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Study on Insulator Flashover Voltage Gradient Correction Considering Soluble Pollution Constituents

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Abstract: Natural polluted insulator surfaces are always coated with various kinds of soluble constituents, and those constituents affect flashover performance differentially. Currently, this fact is not considered either in laboratory experiments or field pollution degree measurements, causing the existing insulation selection method to be deficient. In this paper, a systematic study on insulator flashover voltage gradient correction involving different types of soluble pollution constituents is presented. Using a typical type glass insulator as the sample, its flashover tests, polluted by typical soluble chemicals ($NaCl$, $NaNO_3$, KNO_3, NH_4NO_3, $MgSO_4$, $Ca(NO_3)_2$ and $CaSO_4$), were carried out. Then, the flashover gradient correction was made by combining the flashover performance of each soluble constituent, the equivalent salt deposit density (*ESDD*) contribution of the seven constituents, and the saturation performance of $CaSO_4$. The correction agreed with the flashover test results of insulator polluted by three types of soluble mixture. Research results indicate that the flashover gradient correction method proposed in this paper performs well in reducing the calculating error. It is recommended to carry out component measurements and flashover gradient correction to better select outdoor insulation configuration.

1. Introduction

External insulation equipment on transmission lines or in substations are frequently subjected to various kinds of contamination such as industry emissions, natural salt, dust, bird droppings, and other contaminants [1]. Due to pollution source features, geographical environment, and weather conditions, there is a great diversity of chemical constituents deposited on insulator surfaces during contamination [2].

Plenty of researches have been carried out so far to obtain the main constituents of insulator surface pollution. To sum up, insulator surface pollution is mainly made up of several conductive materials including $NaCl$, $NaNO_3$, KCl, KNO_3, $Mg(NO_3)_2$, $MgSO_4$, NH_4NO_3, NH_4Cl, $(NH_4)_2SO_4$, $Ca(NO_3)_2$, $CaSO_4$, and other contaminants, according to the research data in [3–5].

All these constituents must affect an insulator's electrical properties differentially [6,7], which will probably bring errors to the flashover voltage calculation. Currently, insulator flashover voltage is commonly calculated using an empirical negative exponent formula as follows [8–10]:

$$U_f = A \times ESDD^{-n} \tag{1}$$

The main symbols of this paper were described in Table 1. In this formula, equivalent salt deposit density (*ESDD*) is derived from converting the pollution solution conductivity to the weight of NaCl, and *A* and *n* are obtained through laboratory tests using NaCl as the soluble pollution. So, the formula neglects the influence of other soluble constituents on flashover voltage, which causes deficiency.

Table 1. List of principal symbols and terms.

Symbol	Description	Unit
U_f	flashover voltage	kV
ESDD	equivalent salt deposit density	mg/cm^2
A	coefficient related to the shape of the insulator, insulator surface material, air pressure, power source type, etc.	N/A
n	characteristic exponent characterizing the influence of *ESDD* on U_f	N/A
i	a certain soluble chemical contained in insulator pollution	N/A
$U_{LFOV\Sigma}$	limiting flashover voltage of mixture electrolyte solution	kV
U_{LFOVi}	the limiting flashover voltage of single electrolyte solution of *i*	kV
$\rho_{ESDD\Sigma}$	the *ESDD* of the mixture electrolyte solution	mg/cm^2
ρ_{ESDDi}	the *ESDD* of single electrolyte solution of *i*	mg/cm^2
U_{50}	50% withstand voltage	kV
E_L	flashover voltage gradient	kV/m
L	insulator string's creepage	m
V	volume of the suspension used to collect insulator pollution	mL
A	the area of insulator surface	cm^2
S_a	salinity of the collected suspension	kg/m^3
σ_{20}	volume conductivity at a temperature of 20 °C	S/m
$ESDD_M$	the measured *ESDD* value of insulator surface pollution mixture	mg/cm^2
η_i	*ESDD* contribution percentage of soluble constituent *i* in mixture	N/A
Limiting flashover voltage: the lowest flashover voltage occurs during flashover tests.		
Critical flashover voltage: the theoretical value of the applied voltage when flashover.		
50% withstand voltage: a voltage value under which the withstand probability is 50%.		

