Influence of Sheds Damage on the AC Pollution Flashover Performance of Different Voltage Class Composite Insulators

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ABSTRACT The damage of high-voltage terminal shed of composite insulators can influence the flashover performance of the insulators. The study was carried out experimentally to investigate the flashover characteristics of composite insulators with sheds damage at different voltage levels. The results show that sheds damage would decrease pollution flashover voltage, creepage distance flashover voltage gradient E_L and the dry arc distance flashover voltage gradient E_H, and such decrease range was proportional to damage degree. Besides, with the increase of composite insulator's dry arc distance, effects of sheds damage on pollution flashover voltage, creepage distance flashover voltage gradient E_L and the dry arc distance flashover voltage gradient E_H were gradually decreasing. With the $ESDD$ ranging from 0.1 mg/cm to 0.3 mg/cm^2, AC pollution flashover voltage of 35 kV, 110 kV and 220 kV composite insulators decreased by up to 35.92%, 15.03%, 9.11% respectively; the creepage distance flashover voltage gradient E_L decreased by up to 19.15%, 6.05%, 1.34% respectively; the dry arc distance flashover voltage gradient E_H decreased by up to 35.92%, 15.03%, 9.11% respectively.

INDEX TERMS Composite insulator, sheds damage, pollution flashover characteristics.
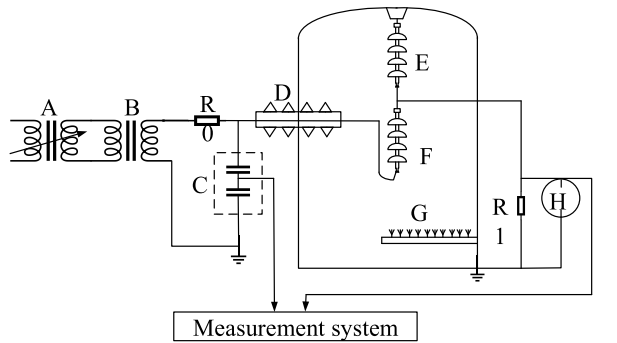
I. INTRODUCTION

Composite insulators, which are extensively used in the power grid, have played an important role in reducing the pollution flashover accidents of power transmission and transformation equipment and ensuring the safety and reliability of the power grid [1]–[3].

In recent years, with the increase of environmental awareness and protection, the number of birds has in-creased dramatically, and the transmission line fault caused by bird activities has risen sharply. The bird-related fault has become the third largest fault only second to lightning stroke and external force damage, and the most dangerous type of bird-related fault has some relevance with birds' pecking composite insulators' sheds [4]–[7]. In Luoyang, Xinxiang and other areas of Henan Province, China, there have been

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many incidents of bird pecking composite insulator. According to statistics, the number of line trips caused by bird pecking composite insulator accounts for about 10% of the total line trips. [8].

Composite insulator sheds damage caused by birds pecking will not only reduce the creepage distance, but also cause electric field distortion [9] which will subsequently aggravate the uneven potential distribution and affect the pollution flashover characteristics of insulators as a result [10]. Up to now, the research on the pollution flashover characteristics of composite insulator at home and abroad mainly focuses on the effect of pollution types, pollution degree, wetting mode, shed profiles, altitude, temperature, hydrophobicity, etc. [11]–[19] on pollution flashover voltage and flashover process, while it has not been further studied and compared that the influence of sheds damage caused by bird pecking on the pollution flashover characteristics of composite insulators at different voltage levels. This paper aims to study the effect

FIGURE 1. The schematic diagram of test set up.

A: Voltage regulator B: Transformer C: Divider D: High-voltage wall bushing R0: Protective resistor E: Insulation protection F: Sample G: Steam R1: Shunt resistor H: Protective discharge tube

of bird peck sheds damage on pollution flashover characteristics of composite insulators at different voltage levels by using 35kV, 110kV and 220kV composite insulators as test samples.

