Assessment of the External Insulation Performance of Post Insulator in Rain: A Review

Xin Qiao
School of Electrical and Electronic Engineering, Harbin University of Science and Technology, Harbin, China.
qiaoxin@hrbust.edu.cn

Abstract. In recent years, the surface discharge of polluted post insulators in rain which affects HVDC transmission has brought great influence to the national economy and people's daily life. In order to improve the strength of the external insulation of HVDC converter stations, this paper mainly focus on the environmental characteristics and areal rainfall of UHV power stations, analyzes the influence of experimental factors (sample treatment mode, rain-drenching mode, pressurization mode and insulation material) on the discharge behavior of post insulators in rain flash experiment, summarizes the relevant standards in the rain flash experiment of large-scals post insulators. The results showed that the effects of different contamination methods on rain flashover are not different, among which spraying method can improve the experimental efficiency, and the quantitative brushing method can reach the specified ash density and salt density more easily; The number and length of water column of composite insulators are lower than that of porcelain insulators, and the number of water droplets between large sheds and the number of water droplets on the edge of large sheds are higher than that of porcelain insulators.

1. Introduction
Post insulators play a role in supporting electrical equipment and electrical insulation in substations and converter stations. With the diversification of power grid operation modes and the improvement of voltage levels, the amount and size of post insulators have also increased significantly. In recent years, due to the changeable environment, more research has focused on the external insulation of the line, that is, the suspension insulator, thus ignoring the significance of the performance of the post insulator for the safe operation of the power station. Especially in rainy weather, it is not uncommon to report accidents caused by surface discharge or flashover of post insulators or bushings. However, the relevant experimental standards can no longer meet the needs of research and engineering design in this case.

Up to now, although the existing insulator test standards have explained the insulator flashover test methods under rain conditions, including suggestions on parameters such as rain amount and rain conductivity. However, the actual research needs are not always met. First, the main reason is that the existing standards are mainly aimed at suspension insulators, and there is no special provision for post insulators. In addition, the existing standards only give some suggestions on the selection of some parameters in the rain test, but do not explain the test layout and actual operation procedures in detail; Second, there are not many test parameters involved in the existing standards, and there are no
suggestions for some factors that may affect the development of the release point and the test conclusion, such as the angle of rain and the size of water droplets.

It can be seen from the published studies that there are some differences in the experimental methods adopted by different researchers. At home and abroad, some studies have been carried out on the characteristics of pollution flashover (after the surface is contaminated, it is put into a fog chamber for fog tolerance test) and rain flashover (the contaminated surface is drenched with clean rain or the clean surface is drenched with rain with certain conductivity).

The early research mainly focused on the influence of umbrella-shaped structure of post insulators on DC pollution characteristics. In recent years, some researchers carried out the research on artificial rain test method and electric field distribution characteristics of post insulators in the early stage [1-8]. The research results obtained the influence laws of umbrella skirt structure and parameters, environmental factors and pollution factors on the rain flash characteristics of large-diameter composite post insulators.

To sum up, in order to update and improve the current insulator test standards and meet the needs of actual engineering operation and maintenance, it is necessary to study the external insulation performance of post insulators under rainfall conditions. Especially for large-size samples, it is of positive significance to explain the mechanism of contaminated surface discharge and the essential difference between polluted rain flash and polluted flash. This paper mainly introduces the conclusions of a series of related research work in recent years, which is believed to have positive guiding significance for future research and engineering design, operation and maintenance.

2. Investigation on the Geographical Location, Environmental Characteristics and Rainfall of UHV/UHV Power Stations in Guangdong

Guangdong is located in the coastal area of southern China, with high topography in northeast and low topography in southwest. The landform belongs to hilly and mountainous areas in the north, basins in the middle and coastal alluvial plains in the south. The climate belongs to subtropical monsoon climate, with abundant rainfall and concentrated in summer. The average annual precipitation in most areas is 1500-2000mm [9-10]. According to the geographical location of 38 rainfall stations in the Pearl River Basin and the daily rainfall data from 1959 to 2012, the spatial distribution of rainfall with daily rainfall exceeding 95% and 99% percentile is analyzed, as shown in the figure.

