RESEARCH ON THE FREQUENT AND PHASE CHARACTERISTICS OF LEAKAGE CURRENT OF ICED INSULATORS

Jiang Yanru[2], Xia Yunfeng[1], Jiang Xingliang[1], Zhang Zhijing[1], Hu Jianlin[1], Shu Lichun[1]
1.State Key Laboratory of Power Transmission Equipment and System Security and New Technology, College of Electrical Engineering of Chongqing University,400030,Chongqing, China
2. Loudi Electric Power Bureau of Hunan Electric Power Corporation, 417000, Loudi, China
xljiang@cqu.edu.cn, xyf0725@163.com

***Abstract**:* The one of precondition to prediction flashover is effective leakage current characteristics of iced insulator, but there is no common agreement about the relation between the flashover and leakage current characteristics, which is one of reason for no perfect prediction flashover system. Based on the AC flashover model, the phase (θ) between the first harmonic of leakage current and operated voltage is studied. It is found that, θ decreases with development of arc. The relationship between the waveform distortion of leakage current and the total harmonic distortion (*THD*) is analyzed by fast Fourier transform (FFT). The *THD* increases slowly with the development of discharge when the icing water conductivity (IWC) is small. While the IWC is large, the *THD* increases firstly and then decreases. There come into being white arc discharge with the minimum of *THD*. Based on the theoretical analysis and experimental verification, it is proposed that *THD* and θ can be used to predict the flashover.

1. INTRODUCTION

As is believed by domestic and foreign scholars, flashover of iced insulators is similar to the discharge of polluted insulators because icing of insulators is a kind of special pollution, and development of leakage current is main factor for the flashover of iced insulators. So the experimental research for the leakage current characteristics of iced insulators can contribute to the mechanism analysis of iced insulators flashover, the establishment of numerical analysis model for iced insulators flashover, and the determination of characteristic parameters for online monitoring of insulators.

2. RESULTS AND DISCUSSION

Phase difference θ between Leakage current and applied voltage and *THD* can be utilized as phase and frequency character parameter to monitoring the icing development state of the insulator string. This iced insulator flashover pre-warning scheme can be divided into two steps: (1) Monitoring leakage current phase characteristic θ, when θ nears 0, it shows faint local electric arc on insulator surfaces. (2) Monitoring leakage current frequency characteristic *THD*, when θ closes to 0, if θ is closing to 0 and there is no minimum value of *THD*, it shows insulator icing is not serious and arc development is still in the security zone, namely insulator may be in safe operation. If there is minimum value of *THD*, it indicates that white arc discharge on local surface of iced insulator may probably develop to flashover.

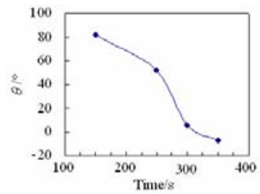


Figure 1: Relation between θ and discharge processing

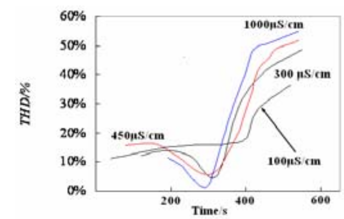


Figure 2: Relationship between THD and discharge processing (The average thickness of ice on monitoring copper is 15mm)

3. CONCLUSION

(1) Phase difference θ between Leakage current and applied voltage decreases with the discharge development of arc. When the insulator did not produce local arc or local arc is faint, the phase of leakage current is ahead of that of applied voltage. When white arcs appear on the insulator surface, the phase of leakage current is lag behind of applied voltage.

(2) When IWC is low, *THD* increases slowly with the development of discharge, and there is no minimum value. When IWC is large, *THD* decreases and then increases with the development of discharge. So there is minimum value of *THD*. The larger of IWC, the earlier *THD* achieve minimum value. When *THD* achieves THD_{min}, white arc begin to appear on the iced insulator surface.

(3) The phase difference (θ) between the leakage current and applied voltage and frequency character parameter (THD_{min}) in safety period can be utilized to the pre-warning of iced insulator flashover.

4. REFERENCES

[1] M. Farzaneh and W.A. Chisholm, Atmospheric Icing of Power Networks [M], Springer, pp 269-325, 2008.