In light of this, researches concerning different soluble constituents were carried out to further reveal insulator flashover voltage characteristics.

In literature [6], researchers studied the flashover performance of insulator polluted by different soluble materials, and proposed that, according to kinetic theory and permeation theory, a lower flashover voltage may be a function of the type of salt.

Researchers in [7] studied the dependence of flashover voltages on the chemical composition of the insulator surface contaminants, and put forward that the limiting flashover voltage of a contaminant containing several salt types may be computed from that of each salt type measured independently:

$$U_{LFOV\Sigma} = (\sum \rho_{ESDDi} U_{LFOVi})/\rho_{ESDD\Sigma} \tag{2}$$

In literature [11], researchers recommended that when calculating the critical flashover voltage and critical current, appropriate arc constants (*A* and *n*) should be selected for different chemical compositions of the pollutants.

Researchers in literature [12] showed the influence of pollution under 12 types of chemical constituents. It is proposed by the authors that in the case of simple salts and salts mixtures, the critical voltages are insensitive to the chemical nature of pollution. The critical currents are influenced by the chemical constitution of pollution for both polarities.

In literature [13], researchers studied the flashover performance of insulator string polluted by $CaSO_4$ and $NaCl$, and reduced the flashover voltage calculation error through considering the slight solubility of $CaSO_4$. It is concluded by the authors of the paper that the current *ESDD* method may fail to reflect specific effects of insulator contamination on its electrical property.

The above studies contributed towards the knowledge of pollution flashover principles and provide a theoretical basis for contamination constituents' effects on the insulation property. However, during laboratory artificial tests, pollution degree measurements, as well as field insulation design, $NaCl$ is still used as the only representation of a conductive constituent. Moreover, few of the previous works proposed a procedure for flashover voltage gradient correction that considers various characteristics of soluble constituents.
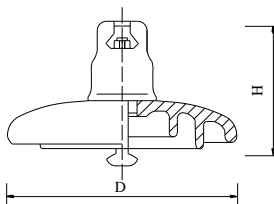
This paper presented a systematical research on insulator flashover voltage gradient correction considering soluble pollution constituents. Firstly, flashover tests of typical type insulator string polluted by $NaCl$, $NaNO_3$, KNO_3, NH_4NO_3, $MgSO_4$, $Ca(NO_3)_2$, and $CaSO_4$ were carried out, respectively. Then, with the flashover test data, the flashover gradient corrections basing on *ESDD* contribution of seven types of constituents and the saturation performance of $CaSO_4$ were analyzed. The corrected flashover gradients agreed with insulator flashover test results under three types of soluble mixtures. This research is intended for contributing to the better design of outdoor insulation in field transmission lines.

2. Sample, Experimental Setups, and Procedure

2.1. Sample

The samples were typical type glass insulators. The technical parameters and profile of the sample are shown in Table 2.

Table 2. Profile parameters of the insulator sample, h is the configuration height, l is the leakage distance, and d is the diameter of insulators.

