.18. I_h vs. RH in the substation

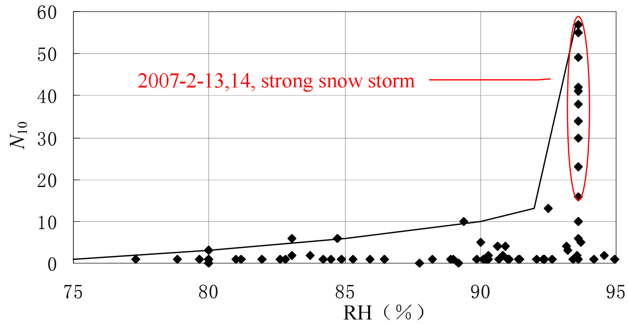


Fig.19. Pulses above 10mA vs. RH in the substation

Fig.18 is the relationship between leakage current and relative humidity in the field. No leakage current above 10mA appears when relative humidity is below 75%. While the relative humidity increases from 75% to 85%, the increase of I_h is slow. When the relative humidity increases from 85% to 92%, the maximum leakage currents increase quickly. In 92% to 95% RH, there are 3 points whose amplitudes are far above other points. They appeared in February and March. In these times, strong snow storm occur in the local areas. Meanwhile, since the temperate is above 0℃, the snow on the insulator surface is easy to melt. So the pollutant layers are likely to be saturated with moisture. Fig. 19 is the relationship between number of leakage current pulses and relative humidity. It also illustrates that many high amplitude leakage current pulses appeared in those days.

4. 2 Leakage current waveform in the field

Fig. 20 is the typical waveforms acquired from the field insulators. The discharges are focused from January to April, especially from February to March.

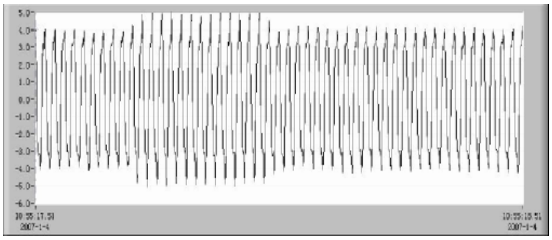
Fig. 20(a) occurred when the insulators were covered with ice. About 10 cycles of leakage current waveforms whose amplitude is higher than 5mA are recorded. The Discharge on the contaminated surface is weak.

Fig. 20(b) occurred when it was snowing. Pulses appear in the peak and trough of the cycle. The amplitude is about 20mA.

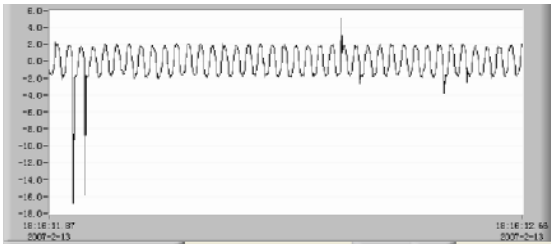
Fig. 20(c) occurred when strong snowstorm happened. It is the most serious discharge the system recorded. 4 cycles of the leakage current waveform, whose amplitudes were much higher than other cycle appear. The peak value is about 45 mA. There must be arc appear on the contaminated surface.

It can be seeing clearly that leakage current waveforms in the field are quite similar with those in the laboratory tests. So it is adequate to evaluate the contamination levels by maximum leakage current using the methods obtained by the laboratory tests.

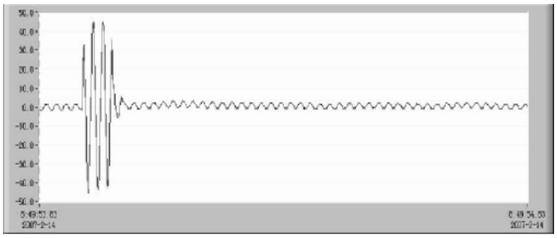
There are still some differences between the leakage current characters in the laboratory tests and in the field. For Fig .20(c), the relative humidity didn't reach 100%, but the contaminated surface must be saturated with moisture because of snow and temperature. It is proved in Fig.18 since the sudden increase of the current has already appeared.