[2] Jiang Xingliang, Yi Hui, Icing and Its Protection for Transmission Line. China Electric Power Press, Beijing, 2002.6-8.

[3] Jiang Xingliang, Shu Lichun, Sun Caixin. Insulation of pollution and Icing for Power System. China Electric Power Press, Beijing, 2009.

RESEARCH ON THE FREQUENT AND PHASE CHARACTERISTICS OF LEAKAGE CURRENT OF ICED INSULATORS

Jiang Xingliang, Xia Yunfeng, Zhang Zhijing, Hu Jianlin, Shu Lichun
College of Electrical Engineering of Chongqing University, 400030, Chongqing, China
State Key Laboratory of Power Transmission Equipment and System Security and New Technology

Jiang Yanru
Loudi Electric Power Bureau of Hunan Electric Power Corporation, 417000, Loudi, China

***Abstract*— The one of precondition to prediction flashover is effective leakage current characteristics of iced insulator, but there is no common agreement about the relation between the flashover and leakage current characteristics, which is one of reason for no perfect prediction flashover system. Based on the AC flashover model, the phase (θ) between the first harmonic of leakage current and operated voltage is studied. It is found that, θ decreases with development of arc. The relationship between the waveform distortion of leakage current and the total harmonic distortion (*THD*) is analyzed by fast Fourier transform (FFT). The *THD* increases slowly with the development of discharge when the icing water conductivity (IWC) is small. While the IWC is large, the *THD* increases firstly and then decreases. There come into being white arc discharge with the minimum of *THD*. Based on the theoretical analysis and experimental verification, it is proposed that *THD* and θ can be used to predict the flashover.**

Keywords-leakage current; insulator; icing water conductivity (IWC); phase; total harmonic distortion (THD)

I. INTRODUCTION

According to incompletely statistics, transmission line fail into tripping thousands of times as a result of icing disaster in China since 1954. Especially in early 2008, icing disaster in south areas of China led to large amounts of tripped accidents for the flashover of iced insulators. All these icing disasters caused extensive damage to power grids and great financial losses to China. With the completion of power grids interconnection in the whole country, transmission electric power from west to east and exchange electric power between south and north of China, super ultra-high voltage (UHV) transmission lines with large transmitting capacity of electric energy are come into facing threaten of icing in the tiny terrain with feature of micro climate [1-3]. Flashover of any insulator strings caused by the icing disaster in the local region may lead to the shut up of power supplying of local power grids. So the service security of whole power grids may be challenged by the iced insulators.

As is believed by domestic and foreign scholars, flashover of iced insulators is similar to the discharge of polluted insulators because icing of insulators is a kind of special pollution [3], and development of leakage current is main factor for the flashover of iced insulators. So the experimental research for the leakage current characteristics of iced insulators can contribute to the mechanism analysis of iced insulators flashover, the establishment of numerical analysis model for iced insulators flashover, and the determination of characteristic parameters for online monitoring of insulators [4-10].

Experiment and operation experience analysis show that most icing flashover of insulator strings of the transmission line results from the pollution on insulators before icing. Based on the experiment, combined with the development law for discharge of insulator strings, the frequency and phase characteristics of leakage current in different icing and pollution, the phase (θ) between the first harmonic of leakage current and operated voltage, the relationship between the waveform distortion of leakage current and the total harmonic distortion (*THD*) are studied. And it is proposed that *THD* and θ can be used to predict the flashover.

II. DISCHARGE MECHANISM OF ICED INSULATOR STRINGS

A. *Icing Flashover Mechanism of Insulator string*

In the process of ice-melting, water films with the characteristic of conductivity will form on the surface of insulators. And the discharge of iced insulators is caused by the leakage current. According to the conclusion in the bibliography [11,12], the discharge of iced insulator string in the arc development of flashover can be simplified as the series circuit composed of arc and residential ice layer. The whole discharge processes can be divided into corona discharge stage with no local arc, intermittent pulse discharge stage with initial bluish violet or pink arc, and the stage with white arc [13]. So the leakage current can be divided into fundamental current, corona streamer current, white arc current and flashover current. The whole discharge process of insulator flashover is affected from insulator string, applied voltage, icing and pollution severity. The possibility of flashover increases with the increase of leakage current, while the leakage current is determined