Material	Profile	Parameters (mm)		
		h	d	l
Glass		146	280	400

2.2. Experimental Setups

The tests were carried out in a multifunction artificial climate chamber. The artificial climate chamber, with a diameter of 7.8 m and a height of 11.6 m, can simulate steam fog conditions. The power was supplied by a 500 kV/2000 kVA pollution test transformer, of which the maximum short current is 75 A and the frequency is 50 Hz. The test circuit is shown in Figure 1, where B is the voltage regulator, T is the test transformer, R_0 is the protective resistance (10 kilo ohms), G is the wall bushing, D is the capacitive voltage divider (1000:1), E is the climate chamber, C is the leakage current measurement system, and S is the sample shown as an insulator string. The setups meet the requirements of pollution flashover test.
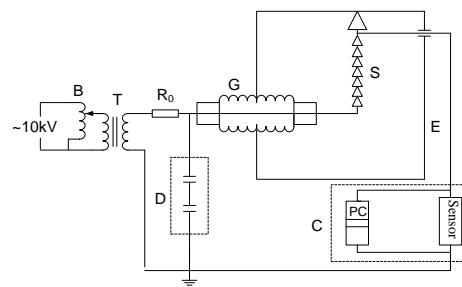
Figure 1. Schematic diagram of the alternating current (AC) test circuit, B—the voltage regulator, T—the test transformer, R_0—the protective resistance, G—the wall bushing, D—the capacitive voltage divider, E—the climate chamber, C—the leakage current measurement system, and S—the insulator string sample.

2.3. Test Procedure

2.3.1. Preparation

Before the tests, all the samples were carefully cleaned by Na_2PO_3 solution so that all traces of dirt and grease were removed. The samples were left to dry naturally indoors to avoid dust or other pollution, and the relative humidity surround was less than 70% RH (Relative Humidity).

2.3.2. Polluting

The dipping method was applied to pollute the sample. The pollution solution was made strictly referring to standards [14,15]. Firstly, the soluble constituent was added until the volume conductivity reached a predetermined value, and then kaolin was added to make the solution into clay suspension. The samples were carefully dipped into and then taken out of the pollution mixture to get a uniform pollution layer coated on the surface.

After each dipping procedure, three pieces of the sample were randomly selected and the average value of their *ESDD* and non-soluble deposit density (*NSDD*) was measured, as was the *ESDD* and *NSDD* of the soaked samples. Based on IEC standard, 300 mL deionized water was used to wipe off the contaminants when measuring the *ESDD*.

NaCl and the other six soluble constituents (KNO_3, NH_4NO_3, $NaNO_3$, $Ca(NO_3)_2$, $CaSO_4$, and $MgSO_4$) were used in this study to make the pollution solution.

2.3.3. Flashover Test

The polluted insulators were firstly precharged by a predicted voltage level and then wetted by steam fog. The fog was generated by a 1.5 t/h boiler, for which the rate was 0.05 ± 0.01 kg/h·m^3. During the flashover test, the temperature in the chamber was maintained between 30 °C and 35 °C through control of the refrigeration system, and the atmospheric pressure was 98.6 kPa in all the experiments.

In the tests, up-and-down method was adopted to get a 50% withstand voltage U_{50}. Each contaminated sample was subjected to at least 10 "valid" individual tests. The applied voltage level in each test was varied through up-and-down voltage. The voltage step was approximately 5% of the expected U_{50}. The first "valid" individual test was selected as being the first one that yields a result different from the preceding ones. Only the individual test and at least 9 following individual tests were taken as useful tests to determine U_{50}.

It is very important to obtain the predicted flashover voltage level for the first up-and-down evaluation. Firstly, a small voltage on the suspended samples was applied, and then the steam fog was opened; the wetting condition of the surface was judged by observing the surface water film situation as well as the variation of recorded leakage current waveform. When the surface water films were formed and connected with each other, or the leakage current reached a high value and then started

decreasing, the insulator pollution surface was treated as wholly wetted. Then, the voltage was lifted until flashover. The final voltage value was taken as the predicted flashover voltage.

When testing, the polluted insulators were firstly precharged by a predicted flashover voltage level, and then the steam fog was opened. If flashover occurred, the voltage applied in the next test was set 5% lower; however, if the current recorded peaks had decreased to values permanently lower than 70% of the maximum peak [14], the withstand of the insulator was considered definitive and the test was stopped—in this case, the applied voltage was set 5% higher in the next test. The U_{50} and relative standard deviation error (σ) are calculated as follows:

$$U_{50} = \frac{\sum(U_i n_i)}{N} \tag{3}$$

$$\sigma = \sqrt{\left(\sum_{i=1}^{N}(U_i - U_{50})^2\right)/(N-1)}/U_{50} \times 100\% \tag{4}$$

where U_i is an applied voltage level, n_i is the number of tests carried out at the same applied voltage U_i, N is the total number of "valid" tests, and σ is the relative standard deviation.

