EXPERIMENTAL STUDY OF PARTIAL ARC PROPAGATION PROCESS AND FLASHOVER CHARACTERISTICS ALONG THE CONTAMINATED INSULATOR STRING

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Abstract: The relationship between the style of partial arc propagation and the distribution of contamination layer was obtained by observing the partial arc extension processes along the insulator strings with uniform and non-uniform distribution of contamination. For uniform distribution of a lower degree of contamination, the partial arcs present a leap-style propagation mode, while for non-uniform distribution or uniform distribution with higher level of pollution, the partial arcs propagate in an alternative mode of progressive-style and leap-style. The arc-over probability is also related with the degree of pollution as well as the distribution condition of contamination layer. The propagation processes of partial arcs on insulator string were observed with high speed camera. Results indicate that the propagation speed of the leap-style arc propagates at higher speed than that of the progressive-style arcs. The leakage current measurement results show that there are high amplitude pulses in the leakage current during the flashover development with the extinction or reignition of the partial spark discharge. The flashover voltage decreases with the increasing of ESDD, but in the case of constant pollution level, the flashover voltage has the minimum value when the ratio of pollution levels between upper and lower surfaces is 1:2, and then increases with the reduction of the ratio.

1 INTRODUCTION

Pollution flashover of high voltage insulators is one of the most important problems for high voltage transmission lines[1]. Because of the environmental pollution, flashover accidents have become frequent in China since 1990s, and the flashovers become one of the most serious threats to the safe operation of electric power system[2]. According to statistics data, the energy loss caused by flashover between 1986 and 1990 is 2.98 times as much as that of 10 years before 1986, and the rate of trip-out caused by flashover along 110~500kV transmission lines still remains at high level[3].

In order to solve the problem of pollution flashover, various studies have been done to establish calculation models for predicting the flashover characteristics along the contaminated insulator strings[4-6]. One of the widespread accepted models for describing the flashover process, which was proposed by Obenuas in 1958, consists of a partial arc in series with the resistance of residual pollution layer[7]. Based on this model, a large number of static models[8] for predicting the flashover have been proposed. However, all of the models cannot exactly describe the real process of flashover, due to the highly dynamic process of the flashover. Therefore, numerous dynamic models[9][10] have been proposed to describe the flashover process. Nevertheless, considering the complicated practical conditions, such as the shape of insulators, the distribution of the pollution layer[11], the humidity in different regions, the stochastic path of partial arc elongation, and the resistance of the remaining pollution layer in series, it is difficult to find an effective method for predicting the contaminated flashover along the contaminated insulator stings under practical conditions[12][13].

The validity of a prediction method depends on two factors: a clear understanding of the physical mechanism of the problem and the development of a realistic computational model[14]. Therefore, it is necessary to make researches on the characteristics of partial arcs and the mechanism of flashover occurrence along insulator strings at different contamination layer distribution and different polluted degree with different distributed conditions of the contamination layer.

The partial arc elongating processes and flashover characteristics along the insulator strings of XWP_2-160 are described in this paper. The differences in the partial arc propagation and flashover process along the uniform and non-uniform contaminated surfaces with different pollution levels are revealed. Based on these results, this paper aims at clarifying the mechanism of partial arc propagation and flashover characteristics.

2 EXPERIMENTAL SETUP AND TEST PROCEDURE

Specific details are provided in the following sections.

2.1 Experimental setup

The circuit diagram of the experimental setup is shown in Fig. 1. This setup, which was prepared according to IEC 507[15], includes a high voltage source, a measuring system and an artificial climate chamber. The voltage source consists of a booster T0, and a 150kV, 600kVA high voltage transformer T1 with a short-circuit impedance of lower than 6%, and a protective resistance R0 of 1950Ω. The measuring system consists of a capacitive divider(D) with a voltage ratio of 10000:1, a Rogowski coil(Y) (Pearson 110A) with a bandwidth of 20MHz, and a transformation ratio of 0.1V/A, and a digital storage oscilloscope DSO (Tektronix DPO4104) for recording the voltage and current waveforms during the flashover process. High-speed camera (Redlake MotionPro HS-4) with a framing rate of 10000fps was used for observing the arc elongation process.