II. TEST DEVICES AND SAMPLES

A. TEXT DEVICES

The experiments were performed in a large multi-functional artificial climate chamber where located in the State Key Laboratory of Power Transmission Equipment & System Security and New Technology. The voltage was applied by a 500kV/2000kVA test transformer with the rated current of 4A, maximum short-circuit current of 75A and short circuit impedance of less than 6%. Test wiring is shown in Figure 1.

A: Voltage regulator B: Transformer C: Divider D: High-voltage wall bushing R0: Protective resistor E: Insulation protection F: Sample G: Steam R1: Shunt resistor H: Protective discharge tube

B. TEXT SAMPLES

Select FXBW-35/70, FXBW4-110/120 and FXBW4-220/100 composite insulators of high voltage trans-mission lines as the test samples, and the shed profiles are shown in Figure 2. The minimum nominal creepage distances of 35kV, 110kV and 220kV composite insulators are 1280mm, 3600mm and 6600mm respectively. JYH250-type grading ring is installed at the high voltage side of FXBW4-110/120 insulator; JYH305-type grading ring is installed at the high voltage side of FXBW4-220/100 insulator and JYH250-type grading ring is installed at the low voltage side. The parameters of the grading ring are shown in Table 1, and Figure 3 is its diagram. The ring diameter, fitting diameter, height of the joint, and pipe diameter of grading ring are represented as ΦD, Φd, ΔH, R respectively.
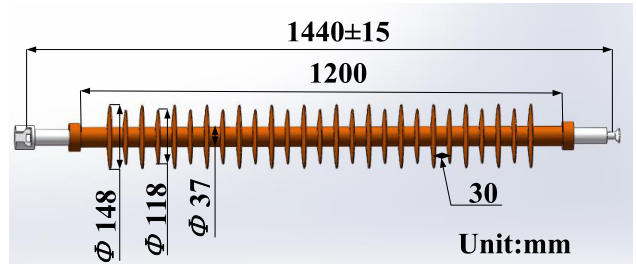
III. MATH INVESTIGATION, CHARACTERISTICS, SIMULATION AND TEST METHODS OF SHEDS DAMAGE

A. INVESTIGATION OF SHEDS DAMAGE

In this paper, 557 pieces of composite insulators pecked by birds were randomly sampled in Henan Province,
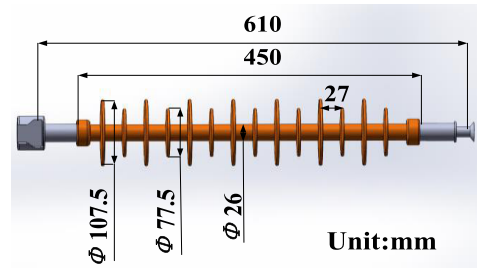
(a) FXBW-35/70

(b) FXBW4-110/120
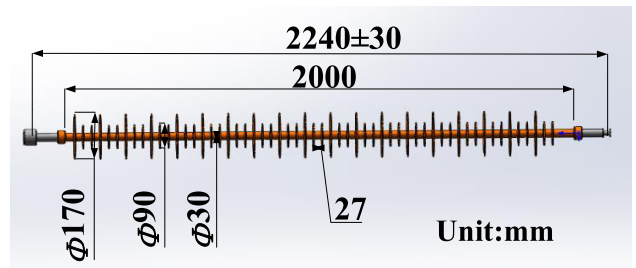
(c) FXBW4-220/100

FIGURE 2. The profile of the tested short samples.

TABLE 1. Parameters of grading rings.

Model	ΦD (mm)	Φd (mm)	ΔH (mm)	R(mm)
JYH250	250	36	70	15
JYH305	305	36	100	20

(a) Main view   (b) Top View

FIGURE 3. The diagram of grading rings.

China. According to analysis based on statistical data above, the sheds damage caused by bird pecking accounted for 48.47% of the total number of bird-related damage.