In summary, the detail procedure of the up-and-down method is shown in Figure 2, and one example of data record was shown in Table 3.
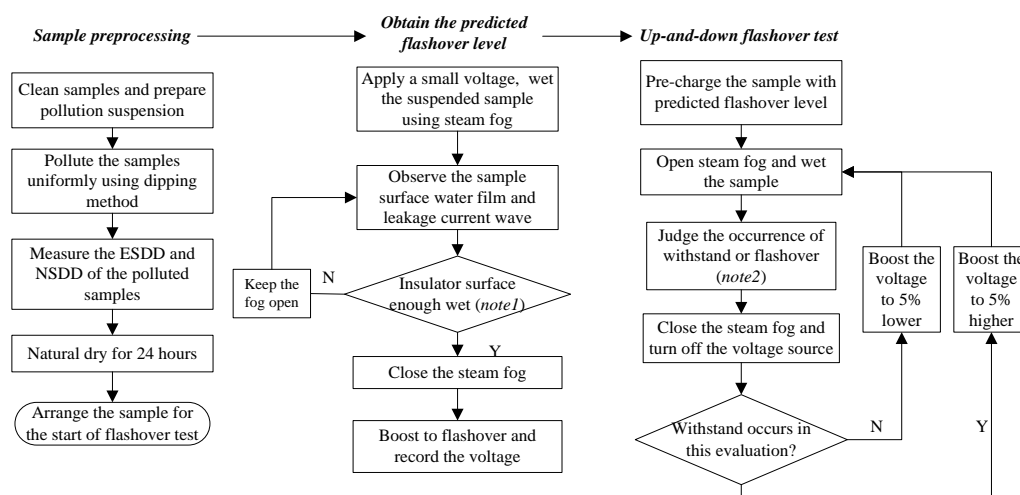
Note:
1. It will take about 15 min for the sample to get enough wet under fog rate of 0.05±0.01 kg/h m³ in the steam fog chamber.
2. If the recorded current wave peaks have decreased to values permanently lower than 70% of the maximum peak, the withstand happens. It will take about 15-20 min to get this definitive.

Figure 2. The diagram for the test procedure.

Table 3. Example for the valid data record.

Sample	Pollution Type	Test Records		*U*/kV, (Flashover ○; Withstand ●)			
3-unit LXY$_4$-160 String	NaCl, *ESDD*: 0.045 mg/cm² *NSDD*: 0.107 mg/cm²	String 1	Test No. Records	*1* 54.1 ○	*2* 52.5 ○	*3* 50.6 ●	*4* 54.0 ○
		String 2	Test No. Records	*1* 51.2 ●	*2* 53.7 ●	*3* 56.4 ●	*4* 60 ●
		String 3	Test No. Records	*1* 56.7 ○	*2* 52.7 ●	*3* 56.4 ●	*4* 60.3 ●
		String 4	Test No. Records	*1* 52 ●	*2* 55.1 ○	*3* 53.4 ●	*4*

(1) For this example, 54.1 kV is the predicted value, and only the 11 bold voltage values are the valid data; (2) Each sample string was only subjected to 3–4 evaluations to avoid pollution loss by a long duration of fog wetting; (3) The 60 kV and 60.3 kV data points are the odd data which may be caused by pollution loss during wetting; (4) It is impossible to control voltage step to ±5% accurately. In actual tests the voltage step was basically 4%–6%.