![Figure 1. Spatial Distribution of Rainfall in South China](image)

According to the spatial distribution map of rainfall in Guangdong Province, it can be seen that extreme precipitation is mainly distributed in the Pearl River Delta region in the southeast. Therefore, Guangzhou, which is located in the center of the Pearl River Delta region, is selected to count the rainfall frequency and rainfall in different months from 2015 to 2017, and a statistical chart is drawn according to the original data, as shown in the figure.
Figure 2. Time Distribution of Rainfall Intensity in Guangzhou

It can be seen from the figure that rainfall in Guangzhou is concentrated from April to September. The most common rainfall is 2-4mm/min, the rainfall is more than 8mm/min and the most frequent months are concentrated in July and August. The highest probability of rainfall occurs at 2-6mm/min, and the torrential rain above 10mm/min also accounts for a certain proportion, so it is necessary to comprehensively consider extreme rainfall and the most frequent rainfall.

China Southern Power Grid has provided us with insulation faults of converter stations of major DC projects within the jurisdiction of China Southern Power Grid from 2005 to 2015, among which there are 6 UHV/UHV power stations with accident reports, which are mainly located in areas with more rainfall in South China. Zhaoqing Converter Station and Dongfang Converter Station are selected for analysis, and their geographical environment characteristics are shown in the following figure:

Figure 3. A Topographic map of Zhaoqing converter station, B Topographic map of Dongfang Converter Station

The geographical environment of Zhaoqing Converter Station is similar to that of Guangzhou Converter Station and Suidong Converter Station. Most of them are located in flat areas such as plains or foothills, and rivers pass by and many lakes are distributed around them. There are also some power stations, such as Congxi Converter Station and Qiaoxiang Converter Station. Their geographical environment is similar to that of Dongfang Converter Station, which is located halfway up the mountain and surrounded by many lakes and reservoirs. The air humidity around these power stations is high. Especially in some places close to industrial areas, there is much floating dust in the air, which is easy to cause flashover accidents.
3. Investigation and Analysis of Rain Flash Accident of Post Insulator in Power Station

The main causes of flashover of external insulation equipment are pollution, fog and rain. However, due to the limitation of test conditions and operation difficulty, the current research work involves much less pollution flashover test in rain than in fog, but accidents in rain are common. Next, several domestic accidents are introduced, such as: in April 2012, the rain flash on the bushing of No.1 main transformer in 500kV substation of Guangxi Power Grid caused the umbrella skirt at the bottom of the bushing to be burned [11]; in June 2015, the high-voltage side bushing of No.500 KV2 main transformer in 500kV Heping substation of Yunnan Power Grid caused electric shock flashover due to rain flash, resulting in phase B single-phase short circuit.

By the end of 1997, 52 AC 500Kv power stations and 26 AC 300Kv substations had been built and put into use in China. According to incomplete statistics, 13 AC 300Kv substation facilities have flashover, 39 times in total, and rain flashover caused by rainfall accounts for 82.1% of the total flashover. There are 9 AC 500Kv substation facilities flashing for 25 times, and rain flashes caused by rainfall account for 96% of the total. There are 20 flashovers in DC ±500kV converter station. Rain flashes caused by rainfall account for 60% of the total.

From accident, the creepage ratio of most equipment with rain flash accidents can meet the local pollution level requirements, and also meet the technical requirements of IEC and relevant national standards, which further shows that the traditional insulator selection does not fully consider the rain flash of equipment. At present, there are some researches on the rain flashover characteristics of external insulation of electrical equipment at home and abroad, but most of the research objects are focused on bushings, and there are few researches on the rain flashover characteristics of composite post insulators in HVDC. Based on the urgent needs of engineering construction and production operation, it is necessary to systematically study the rain flash characteristics of UHV large diameter post insulators.