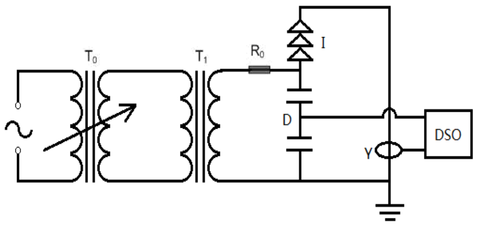


Figure 1: Schematic diagram of experimental apparatus

The insulator string was suspended in the artificial climate chamber with a diameter of 4m, and a height of 5.5m.

The dimensions of the XWP_2-160 insulator are shown in Fig 2.

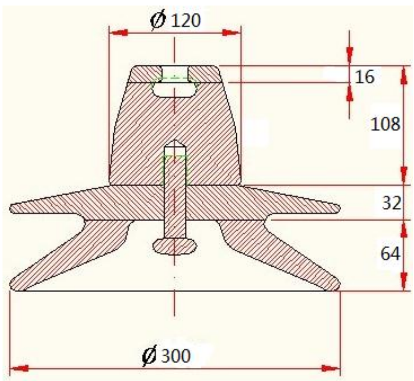


Figure 2: The dimensions of XWP_2-160 insulator

2.2 Test procedure

Ration pasting method was adopted to simulate the artificial pollution in this paper. Non-soluble deposit density (NSDD) was 1mg/cm^2, and equivalent salt deposit density (ESDD) values were 0.01, 0.02, 0.05, 0.1 or 0.2mg/cm2 respectively, for uniform contamination.

In the simulation of the non-uniform pollution distribution, NSDD and ESDD value of upper surface and lower surface of the insulator were proportional as 1:2, 1:5, 1:8, or 1:10 respectively. The total NSDD of the whole insulator was 1mg/cm2, and the ESDD values of the whole insulator were 0.05, 0.1 and 0.2 mg/cm^2, respectively.

The upper and lower surfaces were brushed respectively after the mass of NaCl and kieselgur were calculated according to ESDD, NSDD value and the surface area of each region. After being polluted, the insulators were dried naturally for about 6 ~ 8h.

After drying, the test insulators were hung up vertically as a string in the chamber. 6 nozzles on the wall were used for providing cold clean fog. The conductivity of water was kept at 500μS/cm. Uniform increasing voltage method was applied in the experiments. Under the same contamination condition, the flashover voltage is determined by the average value of 8-10 tests insulator strings tested individually.

3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Partial arc propagation processes

Partial arc initiation and propagation were observed and recorded by high speed camera, as shown in Figure 3. Point-like corona discharges were observed before the occurrence of partial arcs. The occurrence location of point-like corona was random, but there was a tendency to appear on the sheds, because the protrusions of the water droplets on the insulator surface changes the field strength distribution on the insulator surface However, with the increase of the applied voltage, partial arcs come forth and the point-like corona disappeared gradually.

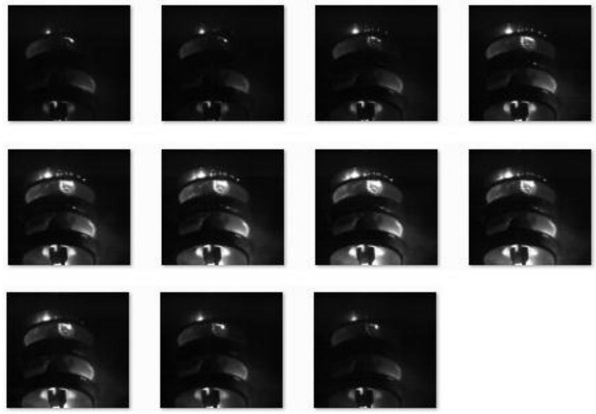
As a result of the occurrence of dry bands, the voltage applied on the insulator string began to concentrate on dry bands, resulting in the occurrence propagation of partial arcs crossing the dry bands. As the partial arc propagated, the energy consumption increased; hence the partial arcs might attenuate, even extinguish. As humidification and drying are double action processes, dry bands might re-humidify and narrowed, which resulted in reignition of the partial arc. With the periodical changes of voltage and current, the brightness of the partial arc would also periodically change. This phenomenon appeared in both uniformly and non-uniformly contaminated distribution layers.

In the situation of non-uniform pollution distribution, the initial partial arc firstly appeared on the lower surface of the insulator， which is similar to what was found in the situation of the uniform contamination distribution， but the initiation voltage of partial arcs was lower than that of uniform pollution distribution.