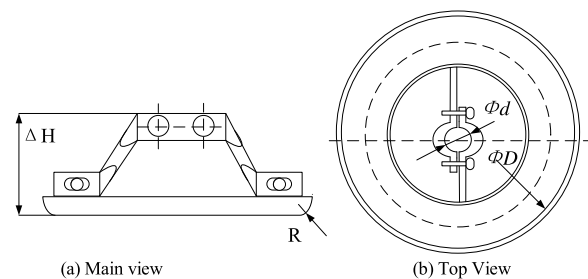L. Ming *et al.*: Influence of Sheds Damage on the AC Pollution Flashover Performance of Different Voltage Class Composite Insulators

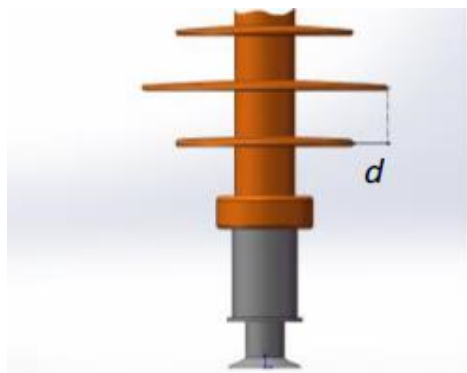**IEEE** *Access*

FIGURE 4. Damage shape.

FIGURE 5. Distance of sheds.

B. CHARACTERISTICS OF SHEDS DAMAGE
1) POSITION FEATURES
Statistics show that the composite insulator sheds damage is mainly in 1∼2 group sheds at the high voltage side, because the birds generally stand to peck at the connection part of the fittings or grading rings on the high voltage side.

2) SHAPE FEATURES
It is found that more than 80% of the shed damage caused by bird pecking are approximately circular, as shown in Figure 4. The reason is that birds generally swivel their beak and move to pick objects.

3) DEGREE FEATURES
Based on the defect area, the damage degree of the shed caused by bird pecking was analyzed. The results show that the maximum damage area of shed caused by bird pecking on a 110kV line is about 12% of the area of a healthy shed. For insulators with large and small sheds, when the damage degree of large shed exceeds the gap distance between two neighboring sheds as shown in Figure 5, the small shed will also be pecked by birds. The damage area and shape of the small shed can be approximately equivalent to the projection of the large damage shed on the small shed.

C. SHEDS DAMAGE SIMULATION
1) ARTIFICIAL SIMULATION METHOD
According to the analysis of the position and shape features of sheds, we selected 2 group of sheds on the high voltage side and the arc-shaped area to simulate defect artificially.

TABLE 2. Simulation parameters.

Insulator type	Damage area (%)	Damage radius from the edge of large shed (mm)	Reduced creepage distance (mm)
FXBW-35/70	6%	20.8	106.4
	12%	28.0	164.0
	25% (Root)	40.7	265.6
FXBW4-110/120	6%	28.7	169.6
	12%	39.2	253.6
	25% (Rod)	50.5	344.0
FXBW4-220/100	6%	37.5	150.0
	12%	50.0	280.0
	28% (Rod)	70.0	520.0

In order to simplify the test, the damage degree of the first two groups of the high voltage side of insulators was set to be consistent.

2) DAMAGE PARAMETER SETTING UP
In this paper, 6% and 12% of the damage area were selected for research, and the case of the shed damage to the rod was also considered. For the 35kV, 110kV, 220kV composite insulator, when the damage reached the rod, the corresponding damage area was about 25%, 25%, 28% respectively. The simulation parameters are shown in Table 2, and the damage simulation diagram is shown in Figure 6.

D. TEST METHOD AND PROCEDURES
The test samples were made using the artificial simulation method. In addition, the artificial pollution tests were carried out based on the method recommended by IEC60507 and the whole test procedure is presented as follows.

1) POLLUTION PRETREATMENT
Before tests, all samples were carefully cleaned to ensure the removal of all traces of dirt and grease and then dried naturally. The surfaces of the samples were coated with a very thin layer of dry kieselguhr to destroy the hydrophobicity at the degree of WC4 or WC5. Because the layer of kieselguhr was very thin, the effect of the kieselguhr on non-soluble deposit density *NSDD* could be ignored.