4. Experimental Method of Rain Flash for Large-Size Post Insulators

4.1. Parameter Requirements of Experimental Equipment

The parameters of the test samples are based on the composite post insulators of Yunnan-Guangzhou UHVDC Inverter Station, and the test samples are designed and tested. See Table 1 for the parameters.

| Sample No. | Rod diameter /mm | Umbrella extension /mm | Height of structure /mm | Creep distance /mm | Arc distance /mm |
|------------|------------------|------------------------|------------------------|-------------------|------------------|
| A          | 20               | 115/83                 | 400                    | 590               | 200              |
| Sample No. | Umbrella spacing /mm | Umbrella extension /mm | Height of structure /mm | Dry arc distance /mm |
| B          | 70               | 71                     | 25                     | 4710              |
| C          | 80               | 80                     | 20                     | 4925              |
| D          | 72               | 70                     | 15                     | 4300              |
| Sample No. | Rod diameter /mm | Umbrella spacing /mm | Umbrella extension /mm | Creep distance /mm | Height of structure /mm |
| E          | 625              | 90                     | 105/75                 | 5930              | 1500             |
| F          | 34               | 158                    | 246/98                 | 485               | 195              |

Main laboratory equipment and parameters:
Output voltage of DC experimental power supply is ±1000kV, rated current is 2A, rated capacity is 2000kVA, voltage stability is ≤0.56%, ripple coefficient is ≤3%, voltage drop is ≤5%, and voltage overshoot is ≤8%, meeting the standards GB/T_22707-2008[12] and IEC [13-14]. Water is used to simulate rainwater, with conductivity of 157μS/cm, according to the standard GB/T775.2-2003 to adjust the rain rate.
The research introduced in this paper was completed in the UHV engineering laboratory [15-16], in which the general method of wet test of high-voltage porcelain bushing under polluted conditions, the selection and determination of polluted substances, the installation of test products and the experimental procedure [17] all meet the standard DL/T383-2010[18].

See fig. 4 for the schematic layout of the experiment, in which the sample is placed vertically at 2m×1m×On the cement base of 0.5m, the horizontal distance between insulator and rain rack is 6m, and the rain angle is 45°[19], the lead-out wire of the wall bushing is connected to the high voltage end of the insulator.

![Fig. 4 Schematic Diagram of Experimental Arrangement of Post Insulators Exposed to Rain](image)

**Fig. 4 Schematic Diagram of Experimental Arrangement of Post Insulators Exposed to Rain**

4.2. *Operation Process of Insulator Rain Flashover Test*

In this paper, the rain flashover characteristics of insulators under different pollution modes [20-21] and pressurization modes are compared. During the test, the ambient temperature in the laboratory is kept between 13 ~ 17 °C and the relative humidity is between 45 ~ 55%. The experimental procedure [22] is as follows:

- **Cleaning.** Before each contamination test, the dirt and grease on the insulator shall be cleaned and dried naturally.
- **The filth configuration.** NaCl of simulated conductive substance and kaolin of simulated inert substance should be mixed together at a ratio of 1:6, and then 0.015 mL of deionized water per square centimeter and 0.02-0.05 [mg/cm] 2 of gelatin in accordance with the standard DL/T383-2010 were added to prepare different concentrations of filthy solutions.
- **Sample pretreatment.** A layer of kaolin is coated on the surface of the sample to make a layer of hydrophilic substance attached to the insulator surface.
- **Spray method contamination:** after the contaminated solution is shaken evenly, spray the sample. Quantitative brushing method staining: smear the contaminated solution onto the surface of the sample evenly.
- **Wet the dirty layer.** The natural dry sample is placed in the fog chamber and injected with steam mist to increase the conductivity of the polluted layer to the maximum, that is, the edge will drip.
- **Increase the pressure evenly.** The samples stained by spraying method and quantitative brushing method were pressurized by uniform pressure increasing method. After 75% flashover voltage is applied during pressurization, the system is turned on for rain until it is stable, and then it rises to flashover at the rate of 2% predicted flashover voltage per second.
- **Constant pressure lifting.** The sample contaminated by spraying method is pressurized by constant pressure lifting method. When pressurizing, take the lowest voltage during flashover by the uniform boosting method as the initial voltage, turn on the system to get wet, if there is no flashover, it will pass the test, and the voltage of the next group of samples will be increased by 5%; In case of flashover, the next group will reduce the voltage by 5%. Take the average value of ten effective test voltages as the obtained flashover voltage.
5. Influence of Experimental Factors on Experimental Results

5.1. Sample Handling Method
The target salt density in the experiment is 0.066, 0.100 and 0.150 mg/cm², use spraying method and quantitative brushing method to stain the surface of sample A. After treatment, measure the salt density on the surface of the sample in two ways and compare them to make an effect comparison diagram, as shown in Figure 5.