Supported by The National Basic Research Program of China (*973 Program*) (2009CB724502)

by the electrical conductivity of ice layer on the surface of insulator. Based on the iced insulator string model and discharge mechanism, the relationship between applied voltage and leakage current on the insulators can be described as:

$$U = AxI^{-n} + (R_{arc} + L_{arc})I + \frac{R_{ice} \cdot I}{1 + j\omega C \cdot R_{ice}} \tag{1}$$

Where, U is applied voltage in kV; A is arc coefficient, x is arc length in cm; n is a constant related with arc current; I is insulator leakage current in mA; R_{arc} is arc resistance in Ω; L_{arc} is arc inductance in H; L is total creep distance of insulator in cm; C is capacitance between the end of arc and electrodes in F; R_{ice} is resistance of residual ice layer in Ω, $R_{ice}=r_{ice}(L-x)$; r_{ice} is resistance of residual ice layer per unit distance in Ω/cm. R_{ice} can be calculated as [11]:

$$R_{ice}(x) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L-x)}{D+2d} + \ln(\frac{D+2d}{4r_a})\right] \tag{2}$$

Where, D is insulator radius in cm; d is icing thickness in cm; r_a is root radius of arc in cm; γ_e is equivalent conductivity of residual ice layer in μS, and γ_e can be calculated as follows [12]:

$$\gamma_e = 0.0675\gamma_{20} + 2.45 \tag{3}$$

Where, γ_{20} is the icing water conductivity at 20℃in μS/cm.

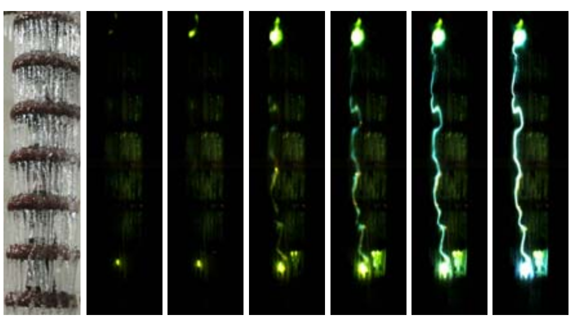


Figure 1. Icing insulator strings and its discharge processing

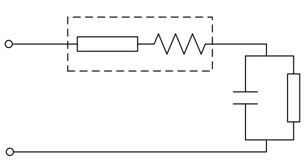


Figure 2. Equivalent circuit for insulator strings of icing flashover

It is recommended by bibliography [11] that ISP (Icing Stress Product) can be utilized as a character parameter of icing flashover for insulators. ISP is expressed as:

$$ISP = \gamma_{20} \cdot w_0 \tag{4}$$

Where, w_0 is the ice weight per unit distance of insulator string.

Based on the equation (4), it can be seen that the flashover of iced insulator is determined by the icing and pollution severity. The pollution severity can be characterized by the conductivity γ_{20} of icing water at 20 ℃. The icing severity can be characterized by the ice weight per unit distance of insulator string.

B. The analysis model of leakage current on the insulator surfaces

The change regularity for component and amplitude of leakage current can be analyzed in the process of pollution discharge. Two kinds of cases can be considered:

a. Without local arc or faint local arc

For this case, x≈0, Rarc≈0, Larc≈0, the average conductance of iced insulator can be calculated as:

$$Y = \frac{1}{R_{ice}} - j\omega C \tag{4}$$

In this case, the leakage currents are capacitive, the capacitive component of leakage current decreases and resistive component increases with the increasing of icing severity.

b. With local arc on the surface of insulator

Iced insulator string can be equivalent to the parallel circuit of resistance for residual ice layer (R_{ice}) and capacitance (C), arc inductance (L_{arc}) and arc resistance R_{arc}). The circuit equation can be expressed as:

$$U = I\left(R_{arc} + j\omega L_{arc} + \frac{1}{1/R_{ice} + 1/j\omega C}\right) \tag{5}$$

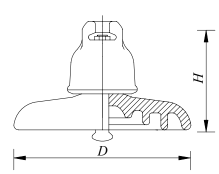
It can be seen from (5) that, the main component of leakage current is resistive, and lesser component of leakage current is inductive.

