Research status of the external insulation pollution flashover of high voltage transmission line

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Abstract. In recent years, China's electric power industry has made great progress, especially the achievements of ultra high voltage and ultra high voltage power transmission and transformation technology have attracted worldwide attention. At present, China has put into operation power transmission projects such as ±660kV yin-East DC extra-high voltage, ±800kV upward, Yunnan-Guangzhou DC extra-high voltage and 1000kV Dongnan Jindong-Jingmen AC extra-high voltage. These long-distance and large-capacity power transmission projects provide strong technical support for the realization of the national strategic goal of "west power transmission to the east and North power transmission to the south". With the rapid industrialization and environmental deterioration, various industrial and natural pollutions deposited on the insulators of high-voltage transmission lines are becoming increasingly serious. In severe weather, such as fog, dew, drizzle and snowmelt, the external insulation strength will be greatly reduced. Therefore, it is very important and necessary to thoroughly study the pollution flashing of uHV and UHV insulators and comprehensively consider the influence of China's complex geographical environment on their external insulation characteristics, which is one of the key issues related to the safe and stable operation of power grid.

Keywords: high voltage transmission line; external insulation; insulator; Surface contamination flashover.

1. Introduction
In recent years, China's electric power industry has made great progress, especially the achievements of ultra high voltage and ultra high voltage power transmission and transformation technology have attracted worldwide attention. At present, China has put into operation power transmission projects such as ±660kV yin-East DC extra-high voltage, ±800kV upward, Yunnan-Guangzhou DC extra-high voltage and 1000kV Dongnan Jindong-Jingmen AC extra-high voltage. These long-distance and large-capacity power transmission projects provide strong technical support for the realization of the national strategic goal of "west power transmission to the east and North power transmission to the south".
However, with the rapid industrialization and environmental deterioration, various industrial and natural pollutions deposited on the insulators of high-voltage transmission lines are becoming increasingly serious. In severe weather, such as fog, dew, drizzle and snowmelt, the external insulation strength will be greatly reduced [1]. At this point, the polluted insulator will discharge along surface flashover under the action of overvoltage or even operating voltage, which is called pollution flashover [2]. It is generally believed that the external insulation level of ultra-high voltage and ultra-high voltage line insulators mainly depends on their pollution tolerance level [3]. The pollution lightning voltage of insulators used in power systems is significantly lower than the operating voltage of the power grid, which is the core factor restricting the external insulation of power systems and also a major technical bottleneck for the current development of ultra-high voltage and ultra-high voltage power transmission and transformation technologies. According to relevant data statistics, the accidents caused by pollution flashover account for the second place in the total accidents of power grid operation, second only to lightning accidents, but the losses caused by them are 10 times of those caused by lightning [4]. In the winter of 2001, the rain, snow and fog in north China and northeast China resulted in 238 transmission lines ranging from 66 kv to 500kV and 34 substations successively [5]. In the winter of 2006, heavy fog in Shandong, Hebei and some areas of Beijing and Tianjin caused 7 flashover of 500kV lines [6]. Since November 2010, the ±660kV Silver-East DC transmission line has been put into operation for 5 times due to pollution flashover, resulting in its forced downvoltage operation, which has caused huge economic losses [7]. Therefore, it is very important and necessary to thoroughly study the pollution flashing of uHV and UHV insulators and comprehensively consider the influence of China's complex geographical environment on their external insulation characteristics, which is one of the key issues related to the safe and stable operation of power grid.

2. Pollution flashover model

Surface pollution flashover of insulators is a complex phenomenon involving electrical, thermal and chemical change processes. It involves knowledge of multiple disciplines such as high voltage and insulation technology, surface science and material science, etc. It is an interdisciplinary problem and has high research difficulty. At present, there is no clear conclusion on the development process and mechanism of insulator pollution flashover at home and abroad. Most researchers believe that the development of insulator pollution flashover must go through four stages: pollution deposition -- wetting -- formation of dry zone and local arc -- development of local arc to flashover. The key to study the mechanism of pollution flashover is to study the process of local arc extension to flashover. At present, a large number of researches have been carried out both at home and abroad. Representative opinions mainly include the following aspects:

(1) Flat plate model: German scholar Obenaus first proposed a model for quantitative analysis of pollution flashover process in 1958 [8], namely a series model of local arc and residual pollution layer.

The mathematical expression of Obenaus model is:

$$U = AXI - n + R(x)I$$  \( (1) \)

Where, \( U \) is the external applied voltage at both ends of the insulator; \( X \) is the local arc length; \( I \) is arc current or leakage current; \( R(x) \) is the residual fouling resistance; \( A \) and \( n \) are arc characteristic constants. It can be seen from Equation (1) that the local arc has the volt-ampere characteristic of falling, while the pollution layer resistance has the volt-ampere characteristic of rising. Therefore, the relationship between voltage \( U \) and current \( I \) will be a "U" shaped curve, and there must be a minimum \( U_{\text{min}} \) to maintain the critical arc.