3. Test Results and Analysis

The insulator flashover voltage gradient can be expressed by:

$$E_L = U_{50}/L \tag{5}$$

Test results are shown in Table 4, where it can be seen that:

(1) The relative errors were lower than 7%, so the dispersion degree of the data acquired by the test procedure is very small. Besides, *NSDD* was controlled narrowly within 0.08–0.12 mg/cm^2 through the dipping method, which means that the effects of *NSDD* on flashover voltage can be neglected.

(2) Insulator flashover performance is quite different under different soluble constituents. For example, when the constituent is $NaNO_3$ and *ESDD* is 0.031 mg/cm^2, insulator E_L is 55.5 kV/m; however, when the soluble constituent is $MgSO_4$ and *ESDD* increases to 0.049 mg/cm^2, the E_L increases to 57.3 kV/m. A higher *ESDD* value does not always mean a lower flashover voltage when the soluble constituent is different.

(3) The negative exponent function in Equation (1) was used to fit the data in Table 2; the results are shown in Figure 3.

Table 4. Test results of insulator strings polluted with different soluble constituents.

| Soluble Constituent	Flashover Parameters	Test Results		
NaCl	*ESDD* (mg/cm^2)	0.027	0.045	0.078
	NSDD (mg/cm^2)	0.132	0.107	0.103
	E_L (kV/m)	51.9	44.8	36.2
	σ (%)	5.2	3.8	3.4
KNO_3	*ESDD* (mg/cm^2)	0.032	0.055	0.072
	NSDD (mg/cm^2)	0.074	0.078	0.087
	E_L (kV/m)	51.8	45.4	43.5
	σ (%)	5.4	5.2	3.3
NH_4NO_3	*ESDD* (mg/cm^2)	0.024	0.039	0.073
	NSDD (mg/cm^2)	0.123	0.119	0.124
	E_L (kV/m)	57.5	51.6	46.2
	σ (%)	4.3	4.6	4.9
$NaNO_3$	*ESDD* (mg/cm^2)	0.031	0.056	0.100
	NSDD (mg/cm^2)	0.105	0.092	0.084
	E_L (kV/m)	55.5	48.5	43.3
	σ (%)	4.7	3.6	4.4
$Ca(NO_3)_2$	*ESDD* (mg/cm^2)	0.026	0.051	0.109
	NSDD (mg/cm^2)	0.090	0.086	0.100
	E_L (kV/m)	61.7	51.4	44.7
	σ (%)	4.7	3.3	3.2
$MgSO_4$	*ESDD* (mg/cm^2)	0.049	0.082	0.160
	NSDD (mg/cm^2)	0.142	0.133	0.151
	E_L (kV/m)	57.3	48.5	44.3
	σ (%)	4.7	4.8	3.2
$CaSO_4$	*ESDD* (mg/cm^2)	0.055	0.145	0.028
	NSDD (mg/cm^2)	0.092	0.088	0.079
	E_L (kV/m)	65.3	56.9	72.8
	σ (%)	5.1	5.6	5.3
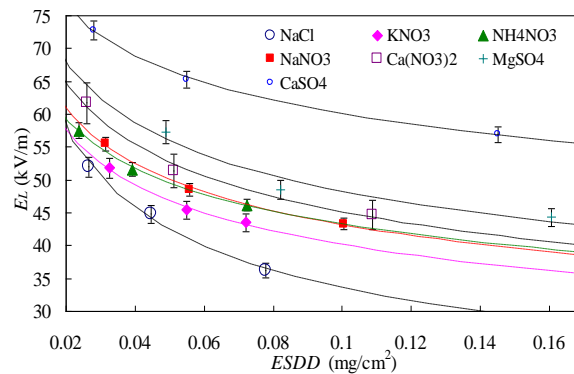
Figure 3. Fitting curves of each soluble constituent using nagative exponent function.