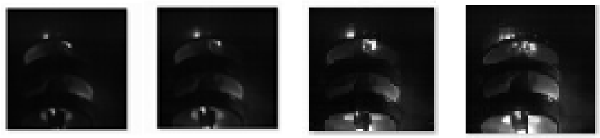
When the pollution distributed on the insulator surface uniformly, the initiation voltage of partial arc decreased, while the intensity of partial arc increased with the increase of ESDD value. Nevertheless, in the case of non-uniform pollution distribution, the initiation voltage and the intensity of partial arc were not only related with ESDD of the whole insulator string, but with the ratio between the contamination degree on both upper and lower surfaces. When the whole ESDD kept constant, the initiation voltage of the partial arc was minimal, the number of partial arcs was maximal, and the discharge intensity was the highest when the ratio between ESDDs on the upper and lower surfaces was 1:2. After that, the initiation voltage increased, and the propagation speed slowed down with the decrease of the ratio of upper surface and lower surface ESDD.

From Figure 3, it can be seen that the partial arcs showed different propagation modes in various pollution distributions. In the case of uniform distribution of the pollution layer, the primary propagation pattern of partial arcs was progressive-style: the partial arcs gradually changed with the periodic variation of leakage current, and the length extends with the increase of applied voltage and leakage current after several periods. Figure 3 shows the progressive propagation process of the partial arcs on the surface of XWP_2-160 insulator string, when ESDD is 0.2mg/cm^2. In Figure 3(a), the interval of two adjacent photographs is 1ms. As can be seen in Figure 3(a), the partial arcs became brighter gradually at first, and then dim. And in Figure 3(b), the interval of two adjacent photographs is 10ms, so it can be seen that the arcs became longer and brighter than the previous ones with the increase of applied voltage and leakage current.

When the ESDD value was 0.01, 0.02 or 0.05mg/cm^2, the partial arcs exhibited slight brightness, higher propagation speed, and higher initiation voltage. In contrast, when the ESDD value was 0.1, 0.2 or 0.3mg/cm^2, the partial arcs showed higher brightness, lower propagation speed and lower initiation voltage.



a. Variation of partial arcs within a half period



b. Partial arcs at intervals of a half period

Figure 3: The progressive-style propagation process

Under the condition of non-uniform, or uniform distribution of the contaminated layer with the pollution degree of no more than 0.1mg/cm^2, the partial arcs showed the leap-style propagation mode: a spark rapidly ignited from the arc foot, and then it changed into partial arc immediately. This propagation process is shown in Figure 4.

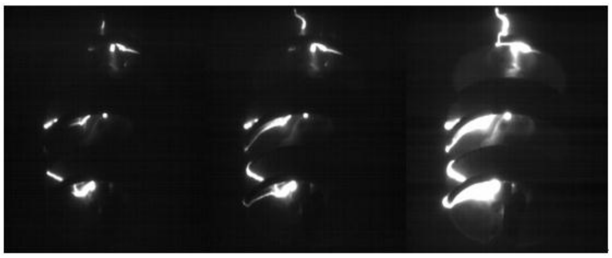


Figure 4: The leap-style propagation process

In the case of uniform distribution pollution layer with the ESDD of higher than 0.1mg/cm^2, the partial arcs showed a progressive-style propagation mode. Comparatively, in the case of ESDD less than 0.1mg/cm^2, or non-uniform pollution layer, the partial arcs propagated alternately in the progressive-style and leap-style. For the comparison between Figure 3 and Figure 4, it can be seen that the speed of leap-style is far more than that of progressive-style.

During the extending process, the partial arcs did not entirely cling to the insulator surface, sometimes it short-circuited sheds of the insulator string, which is defined as arc-over. The arc-over phenomenon is shown in Figure 5. Arc-over tended to occur when the ESDD value was no less than 1mg/cm^2 and the pollution layer distributed uniformly. Under the condition of the non-uniform pollution distribution, the probability of the occurrence of arc-over was the maximum when the ratio between pollution levels of upper and lower surfaces is 1:2, and then decrease with the ratio reducing. Arc-over shortened the leakage length of the insulator string, leading to the drop of the withstand voltage.

Figure 5: Arc-over phenomena

3.2 Flashover process analysis

Before the occurrence of flashover, the value of the leakage current was small, namely, at the order of hundreds milliamp. Only when the ESDD value was over 0.1mg/cm^2, the leakage current value reached a value of more than 1A and the partial arcs became noticeably bright, as shown in Figure 6. During the pre-flashover period, the voltage plummeted from the peak, and the leakage current increased to dozens of amperes within half of period, and the arc lightened and extended through the whole insulator string. The following directions serve the purpose of obtaining a uniform layout.