III. EXPERIMENT VERIFICATION OF LEAKAGE CURRENT ANALYSIS MODEL

A. Condition of the leakage current measurement experiment

Technical parameters of the tested insulator is shown in Tab.1

TABLE I. MAIN DIMENSIONS, PARAMETERS AND CONFIGURATION OF IEC STANDARD SUSPENSION INSULATOR

Main Dimensions and Parameters	Configuration
Diameter(D)= 305 mm	
Height(H)=255 mm	
Leakage distance=305 mm	
Rated Failing Load=160 kN	

The test circuit of the flashover test is shown in Figure 3. In the circuit, T is a voltage regulator; B is the 500-kV testing transformer; and are protective resistors; H is a 330-kV wall bushing; K is the artificial climate chamber; S is the tested insulator string; F is a voltage divider; and are the resistors of a current divider, and OSC is a TDS5052B digital oscilloscope,of which the two channels can be used to display and measure the voltage wave acquired from the low-volt arm of the voltagedivider and the leakage current wave acquired from the currentdivider.

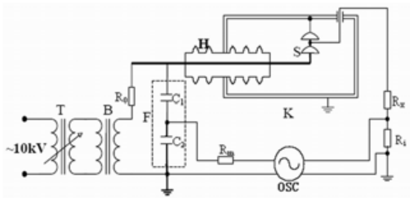


Figure 3. Test circuit of the flashover test of the ice-covered insulator string

The experimental investigations were carried out in the multi-function artificial climate chamber with a diameter of 7.8 m and a height of 11.6 m. The minimum temperature in the chamber can be adjusted to -45℃, and the wind velocity can be adjusted to 0-12m/s [14-19].

The polluted insulator string of 7 units was hung up in the artificial climate chamber about 5 h after the ice severity was controlled well. Then a prepared ac voltage with the frequency of 50 Hz was applied to the insulator string. At the same time the LC and test voltage were sampled at a rate of 2 Ms/s, and the sampling length was 0.2 s. Then the LC and test voltage signal were transferred to a data buffer and stored. The data acquisition system mainly consisted of potential dividers, a TDS5052B digital oscilloscope, and a computer.

In order to make every test results comparable, insulator strings used for icing are all laid out in the same way every time. Temperature, wind speed, drop size and other conditions in artificial climate chamber are controlled strictly.

As the Salty substances is soluble in water easily in icing and melting period, insulator string is iced by Icing-Water-Conductivity Method (IWCM) which is recommended by IEEE Std. 1783TM-2009. And the icing water conductivity (γ_{20}) is taken 100μS/cm, 300μS/cm, 450μS/cm, and 1000μS/cm respectively.

Due to the weight of ice on insulator string is proportional to average thickness office on the monitoring copper, so icing severity can be reflected by the ice thickness of the monitoring copper [20-22]. A monitoring copper with 28 mm in diameter and 1 r/min in rotating speed is set on the head, waist, and the end of the insulator string. To simulate the actual operation of the power transmission lines, the ice thickness on the three monitoring coppers and there average value is measured after icing procedure. Then the temperature of the artificial room is elevated to melt the ice. Applied constant voltage is added to the tested insulator string in 5 seconds when the ice on the insulator is humid and water-dropping. The applying of voltage to the insulator string and the recording of leakage are done at the same time. So the recorded leakage current is the leakage current of the controlled ice thickness of the monitoring copper. The experiment procedure is shot by the High Speed Camera System of HG-100K, and the appearing time of violet and white arc is recorded.

B. Relation between the Discharge development and leakage phase character

It is supposed that the phase difference between leakage current and applied voltage for insulator string is θ. Experiment result shows that leakage current wave form distort during the test process. And θ could be expressed by the time delay Δt (mS) between fundamental component of leakage currents and the applied voltage:

$$\theta = \frac{\Delta t}{T} \times 360 \tag{6}$$

Where, T is the periodic voltage time in 20 mS.

The relation between discharge development and θ is shown as in Figure 4. With the development of discharge, θ decreased. For example, When the test time of leakage currents gets 143s、239s、296s and 352s，the value of θ are 83°、53°、6°and -7.5°.