![Figure 5. Comparison of Deviation between Measured Salt Density and Target Salt Density by Spraying Method and Quantitative Brushing Method](image)

It can be seen from Figure 5 that the deviation between spraying method and target salt density is larger than quantitative brushing method, with the deviation range of spraying method being 6%-12% and quantitative brushing method being 3%-9.9%, both of which are within the allowable range of the project, and the pollution distribution is uniform, meeting the experimental requirements.

Use sample a to measure the flashover voltage of spraying method and quantitative brushing method, as shown in figure 6.

![Figure 6. Flashover Voltage Values of Different Contamination Modes](image)

The flashover voltage value of spraying method is lower than that of quantitative brushing method. The reason may be that the deviation between the measured salt density and the target salt density of spraying method is small, and the pollution degree of insulator surface is uniform, which is less affected by human activities [22-23].
Quantitative brushing method is greatly influenced by human factors, and the experimental data are scattered. However, there are few steps in parameter measurement, and only the quality of salt and ash and the surface area of the sample need to be measured, which makes it easier to achieve consistency with the target for the specified ash density and salt density. Moreover, it is not limited by the site and climate, and can be operated by many people at the same time, which is easy to meet the requirements of different experimental environments. The pollution can be made as uniform as possible through training due to the influence of human factors in painting process.

The repeatability of the pollution process by spraying method is poor, and the pretreatment needs to wipe the surface of the sample with effort, which may damage the surface insulation material, and it is necessary to spray the pollution within 15min minutes of pretreatment, otherwise it is difficult for the pollution to adsorb the surface, the adhesion effect between the pollution and the surface of the sample is not ideal, and it is difficult for the pollution to reach the ideal distribution state. The pollution spraying device has a great influence on the experimental results, and the pressure requirement of the watering can is higher. Contaminated solution configuration is difficult to achieve the specified salt density and ash density, and there are many measurement links [24].

It takes about 90 minutes for each person to brush sample A when the manual quantitative brushing method is applied. In order to shorten the experimental period and improve the efficiency, three or more people are usually needed. When spraying dirt on the machine, one person should be assigned to prepare the dirt and one person should be assigned to stain the dirt, and it only takes about 15min to spray the sample A. It can be seen from Figure 4-1 that the deviation of spraying method is slightly larger than that of quantitative brushing method, and the contamination on the surface of the sample is evenly distributed. The manpower and time required by spraying method are obviously less than that of quantitative brushing method, so spraying method can effectively improve the experimental efficiency.

5.2. Ways of Rainfall Test

5.2.1. Electrical conductivity of rainwater. Experiments on the influence of different conductivity on flashover voltage of post insulators are carried out with samples B, C and D, and the experimental results are shown in Figure 7.

The flashover voltage of post insulators with different umbrella skirt structures decreases with the increase of rainwater conductivity, and there is no obvious difference in the decreasing range. Because different post insulators have similar sewage columns, similar bridging degree and similar pollution loss, they do not change with rainwater conductivity. The increase of rainwater conductivity is equivalent to
the increase of salt density, but has less influence than salt density, so the flashover voltage decreases with the increase of rainwater conductivity, but the amplitude is less than the increase of salt density.

5.2.2. Amount of Rain. Considering the most frequent rainfall in Guangdong Province, the influence of rainfall amount of 2, 5 and 10mm/min on the flashover voltage of post insulators was studied with the conductivity of sample B at 300μs/cm. The experimental results are shown in Figure 8.

![Figure 8](image)

**Figure 8.** Pollution Lightning Voltage and Rain Lightning Voltage of Casing Unit Insulation Height under Different Rainfall

The rain lightning pressure of flashover decreases with the increase of rainfall, and the rain lightning pressure is higher than the pollution lightning pressure when rainfall is small. Because the rainfall is small, the conductivity of polluted layer becomes larger after getting wet, which is equivalent to increasing salt density to a certain extent; With the increase of rainfall, the sewage column flowing from the edge of umbrella skirt becomes thicker and longer, and the bridge degree becomes more serious, so the rain and lightning pressure decreases.