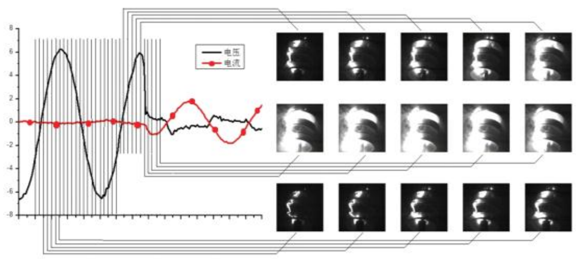
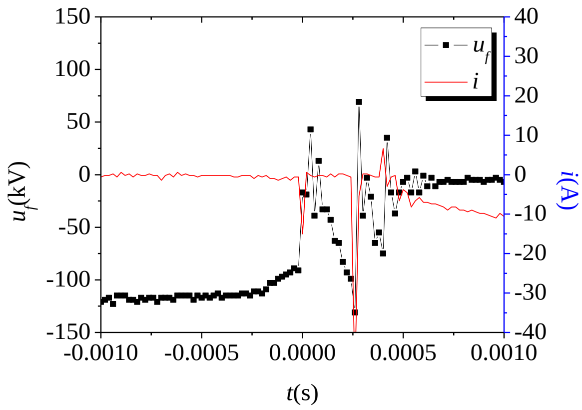
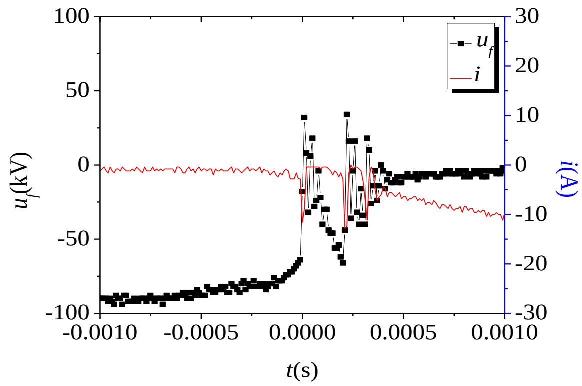


Figure 6: Flashover process while ESDD value is 0.1mg/cm^2

In the flashover process, several current pulses with a width of about 40μs and amplitude of above 50A were detected at the low ESDD value (≤ 0.05mg/cm^2) and the number of the current pulses was irrelevant to the contamination level. At the same ESDD value, the number of the current pulses was 1～3. The current pulses in the flashover process are as shown in Figure 7.



a. Flashover process (0.01mg/cm^2)



b. Flashover process (0.05mg/cm^2)

Figure 7: Flashover process on insulator strings under different degrees of pollution

The occurrence of current pulses may be attributed to the gas discharge process in the flashover. In the pre-flashover period, the resistance of the partial arc was minimal and the voltage was mostly applied on the residual pollution layer, which led to serious distortion of the electric field on the arc foot. The spark channel on the insulator surface was not that stable, it probably extinguished and then reignited; therefore, several leakage current pulses appeared in the flashover process. After the spark connected all the contiguous partial arcs, the flashover ignited rapidly. When a stable arc channel formed, the leakage current kept constant.

The number of current pulses of XWP_2-160 insulator strings during flashover was recorded， and it has no definite relationship with either ESDD or applied voltage. However, the maximum pulse amplitude and flashover voltage were associated with ESDD. The pulse amplitude decreased with the increase of the pollution degree,

It was found by observing the voltage and current waveforms in the flashover processes that no current pulses occurred when the pollution layer distributed non-uniformly, which is different to the situation with uniform distribution, it expresses that the occurrence of current pulses before flashover are related with the distribution of the pollution layer on the insulator surface.

3.3 Flashover voltage

Flashover voltage values in the situation of uniform contamination distribution are shown in table 1, and the fitting curve is shown in Figure 8.