Obenaus model in mathematics for the first time when flashing must satisfy the conditions of voltage, but is derived on the basis of the model of critical flashover voltage is only part of the pollution flashover occurred necessary conditions rather than sufficient conditions, means that flashing occurs inevitably meet critical flashover voltage of the model are given, but meet this condition pollution flashover voltage may not occur, the reason for this is that Obenaus model is a static model, in the process of derivation and arc does not take into account in the development of the fouling layer surface.
(2) Energy Model: Hampton, through an interesting water column experiment, proposed that local arc extension and completion of flashover is a problem of energy stability. When arc root is replaced by arc in the direction of arc development, the current increases and the local arc is in the form of development extension. He believed that flashover would occur when the voltage gradient $E_a$ of the local arc is less than the voltage gradient $E_p$ of the fouling resistance. Therefore, Hampton's conditional criterion for the development of local arc into flashover is [9]:

$$\begin{align*}
E_a &< E_p \\
\frac{dI}{dx} &> 0
\end{align*}$$

(2)

Where: $I$ is the arc current; $X$ is the arc length.

Hesketh later also made a consistent discriminant with Hampton, and proved that Hampton's two conditional criteria were equivalent through mathematical methods [10]. Wilkins put forward the criterion for arc development from the perspective of energy as $\frac{dI}{dx} > 0$ or $\frac{dP}{dx} > 0$ ($P$ is the energy obtained by the arc from the source and $x$ is the arc length). Neither Hampton nor Wilkins, however, can explain the physical nature of arc extension.

(3) A widely accepted explanation is that the arc is pulled by external forces during its development. Jolly think local arc in the process of extending along the fouling layer surface mainly by electrostatic force, electromagnetic force and the thermal buoyancy effect, he reckons the 100 ma, a typical arc $\Omega 30$ k, the arc root radius of 0.15 cm is the size of several kinds of force, the electrostatic field force 2.8 u N, thermal buoyancy 0.13 u N (temperature of 5000 k), the electromagnetic 1.6 x 10-4 mu N, due to electromagnetic force is far less than other two kinds of forces, and thus can ignore [11]. He thinks that electrostatic force plays the main role at small current and thermal buoyancy will play the leading role at large current. Pollution flashover is the electrical breakdown process, and the arc extension is caused by the electric field intensity of the arc head exceeding the air breakdown intensity. Although the theory of electrical breakdown can well explain the rapid development of arc (4000~5000 m/s), it cannot explain the slow development of arc (only a few meters /m~ tens of meters /m).

Another by domestic tsinghua university Li Shunyuan the views put forward by [12], they think that the development of the electric arc is caused by thermal ionization head strong arc, critical flashover is the temperature of plasma arc ion temperature, they arc temperature measured more than 5000 k, before flashover of up to 12500 k, already meet the Na atom ionization temperature. Chongqing University calculated the electric field of the local arc by using the simulated charge method, and believed that the vertical component of the field strength of the arc head played an important role in the development of pollution flashover, and the dominant factor for the development of the arc was the strong thermoelectric separation of the arc head [13]. But thermoelectric ionization theory obviously cannot explain the rapid development of electric arcs.

(4) Based on the flat plate model and Hampton criterion, Sundararajan et al. [14] proposed a dynamic model for the development of flat surface arc, which assumed that the insulator surface was uniformly stained and wet, and only one arc existed. There are two problems in the model. One is that the dynamic model relies on Hampton criterion and its reliability is poor. Second, the model is too simple to consider the residual pollution layer and does not consider the time-varying characteristics. In consideration of the influence of current, evaporation and other factors on residual fouling resistance, Rizk proposed a dynamic model to describe arc development [15]. According to the relationship between arc velocity and current value observed in previous experiments, he believed that the arc also develops at a certain speed when the current is constant. However, the experiment proved that the local arc presented diversity when developing on the surface of the fouling layer, and the phenomenon of development, stagnation and even retreat would occur [16]. It can be seen that Rizk model also has defects.

In conclusion, the current pollution flashover model is mainly a static model that ignores the arc development conditions, while a small number of dynamic models still have obvious defects. Therefore, in-depth study on the development mechanism of local arc has guiding theoretical significance for improving the surface anti-pollution flashover intensity of insulators.
3. External insulation research methods

The selection of insulators is the key to the design of power transmission and transformation engineering. Reasonable external insulation configuration can effectively prevent accidents caused by pollution flaking of insulators and ensure the safe and reliable operation of power grid. The selection of insulators generally comes from two aspects: one is based on operating experience, and the other is based on experimental research. Generally speaking, the external insulation design methods mainly include the empirical method, creepage specific distance method, and pollution withstand voltage method (artificial pollution test method), etc. These methods have their own advantages and disadvantages.