5.2.3. Angle of Rainfall Test. Simulate the situation of wind accompanying rainfall, and use sample E to study the influence of rain angles of 0, 35, 45 and 55 on the flashover voltage of post insulators. The experimental results are shown in Figure 9.

![Figure 9](image)

**Figure 9.** Rain and Lightning Voltage of Casing Unit Insulation Height with Different Rain Angle

It can be seen from the figure that the rain angle has a great influence on the effect. The general trend is that the greater the angle is, the lower the rain lightning pressure is, and when the angle is 45, the rain lightning pressure is the lowest and 0 is the highest. Because the umbrella skirt on the upper part of the post insulator can block rainwater from flowing to the lower part at 0, most of the umbrella skirts are
still relatively dry; When the angle is 45, the rain collects on one side, and the surface of umbrella skirt is uneven, which makes it easier to have rain flash.

5.3. Pressurization Mode
The influence of uniform voltage boost method and withstand voltage rise and fall method on rain flash is compared with sample F put into the environment of different salt deposit density at 0.04, 0.08, 0.12, 0.16, 0.2mg/cm². The flashover voltage of insulators and salt density conform to the power function relationship [25-26], and the experimental results are shown in Figure 10.

Fig. 10. Rain and Lightning Pressure of Uniform Boosting Method and Constant Pressure Lifting Method Under Different Pollution Conditions

With the increase of pollution degree, the rain and lightning pressure of the two pressurization methods all decrease nonlinearly, and the change rate is similar, from rapid decrease to slow decrease, and the difference is getting greater and greater. The rain and lightning voltage of uniform boosting method is always greater than that of constant pressure lifting method.

When the voltage rises, the leakage current increases, and a dry area is formed on the insulator surface to cause local arc. The arc temperature makes the dry area on the insulator surface gradually expand. Because the boosting process is short, the dry area formed by local arc can no longer be wetted in time, which makes the insulator surface wetted unevenly, resulting in relatively high flashover voltage of insulator [27].

Constant voltage rising and falling method makes insulators wet gradually under the condition of constant voltage. Because the test period is long, the dry area formed by local arc may be re-wetted, and the wetted surface may also form a dry area. After this process is repeated, the insulator surface gradually reaches saturation and wetting, and its wetting is relatively uniform, so the insulator flashover voltage is relatively low [27].

6. Influence of Insulator Material on Rain Flash Along Surface Discharge
Porcelain and composite post insulators with similar parameters are selected to study the influence of materials on rain flash. The parameters are shown in Table 2.

Table 2. Parameters of Porcelain and Composite Post Insulators

| Sample No. | Umbrella spacing /mm | Umbrella extension /mm | Creep distance /mm | Insulation height /mm |
|------------|----------------------|------------------------|-------------------|-----------------------|
| G (porcelain) | 80/38 | 64/46 | 3295 | 1020 |
| H (compound) | 79/39 | 67/51 | 3235 | 1010 |
| I (porcelain) | 76/38 | 90/70 | 6400 | 1400 |
| J (compound) | 80/40 | 80/60 | 7215 | 1800 |
Samples G and H were exposed to rain at a rate of 2mm/min and an angle of 45°. Rainwater conductivity is 300μs/cm. And the salt density is 0.03, 0.05 and 0.08 mg/cm². Experiments were conducted separately, and the experimental results are shown in Figure 11.

![Figure 11. Rain and Lightning Voltage of Porcelain and Composite Post Insulators](image)

The lightning voltage per unit insulation height of porcelain post insulators is lower than that of composite post insulators, and the difference is smaller with the increase of salt density.

Use tap water to simulate rainwater, and select samples I and J at a rain angle of 45°, the conductivity is 157μs/cm. The number of water drops on the edge of the insulator umbrella, the number of water drops between the insulator umbrella, the number of water columns and the length of the insulator umbrella were taken as the characteristic parameters of the support insulator's rain performance [28], and the experimental results are shown in Figure 12.