Table 1: Flashover voltage under the condition of uniform pollution distribution

ESDD mg/cm^2	0.01	0.02	0.05	0.1	0.2
U_f(peak) kV	129	121	103	88	52.4
	121	110	88	77	38.8
	125	119	98	65.6	42.8
	\	127	80	65	52.4
	\	121	80	78.8	50.8
	\	109	90	65.2	46
Average kV	125	117.83	89.83	70.32	48.8

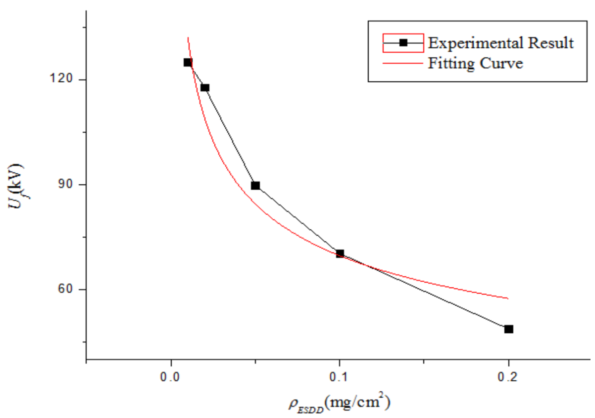


Figure 8: Flashover characteristics of uniform contamination insulator string

In Figure 8, the flashover voltage decreased with the increasing of ESDD value, and the variation trend of the U_f-ρ_{ESDD} curve was corresponded to previous results. The fitting formula is

$$U_f = A\rho_{ESDD}{}^{-n}$$

And the equation of fitting result is

$$U_f = 36.72\rho_{ESDD}{}^{-0.28}$$

Flashover voltages in the situation of non-uniform contamination distribution are shown in table 2.

Table 2: Flashover voltage under the condition of non-uniform pollution distribution

ESDD mg/cm^2	K	U_f(peak) kV			Average kV
0.05	2	75.6	84.4	83.6	81.2
	5	92.8	93	99	94.93
	8	95	101	98	98
	10	103	101	95	99.67
0.1	2	60.4	53.2	57.2	56.93
	5	68.4	61.2	63.6	64.4
	8	66.8	62.8	61.2	63.6
	10	70.8	66.8	61.2	66.26
0.2	2	44	42	44	43.33
	5	46	50	44	46.67
	8	48	49	50	49
	10	52	50	49	50.33

K is the ratio between the contamination degrees on the lower and upper surfaces, and each U_f value is the average flashover voltage of 3 insulator strings. The results mentioned in Table 2 are shown in Figure 9.

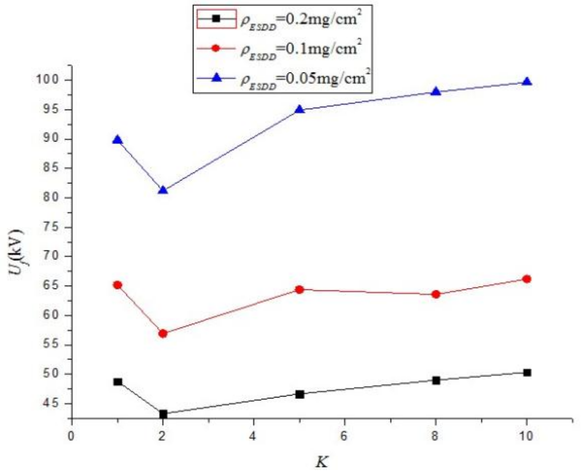


Figure 9: The relationship between flashover voltage and K

From Figure 9, it can be seen that the minimum of flashover voltage was at K=2, in other words, when the ratio between the contamination degrees on lower and upper surface is 2, the flashover voltage had the minimum value for the constant pollution level. And then, the flashover voltage increased with increasing of K when $K \geqslant 2$.

4 CONCLUSION

a. There are two propagation patterns of partial arcs: progressive-style and leap-style. When the contamination distribution was uniform and ESDD was no less than 0.1mg/cm^2, the propagation mode of the partial arcs was progressive-style. When the pollution layer was light on the upper surface and heavy on the lower surface, the partial arc propagation pattern is an alternation of leap-style and progressive-style propagations.

b. If the pollution layer distributes un-uniformly, the possibility of the occurrence of arc-over reduced.

c. In the case of non-uniform contamination distribution, and the ESDD ratio between the upper and lower surfaces was 1:2, the partial discharge had the maximal intensity, then its intensity alleviated with the decrease of the ratio.

d. The spark channel on the pollution layer is not as stable as that in the air gap. In consequence, the surface discharge might extinguish and restrike in the flashover duration, which is the reason for the occurrence of current impulses.

e. On condition that the ratio between the contamination degrees on lower and upper surface is 2 or so, the flashover voltage had the minimum value of the constant pollution level, when $K \geqslant 2$, the ratio lager, the flashover voltage higher.

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