2) ARTIFICIAL POLLUTING
The solid layer method was used to form the pollution layer on the samples, following the procedures prescribed in standard IEC 60507. Kieselguhr is used as inert materials, and industrial pure sodium chloride is used as conductive material, the ratio of non-soluble deposit density *NSDD* to equivalent soluble deposit density *ESDD* is 6:1. The ratio of pollution on upper and lower sheds surface of the insulator is 1:1.
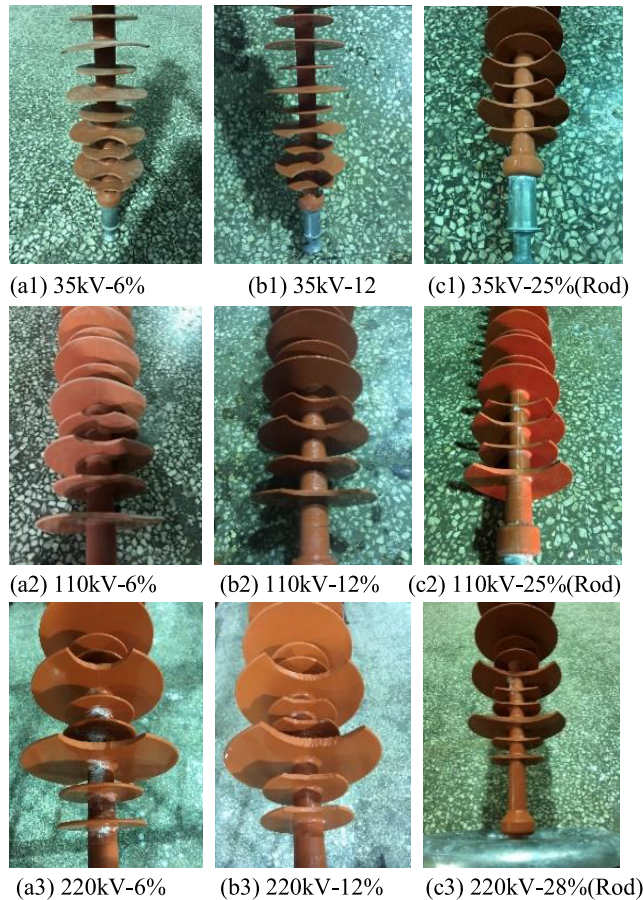
FIGURE 6. Diagram of sheds damage of 35kV, 110kV, 220kV composite insulators.

3) WET TREATMENT OF TEST SAMPLE

The steam fog is applied to wet the pollution layer with the output rate of 0.06 ± 0.01kg/h.m^3. The spray direction of the fog is perpendicular to the axis direction of the insulator string.

4) FLASHOVER TEST

The flashover tests were carried out on three identical samples by rise-voltage method, with an interval of 5 minutes. Among the four flashover values of each sample, the lowest three flashover voltage values were taken. That is, the average value of nine flashover voltages of three samples was taken as the flashover voltage U_f.

IV. TEST RESULTS AND ANALYSIS

A. INFLUENCE OF SHEDS DAMAGE ON AC POLLUTION FLASHOVER VOLTAGE

In this paper, under the condition of *ESDD* of 0.1, 0.15, 0.2 and 0.3mg/cm^2, the artificial AC pollution flashover characteristics of 35kV, 110kV and 220kV composite insulators with three kinds of damage (damage area of 6%, damage area of 12% and damage to root) were tested. The results of pollution flashover voltage test are shown in U_f in Table 3.
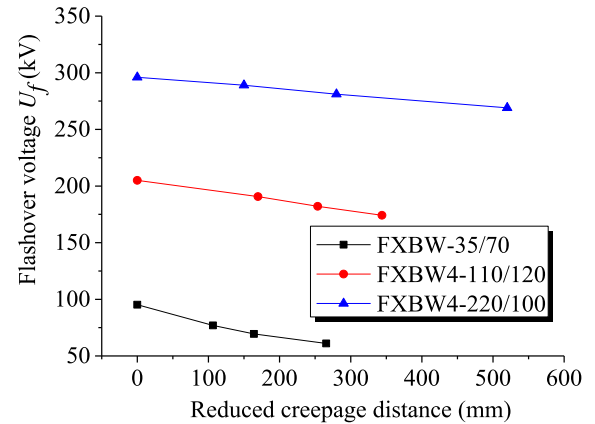

FIGURE 7. AC pollution flashover voltage of 35kV, 110kV, 220kV composite insulators (*ESDD*=0.1 mg/cm^2).