The moisture exposure of insulators has great influence on artificial contamination test. In uniform voltage boost test, it is very important to choose when to apply voltage because the time of voltage boost can be controlled manually. If the insulation surface is not fully damp when voltage is applied, then there is an irregular dry area on the insulator surface that is not damp, which will lead to greater dispersion of the test voltage. When voltage is applied, insulator samples have been exposed to moisture in the fog chamber for a long time and serious pollution loss has occurred on the surface. In this case, the distribution of insulator conductivity along the surface is uneven, which will also increase the uncertainty of test results. If the selected moisture exposure time is appropriate, that is, the surface of the insulator just reaches the saturated moisture state, then the surface state of the insulator along the string is relatively consistent, then the dispersion of the data obtained by the test method can be reduced.

![Drift bridge winding discharge diagram and its schematic diagram.](image)

4. Research status of external insulation characteristics of insulators under different suspension modes

The pollution flashover characteristics of pollution-suspended insulators at home and abroad are mainly concentrated on single string insulators, and the influence of different suspension modes on the pollution flashover characteristics of insulator strings is seldom involved. With the continuous increase of the voltage class of the transmission line, the number of split wires increases, and the stress on the tower increases. Therefore, the mechanical strength of the line suspension insulator becomes more and more demanding. Under uhv voltage grade, type "I" series of mechanical strength may be difficult to meet the design requirements, then you need to use double i-shape insulator series-parallel (hereinafter referred to as "double series-parallel" or "type II series") or more of the series-parallel type I insulator (hereinafter referred to as the "in") suspension method, using "II" type series and parallel structure, more through hardware plate connection between insulator string, as shown in Figure 2.
Xzp-210 and XZP-300 are two kinds of porcelain insulators used in Chongqing University to also study the influence of arrangement mode on dc dirty lightning pressure. The suspension mode involves "I" type string, "II" type string and "V" type string. The results show that the pollution lightning pressure of insulator strings is different under different arrangements. Compared with "V" type string, the law of pollution lightning pressure difference is more complicated, which is related to the umbrella shape of insulator, the Angle of "V" type string, salt density and other factors. For bell jar type porcelain insulator, the pollution lightning pressure of "V" type string is slightly lower than that of "I" type string when the included Angle is 60°, and significantly higher than that of "II" type string when the included Angle is greater than 90°. The "II" string had slightly lower dirty lightning pressure than the "I" string, but the difference was not significant. Of all suspension forms, the "Y" string has the lowest dirty lightning pressure, so it is not recommended to use the "Y" string structure in practical engineering applications. China Electric Power Research Institute has also carried out flashover test on the "Y" type insulator string, contrary to the conclusion obtained in the literature. This is because, in fact, literature type "Y" adopted by the string structure is unreasonable, as shown in figure 7, the "Y" string is a "V" type string on the upper and the lower part of "I" type string structure, such easy to cause the upper on both sides of the leakage current on the insulator string all through the lower part, for the production and the development in the next part of the arc provided favorable conditions. Therefore, the reasonable "Y" type string should have a structure of "V" type string in the upper part and "II" type string in the lower part. In this way, the structure of both sides of the insulator string is symmetrical, which does not create favorable conditions for the development of arc artificially, and its insulation performance is comparable to that of "I" type string or "II" type string. According to the research of Tsinghua University, the improved "Y" type string (the upper part of the "V" type string has an included Angle of 100°, and the lower part of the "II" type string has an interval of 50cm) has a polluted lightning pressure about 5% higher than the single string (the "I" type string). The reason why the improved "Y" type string has higher pollution lightning pressure is that the "V" type string structure is conducive to the escape of ionized air generated by partial discharge, which makes the arc develop close to the surface of the insulator, and the degree of floating arc is lighter than that of hanging string. On the other hand, as the insulator is in an inclined state in the test, the pollution on the surface of the "V" string under the action of gravity is easy to be lost after saturation and moisture, and the loss is faster, so as to increase the pollution lightning pressure.

5. Conclusion
To sum up, according to the insulator string in ac, dc pollution flashover characteristics of research results, for use in uhv transmission lines in the advice of the insulator string is: in porcelain insulator should be used with caution, if used, need to increase the parallel bunches of insulator piece of 8% increase (recommended), to ensure its fouling resistance. The pollution lightning pressure of multi-series and parallel composite insulators is not much different from that of single series, which is within 5%. Therefore, multi-series and parallel insulators can be used without changing the original insulation distance (or increasing 5%). It is suggested that the reduction of pollution flashover probability should be considered when N≥4 is used in practice, and the insulation distance of each string of insulators should be increased by 5% to ensure insulation performance. Under the reasonable "Y" type suspension...
mode, the polluted lightning pressure of insulator string is comparable to or even more than that of single string, which is within the acceptable scope of the project. Under the condition that factors such as tower window size need to be satisfied, the insulator string can be configured in the UHV line with the string length optimization margin.

Acknowledgements
This work was supported by the scientific research project of State Grid Corporation of China.

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