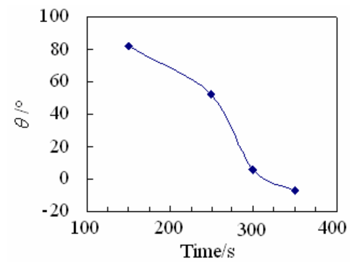


Figure 4. Relation between θ and discharge processing

(1) As the insulator did not produce local arc or local arc is faint, the average conductance of insulator surface is determined by formula (4). Resistance of residual R_{ice} ice layer is large, namely $1/R_{ice}$ is small. C is nearly the capacitance of insulator string, and ωC is larger than $1/R_{ice}$. Under the applied voltage, resistive leakage current I_R is small and capacitive leakage I_C current is large. So capacitive leakage current I_C is the main component with the θ value of 80°~90°, which names that the phase of leakage current is ahead that of applied voltage.

(2) As the local arc appear one the insulator surface, the ice layer come into further melting and water film will form on the iced insulator surface. The resistive components of leakage current increase gradually, θ decreases capacitive component do not change. When the blue white local arcs appear, the leakage current and applied voltage satisfies the formula (5). So resistive leakage current I_C is the main component and smaller component of inductive leakage current with the θ value of -7.5°. With the development of local arc, influences of arc inductance increase.

It can be seen from the upward analysis that θ can be defined as one of character parameters to judge whether partial arcs appear on the icing insulator.

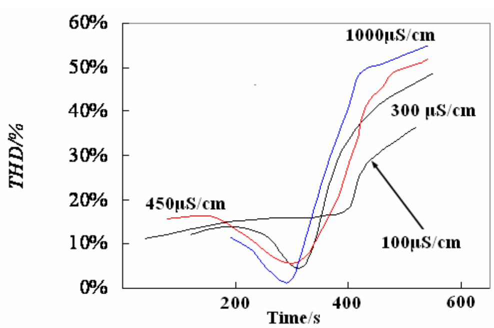
C. Relationship between leakage current frequency character and the discharge development of arc on iced insulator surface

The information for discharge of iced insulators can be characterized by the frequency spectrum of distorted leakage current with different frequency components. The frequency scope of leakage current is smaller than 1 kHz [9, 10]. The total harmonic content (*HD*), total distortion (*THD*) can be expressed as:

$$\begin{cases} HD = \sqrt{\sum_{n=2}^{\infty} I_n^2} \\ THD = HD / I_1 \end{cases} \quad (5)$$

Where, In is nth harmonic components of leakage current, because the frequency range of leakage current is generally less than 1kHZ, so n=2,3,4…19. And *i* is odd harmonic sequence, *i*=3,5…19.

In the test, the leakage current is stored in the compute in different IWC and icing severity. Then the *THD* of leakage current is analyzed by FFT. The relationship between *THD* and the discharge development in different icing severity is shown as in Figure 5.



(The average thickness of ice on monitoring copper is 15mm)

Figure 5. Figure 3 Relationship between THD and discharge processing

(1) As the insulator did not produce local arc or local arc is faint, *THD* in different conductivity of ice is approximately 10%. The relationship between *THD* and the conductivity of ice is no obvious, and the *THD* in higher conductivity (γ_{20}=1000μS/cm) may be smaller then the in lower conductivity (γ_{20}=100μS/cm), this is due to the distortion of leakage current is mainly caused by the noise with a lot of randomness unrelated to the IWC. So the leakage current is correspondence with the no inductive component of leakage current as in formula (4). As the local arc appear one the insulator surface, the ice layer come into further melting and water film will form on the iced insulator surface. The variation tendency of *THD* for leakage current will change as a result of IWC. When γ_{20} is low (such as γ_{20}=100μS/cm), *THD* gradually increases with the development of discharge development, no minimum value exits. When γ_{20} is large, *THD* decreases with the development of discharge processing, finally achieve the minimum value, the larger the conductivity, the sooner time it costs. For instance, when γ_{20} is 300μS/cm, the time it reaches the minimum value is 332s, when γ_{20} is 450μS/cm and 1000μS/cm respectively, the time is 306s and 286 s.