Due to the influence of the creepage distance on the pollution flashover voltage, the damage area is converted into the reduced creepage distance for analyzing the influence of the damage degree on the pollution flashover voltage. Take the change of the flashover voltage of the 35kV, 110kV, and 220kV composite insulators with the *ESDD* of 0.1mg/cm^2 as an example, shown in Figure 7.

It can be seen from Figure 7 that the shed damage results in the decrease of pollution flashover voltage of composite insulators. With the increase of damage degree, the decreasing range of pollution flashover voltage increases. The reason is that the reduced creepage distance increases with the increase of damage degree, and the pollution flashover voltage is positively related to the creepage distance by the Obenaus pollution flashover model theory. For example, for 110kV composite insulators, the reduced creepage distance under the condition of three damage degrees are 169.6mm, 253.6mm and 344.0mm respectively.

With the increase of insulator voltage level and dry arc distance, the influence of damage degree on flashover voltage gradually weakens. For example, when the *ESDD* is 0.1mg/cm^2, the AC pollution flashover voltage of 35kV, 110kV and 220kV composite insulators with 12% damage area will be reduced by 27.02%, 11.17% and 5.03% respectively compared with those in the intact condition. The reason is that with the increase of the dry arc distance, the decreasing proportion of the composite insulator's creepage distance to dry arc distance ratio *L/H* decreases. For example, for a composite insulator at three voltage levels of 35kV, 110kV, and 220kV, *L/H* is reduced by 12.81%, 7.04%, and 4.24% respectively, when the damage area is 12%.

B. INFLUENCE OF SHEDS DAMAGE ON AC POLLUTION FLASHOVER VOLTAGE GRADIENT

The flashover voltage of insulator is related to the creepage distance *L* and the dry arc distance *H*. In this paper, the creepage distance flashover voltage gradient E_L and the dry arc distance flashover voltage gradient E_H are selected respectively to analyze the influence of the sheds damage on

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TABLE 3. AC pollution flashover voltage U_F, creepage distance flashover voltage gradient E_L and dry arc distance flashover voltage gradient E_H of 35kV, 110kV, 220kV composite insulators($\sigma = 1.00\% \sim 7.89\%$).

Voltage level	Damage area (%)	Reduced distance (mm)	Contamination degree *ESDD* (mg/cm²)											
			0.1			0.15			0.20			0.30		
			U_f	E_L	E_H	U_f	E_L	E_H	U_f	E_L	E_H	U_f	E_L	E_H
			kV	kV/cm	kV/cm	kV	kV/cm	kV/cm	kV	kV/cm	kV/cm	kV	kV/cm	kV/cm
35kV	0	0	95.2	0.74	2.12	90.8	0.71	2.02	87.1	0.68	1.94	82.2	0.64	1.83
	6%	106.4	77.0	0.66	1.71	72.0	0.61	1.60	69.1	0.59	1.54	65.9	0.56	1.46
	12%	164.0	69.5	0.62	1.54	63.1	0.57	1.40	59.3	0.53	1.32	57.3	0.51	1.27
	25%	265.6	61.0	0.60	1.36	59.0	0.58	1.31	55.7	0.55	1.24	51.6	0.51	1.15
110kV	0	0	205.0	0.57	1.71	171.5	0.48	1.43	155.3	0.43	1.29	135.2	0.38	1.13
	6%	169.6	190.7	0.56	1.59	160.0	0.47	1.33	145.3	0.42	1.21	126.5	0.37	1.05
	12%	253.6	182.1	0.54	1.52	150.2	0.45	1.25	136.9	0.41	1.14	120.9	0.36	1.01
	25%	344.0	174.2	0.54	1.45	143.4	0.44	1.20	130.7	0.40	1.09	115.0	0.35	0.96
220kV	0	0	296.0	0.45	1.48	260.0	0.39	1.30	239.5	0.36	1.20	215.5	0.33	1.08
	6%	150.0	289.0	0.45	1.45	254.0	0.39	1.27	234.1	0.36	1.17	210.2	0.33	1.05
	12%	280.0	281.1	0.45	1.41	248.2	0.39	1.24	228.7	0.36	1.14	204.8	0.32	1.02
	28%	520.0	269.0	0.44	1.35	235.6	0.39	1.18	217.8	0.36	1.09	196.0	0.32	0.98