（a）2007-1-4-10:55, RH＝87%



（b）2007-2-13-18:16, RH=93% (snow)



（c）2007-2-14-8:49, RH=91% (Snowstorm)

Fig.20. Leakage current waveform in the substation.

4. 3 Assessment of the insulation level

Since leakage currents in the substation are similar with those in the lab, the insulation level in the field can be assessed by the method developed in the laboratory. The parameters of the insulators are shown in Table.5.

Table.5 Parameters of the monitored insulators

Creepage ratio （cm/kV）	Service voltage （KV）	Highest service voltage （KV）	Creepage distance (cm)	f
2.0	220	253	506	12

Table 6 shows the results of the assessment. For each relative humidity, the maximum leakage current in all the pulses are used to assess the insulation levels. All the results are corresponding well. The threat of flashover is very low. Furthermore, SDD of the insulators are also evaluated based on Fig.7. SDD is about 0.025~0.03 mg/cm^2, which is 2~3 times lower than that measured ESDD in the field. Considering the distributions and the composition of the contaminants, this value fits well with the conditions in this area.

Table.6 Assessment of the insulation levels in the field.

RH	I_h (mA)	K	ESDD (mg/cm^2)
85%	8	1.62	
90%	20	1.64	0.025~0.030
99%	45	1.65	

5. Conclusions

(1) A multi channel leakage current monitoring system is developed. The specially designed leakage current sensor is precise and well protected.

(2) Discharge phenomenon in the laboratory tests is investigated. The discharge phenomenon is quite different between lightly and heavily polluted insulators. However, relationship is found between maximum leakage current (I_h) and discharge phenomenon.

(3) A new parameter (I^*) that includes the maximum leakage current, the form factor and the leakage distance is introduced. A model is developed to estimate the pollution flashover voltage based on I^*. The model is validated by the experimental data. The results show that the model actually predicts flashover voltages for different kinds of insulators.

(4) The effect of altitude to leakage current is studied. The relationship between I^* and E_f wouldn't change for different altitudes. So the effect of air pressure can be neglected when using maximum leakage current to estimate the flashover voltage.

(5) The relationship between leakage current and relative humidity is studied. When vapour in the air changes from 99% (critical saturation) to 100% (over saturation), I_h increase suddenly. The relationship between I^* and E_f doesn't change for different altitudes.

(6) A flashover prediction method is developed. Maximum leakage currents in different RH is used to estimate flashover voltages for different kinds of insulators when their contaminate layers are saturated with moisture.

(7) Leakage currents of the field insulators are analyzed. Leakage current characters and waveforms in different relative humidity in the field are similar with those in the lab. But due to the strong snow storm, the pollutant layers are saturated with moisture when relative humidity is only 92% to 95%. Waveform for strong discharge is observed in the field, its amplitude is about 45 mA. The insulation levels of the field insulators are assess using the methods developed by laboratory tests. The results fit well with local condition.

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Reference

[1] M. Teguar, A. Abimouloud, A. Mekhaldi, A. Boubakeur, "Influence of discontinuous pollution width on the surface conduction. Frequency characteristics of the leakage current", *2000 Conference on Electrical Insulation and Dielectric Phenomena, Victoria, BC*, vol.1, pp. 211-214, 2000.

[2] M.A.M. Piah, and A. Darus. "Modeling leakage current and electric field behavior of wet contaminated insulators", *IEEE Transactions on Power Delivery*, vol.19, No.1, pp. 432-433, 2004.

[3] G. Ramos N. M, T. Campillo. R and K Naito. “A study on the characteristics of various conductive contaminants accumulated on high voltage insulators”, *IEEE Transactions on Power Delivery*, vol.8, No.4, pp. 1842-1850, 1993.
[4] R. Sundararajan and R.S. Gorur. “Role of Non-soluble Contaminants on the Flashover Voltage of Porcelain Insulators”, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.3, No.1, pp. 113~118, 1996.
[5] Schneider, H. M, “Measurements of contamination on post insulators in HVDC converter stations”, *IEEE Transactions on Power Delivery*, Vol.3, No.1, pp. 398-404, 1988.
[6] Karady, G. “The effect of fog parameters on the testing of artificially contaminated insulators in a fog chamber”, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-94, No. 2, pp. 378-387, 1975.