With the emergence of the white arc, the leakage current increase sharply in different IWC. However, *THD* have a different variation tendency in different IWC, when γ_{20} is 100μS/cm, the maximum value of *THD* is about 35%, when γ_{20} take the value of 300μS/cm and 1000μS/cm, the maximum value of *THD* is more than 56%, which is caused by crystal tomography effect. Based on the equation (6) and (7), it can be deduced that the resistance of residual ice layer is an increasing function of ice thickness for the very small value of arc root radius. So leakage current increases with the IWC and ice thickness. As the conductivity of ice layer increases, the residual ice resistance decreased, resulting in increasing of the leakage current magnitude and further leading to the aggravation of discharge. As the distortion of leakage current is caused by the local arc discharges on the surface of insulator. While conductivity increases, discharge is more significant, causing more serious leakage current distortion and larger *THD*. Experimental research show that when *THD* is more than the intensive of surface arc on insulator, the discharge duration is longer, may be resulting in flashover.

The previous analysis shows that the state of the insulator surface can be judged by monitoring *THD* of the insulator surface. As the conductivity of ice is small, *THD* increase slowly with the development of discharge development, in this case, no extreme values exist. As the conductivity of ice is large, there is exists a minimum value of *THD* with the development of discharge. It is supposed that ice thickness d=5mm, and γ_{20} are 100μS/cm, 300μS/cm, 450μS/cm and 1000μS/cm respectively, THD_{min} are 5%, 6% and 2%, then white arc discharge appeals on the insulator surface.

IV. LEAKAGE CURRENT CHARACTER PARAMETERS OF FREQUENCY AND PHASE FOR EARLY WARNING OF ICING FLASHOVER

The development of leakage current in iced insulator flashover can be divided in to the period of safety, forecasting and danger. As the iced insulator flashover is similar to the polluted insulator, the pre-warning for flashover of iced insulator can be realized in safety period by leakage current. And it can give operation department enough time to take action.

This studies show that when θ near 0 and *THD* in minimum point, there be white arc discharge on the insulator surface, while the leakage development is in the period of safety. So θ and *THD* can be utilized as phase and frequency character parameter to monitoring the icing development state of the insulator string. This iced insulator flashover pre-warning can be divided into two steps: (1) Monitoring leakage current phase characteristic θ, when θ nears 0, it shows faint local electric arc on insulator surfaces. (2) Monitoring leakage current frequency characteristic *THD*, when θ closes to 0, if θ is closing to 0 and there is no minimum value of *THD*, it shows insulator icing is not serious and arc development is still in the security zone, namely insulator may be in safe operation. If there is minimum value of *THD*, it indicates that white arc discharge on local surface of iced insulator may probably develop to flashover.

V. Conclusions

(1) Phase difference θ between Leakage current and applied voltage decreases with the discharge development of arc. When the insulator did not produce local arc or local arc is faint, the phase of leakage current is ahead of that of applied voltage. When white arcs appear on the insulator surface, the phase of leakage current is lag behind of applied voltage.

(2) When IWC is low, *THD* increases slowly with the development of discharge, and there is no minimum value. When IWC is large, *THD* decreases and then increases with the development of discharge. So there is minimum value of *THD*. The larger of IWC, the earlier *THD* achieve minimum value. When *THD* achieves THD_{min}, white arc begin to appear on the iced insulator surface.

(3) The phase difference (θ) between the leakage current and applied voltage and frequency character parameter (THD_{min}) in safety period can be utilized to the pre-warning of iced insulator flashover.

Acknowledgment

This work was supported by National Basic Research Program of China (973 Program: 2009CB724501).

References

[1] Jiang Xingliang, Yi Hui, Icing and Its Protection for Transmission Line. China Electric Power Press, Beijing, 2002.6-8.

[2] Jiang Xingliang, Shu Lichun, Sun Caixin. Insulation of pollution and Icing for Power System. China Electric Power Press, Beijing, 2009.

[3] Sun Caixin, SiMa Wenxia, Shu Lichun, Atmospheric environment and electrical outer insulation. China Electric Power Press, Beijing, 2002.

[4] M. Hara and C.L. Phan, “A study of the leakage current of H.V. insulators under glaze and rime”, Canadian. Electr. Eng. J., Vol. 3, pp.84-91, 1978.