the pollution flash voltage gradient of the composite insulator. Calculation formula of E_L and E_H is as follows, and the unit of them is kV/cm.

$$E_L = U_f/L \qquad (1)$$
$$E_H = U_f/H \qquad (2)$$

where L is creepage distance, H is dry arc distance, U_f is pollution flashover voltage.

Based on the values of pollution flashover voltage of 35kV, 110kV and 220kV composite insulators and the creepage distance and dry arc distance of composite insulators with sheds damage, the creepage distance pollution flashover voltage gradient E_L and the dry arc distance flashover voltage gradient E_H can be calculated, as shown in Table 3.

1) THE INFLUENCE ON E_L
For example, the variation of the 35kV, 110kV, and 220kV composite insulators' E_L with the degree of contamination *ESDD*=0.1mg/cm² is shown in Figure 8.

It can be seen from Figure 8 that sheds damage leads to the decrease of composite insulator's E_L and the extent increases with the increase of damage degree. For example, when *ESDD*=0.1mg/cm² and the creepage distances are 106.4mm, 164.0mm, and 265.6mm, the 35kV composite insulator's E_L are 0.66kV/cm, 0.62kV/cm, and 0.60kV/cm, respectively, which are 0.08kV/cm, 0.12kV/cm, and 0.14kV/cm lower than those in the intact condition respectively. According to the Obenaus pollution flashover model theory, the

pollution flashover voltage is positively related to the creepage distance. Besides, the decrease amplitude of pollution flashover voltage is larger than that of surface creepage distance, and the difference increases gradually with the increase of damage degree. For example, when *ESDD* is 0.1mg/cm², the pollution flashover voltage of 35kV composite insulators with three degrees of damage decreases by 19.12%, 27.00% and 35.92%, and the creepage distance decreases by 8.31%, 12.81% and 20.75% respectively.

With the increase of insulator voltage level and dry arc distane, the influence of damage degree on E_L gradually weakens. For example, when *ESDD* is 0.1mg/cm², the E_L of 35kV, 110kV and 220kV composite insulators with damage area of 12% are 0.62kV/cm, 0.54kV/cm and 0.45kV/cm respectively, which are 16.29%, 4.43% and 0.83% lower than those in the intact condition. The reason is that with the increase of insulator voltage level, the composite insulator's L/H decreases.

2) THE INFLUENCE ON E_H
The variation of the 35kV, 110kV, and 220kV composite insulators' E_H with the degree of contamination *ESDD*=0.1mg/cm² is shown in Figure 9.