![Figure 12. Characterization Parameters of Porcelain and Composite Post Insulators](image)
The number of water droplets between large umbrellas and the edge of large umbrellas made of silicone rubber is higher than that of porcelain insulators, while the number and length of water columns at the edge of large umbrellas are lower than that of porcelain insulators.

Ceramic and silicone rubber materials exert slight influence on the shape of water droplets. The rain areas of the two insulators are similar, so it can be considered that the difference of rain characteristics is basically caused by materials. The hydrophilicity and hydrophobicity of ceramics and composite materials are different. Because ceramics are mainly inorganic and composite materials are mainly organic, the surface of porcelain insulator is slightly hydrophilic and composite insulator is slightly hydrophobic.

The hydrophobicity of composite materials makes rainwater fall on the surface and converge into water flow, which is thinner and distributed more dispersedly and randomly. Therefore, when the umbrella skirt drips, it cannot get subsequent water supplement, which makes it easier to break. The number and length of water column between composite insulators will be smaller than that of porcelain insulators, which greatly increases the utilization rate of creepage and reduces the probability of arc bridging umbrella skirt and rain flash.

Under the condition of simulated rainfall and pollution, more salt or ash will be taken away by raindrops due to the hydrophilicity of ceramics, which is equivalent to increasing the gray scale and salinity. Therefore, the electrical conductivity becomes stronger, and the voltage of rain and lightning will decrease.

The above analysis is consistent with the experimental conclusion, that is, the rain and lightning voltage of porcelain insulator is about 5% lower than that of composite material. Therefore, in areas with heavy rainfall, composite post insulators can be considered for new converter stations and substations. If porcelain post insulators are used in existing transmission projects, certain measures must be taken to prevent rain flash accidents, such as coating RTV on the surface of porcelain post insulators to enhance their surface hydrophobicity.

In this paper, according to the related research results of rain flashover of large-size post insulators, the test layout and practical operation procedures in the process of artificial rain flashover test are described in detail, and some related suggestions are put forward for some parameters and standards in the test process. The effects of pollution mode, rain condition, pressure mode and material on the rain flashover characteristics of post insulators are analyzed, and the differences between them are compared and analyzed, and some practical solutions are put forward. The main conclusions are as follows:

1. The staining methods of samples under heavy rainfall were studied, and the quantitative brushing method and spraying method were compared. The experimental results show that there is little deviation between the two methods. The spraying method is repeatable for the same experimenter and reproducible for different experimenters. The manpower and staining time required are obviously less than those of the quantitative brushing method, which can improve the experimental efficiency. Quantitative brushing method is easier to achieve the target salt density designed by experiment.

2. The composite post insulator is tested by simulating different rain environments. It is concluded that the rain lightning voltage of post insulator decreases with the increase of rain conductivity and has nothing to do with umbrella skirt structure. The rain lightning voltage of post insulator decreases with the increase of rain amount, and the rain lightning voltage is higher than the pollution lightning voltage when rainfall is small, and the rain lightning voltage decreases with the increase of rain angle.

3. The effects of uniform boosting method and constant voltage lifting method on the rain flash characteristics of composite post insulators are studied. The experimental results show that with the increase of salt density, the difference of flashover voltage curves between the two pressurization methods becomes larger, and the flashover voltage of the uniform boosting method is higher than that of the constant voltage lifting method. According to the experimental data, the reasons for this result are analyzed, which are mainly due to the difference of moisture uniformity.

4. After comparing the differences of rain characteristics of different post insulators, it is concluded that when the umbrella skirt parameters are similar and the rain rate is the same, the water column number and length of large umbrella of composite post insulator are obviously lower than those of...
porcelain post insulator, while the water drop number between large umbrellas and the water drop number at the edge of large umbrella are higher than those of porcelain post insulator. When studying the influence on rain lightning voltage, it is concluded that the rain lightning voltage per unit insulation height of porcelain post insulators is lower than that of composite post insulators, and the difference becomes smaller with the increase of salt density. Combined with the above conclusions, this paper analyzes the reasons for the influence of materials on the rain characteristics of post insulators, and puts forward that RTV can be coated on the surface of porcelain post insulators to prevent rain flash accidents.

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