[5] Yong Liu and B.X.Du, “Recurrent Plot Analysis of Leakage Current on Flashover Performance of Rime-iced Composite Insulator”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.17, No.2, pp.465-472.2010.

[6] C.Volat, F. Meghnefi, M. Farzaneh and H. Ezzaidi, “Monitoring Leakage Current of Ice-covered Station Post Insulators using Artificial Neural Networks”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.17, No.2, pp.443-450.2010.

[7] M.Hara and C.L.Phan, “Leakage Current and Flashover Performance of Iced Insulators”, IEEE Trans. Power Apparatus Syst., Vol. 98, pp. 849-859, 1979.

[8] C. Volat, F. Meghnefi, and M. Farzaneh, “Analysis of Leakage Current of an Ice-Covered Insulator during Ice Accretion”, Proceeding of the IEEE PES Transmission and Distribution Conference, Dallas, USA, pp. 485-490, 2006.

[9] F. Meghnefi, C.Volat and M. Farzaneh, “Temporal and Frequency Study of the Evolution of the Waveform of the Leakage Current of the Ice-Covered Insulators”, 11th Intern. Workshop on Atmospheric Icing of Structures (IWAIS), Montreal, QC, Canada, paper IW36, pp. 1-6, 2005.

[10] F. Meghnefi, C.Volat and M.Farzaneh, “Temporal and Frequency Analysis of the Leakage Current of a Station Post Insulator During Ice Accretion”, IEEE Trans. Dielectr. Electr. Insul., Special Issue on Ice-Covered Insulators, Vol. 14, pp. 1381-1389, 2007.

[11] M. Farzaneh and W.A. Chisholm, Atmospheric Icing of Power Networks [M], Springer, pp 269-325, 2008.

[12] C.Tavakoli, M.Farzaneh, I.Fofana, “Dynamics and Modeling of AC Arc on Surface of Ice”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.13, No.6, pp.1278-1285.2006.

[13] Cai Wei, Yu Tao, Liu Yunpeng, et al, Icing Flashover Leakage Current of Long Insulator Strings in 500kV Transmission Line[J]. High Voltage Engineering, 2009,vol.35,No.10,2535~2539.

[14] Jianlin Hu, Caixin Sun, Xingliang Jiang, Zhijin Zhang and Lichun Shu, “Flashover Performance of Pre-contaminated and Ice-covered Composite Insulators to be Used in 1000 kV UHV AC Transmission Lines”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.14, No.6, pp.1347-1356.2007.

[15] Xingliang Jiang, Shaohua Wang, Zhijin Zhang, Shujiao Xie, Yan Wang, “Study on AC Flashover Performance and Discharge Process of Polluted and Iced IEC Standard Suspension Insulator String”, IEEE Transactions on Power Delivery, Vol.22, No.1, pp.472-479.2007

[16] IEEE Standard Techniques for High-Voltage Testing, IEEE Std.4-1995, Mar. 1995.

[17] IEEE Guide for Test Methods and Procedures to Evaluate the Electrical Performance of Insulators in Freezing Conditions, IEEE Std. 1783™-2009

[18] High Voltage Test Techniques, IEC Intern. Std. IEC 60-1, Nov., 1989.

[19] Artificial Pollution Test for Insulators Used for dc Systems, IEC Tech. Rep. 1245, 1993.

[20] M. Farazaneh and J.Kiernicki, “Flashover Problems Caused by Ice Build-up on Insulators,” IEEE Elect. Insul. Mag., vol.11, no.2, pp.5-17, Mar. /Apr. 1995.

[21] M. Farzaneh and W. Chisholm, “Insulator icing test methods, selection criteria and mitigation alternatives,” IEEE Trans. Dielect. Elect. Insul., Vol. 14, No. 6, pp. 1462–1473, Dec. 2007.

[22] W. Chisholm, J. Kuffel, and M. Farzaneh, “The Icing Stress Product: A Measure for Testing and Design of Outdoor Insulators in Freezing Conditions,” Proc. 2nd Intern. Workshop on High Voltage Eng., Tottori, Japan, pp.95-109, 1997.