It can be seen from Figure 9 that sheds damage has an effect on the composite insulator's E_H, and the degree of influence is related to the reduced creepage distance and insulator voltage level. E_H decreases with the increase of damage degree. For example, for 35kV composite insulators,
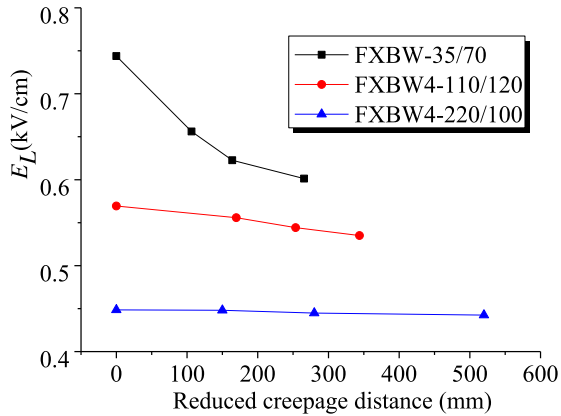
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FIGURE 8. The creepage distance flashover voltage gradient E_L of 35kV, 110kV, 220kV composite insulators ($ESDD$=0.1mg/cm²).

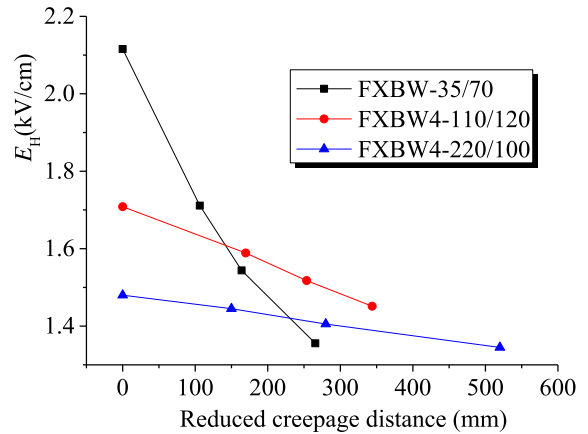**FIGURE 9.** The dry arc distance flashover voltage gradient E_H of 35kV, 110kV, 220kV composite insulators ($ESDD$=0.1mg/cm²).

when the $ESDD$ is 0.1mg/cm² and E_H at the reduced creepage distance of 106.4mm, 164.0mm, and 265.6mm are 1.71kV/cm, 1.54kV/cm, and 1.36kV/cm respectively. Compared with the intact condition, E_H is reduced by 0.41kV/cm, 0.58kV/cm, and 0.76kV/cm, respectively. The reason is that the reduced creepage distance increases with the increase of damage degree, and the pollution flashover voltage is positively related to the creepage distance by the Obenaus pollution flashover model theory. Therefore, the decrease amplitude of E_H increases due to the increase of pollution flashover voltage's decrease amplitude and the constant value of H.

With the increase of the insulator dry arc distance, the influence of damage degree on E_H gradually weakens. For example, the dry arc distance flashover voltage gradient E_H of the 35kV, 110kV, and 220kV composite insulators with a contamination degree of $ESDD$=0.1mg/cm² and damage area of 12% are 1.54kV/cm, 1.52kV/cm, and 1.41kV/cm respectively, which are 27.02%, 11.17%, and 5.03% lower than those in the intact condition. The reason is that the creepage height ratio L/H of the composite insulator decreases with the increase of dry arc distance.

V. CONCLUSION

Sheds damage results in the decrease of AC pollution flashover. With the increase of damage degree, the drop amplitude of pollution flashover voltage increases. As the insulator voltage level and dry arc distance increase, the influence on pollution flashover voltage decreases gradually. The contamination degree of $ESDD$ is 0.1~0.3mg/cm², the pollution flashover voltages of 35kV,110kV and 220kV composite insulators decrease by up to 35.92%, 15.03% and 9.11% respectively under the condition of root damage.

The influence of sheds damage on the creepage distance flashover voltage gradient E_L and the dry arc distance flashover voltage gradient E_H of composite insulators is related to reduced creepage distance and voltage level. The E_H and E_L of the low voltage level insulator decreases as the damage degree increases. With the increase of insulator

voltage level and dry arc distance, the influence on the E_L and E_H gradually decreases. When the contamination degree of $ESDD$ is 0.1~0.3mg/cm², the E_L of 35kV, 110kV and 220kV composite insulators decrease by 19.15%, 6.05% and 1.34% respectively, and the E_H decreases by 35.92%, 15.03% and 9.11% respectively under the condition of root damage.

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