The curves fall into the 3% error bars of the data points, meaning the fit is good. It can be seen from the figure that different soluble constituent corresponds to different E_L–$ESDD$ variation trends. Given the same $ESDD$, the flashover gradient of slightly soluble salt $CaSO_4$ is always the highest, and it decreases the most slowly with the increase of $ESDD$. The flashover gradient of NaCl is always the lowest, and it decreases the fastest with the increase of $ESDD$.

Fitting results of coefficients A and n are shown in Table 5.

Table 5. Fitting results of insulator flashover gradient with different soluble constituents

Salt	$E_{Li} = A_i \times ESDD^{-ni}$						
	NaCl	**NH_4NO_3**	**KNO_3**	**$Ca(NO_3)_2$**	**$CaSO_4$**	**$MgSO_4$**	**$NaNO_3$**
A	15.5	27.4	23.8	26.9	36.2	29.5	26.4
n	0.34	0.19	0.22	0.22	0.18	0.21	0.21

For the seven kinds soluble constituents, the A value of the insulator sample varies within 15.5–36.2, n varies within 0.19–0.34. It indicates that different soluble constituent corresponds to very different E_L-$ESDD$ relationship, and A is also associated with pollution chemical type. In summary, consideration of chemical compositions is necessary when calculating insulator pollution flashover voltage.

Flashover tests of the insulator sample polluted by soluble constituents' mixture were also carried out. The components and their weight percentage of the pollution mixtures were determined basically according to the data in [16–18]. In this study, three types of pollution mixtures were simulated, which represented a highway area, chemical plan area, and seaside, respectively. Test results are shown in Table 6.

Table 6. Test results of insulator strings polluted with three types of soluble constituents mixture.

Pollution Mixture Based on Weight Percentage	Parameters	Test Results
Type I: $CaSO_4$ 57.5%, NaCl 13.1%, KNO_3 9%, $NaNO_3$ 8.7%, NH_4NO_3 6.4%, $MgSO_4$ 3.7%	$ESDD$ (mg/cm^2) $NSDD$ (mg/cm^2) E_L (kV/m) σ (%)	0.081 0.117 50.6 5.1
Type II: $CaSO_4$ 54.3%, NaCl 10.3%, $NaNO_3$ 2.2%, KNO_3 6.3%, $Ca(NO_3)_2$ 20.7%, $MgSO_4$ 4.2%	$ESDD$ (mg/cm^2) $NSDD$ (mg/cm^2) E_L (kV/m) σ (%)	0.082 0.128 47.8 4.7
Type III: $CaSO_4$ 59.4%, NaCl 13.6%, KNO_3 9.5%, $Ca(NO_3)_2$ 7.8%, $MgSO_4$ 7.9%	$ESDD$ (mg/cm^2) $NSDD$ (mg/cm^2) E_L (kV/m) σ (%)	0.251 0.112 32.8 4.6

It can be seen from Table 6 that under different types of pollution mixtures, the flashover performance varies. For example, when ESDD was about 0.081 mg/cm^2, the E_L under Type I pollution was 50.6 kV/cm, while that under Type II was 47.8 kV, a decrease of 6%.

Using the traditional method, which is only based on insulator flashover performance under NaCl (shown in Equation (1)), the flashover voltage gradient under pollution mixture was calculated. Calculation results and relative errors are shown in Table 7.

Table 7. Test results of insulator strings polluted with three types of soluble constituents mixture, E_L* means the calculated value of flashover gradient.

Mixture Type	*ESDD* (mg/cm^2)	Calculated Value E_L* (kV/m)	Relative Error Δ (%)
Type I	0.081	33.8	33.2
Type II	0.082	35.2	26.3
Type III	0.251	22.5	31.4
$\Delta = (E_L - E_L^*)/E_L \times 100\%$			

The relative errors are very high, meaning that the traditional flashover voltage calculation method leads to serious deviation in guiding external insulation design of field operating lines which are inevitably polluted by various kinds of constituents. A correction procedure should be proposed to consider the factors of soluble constituents and to optimize the flashover voltage calculation results.

4. Correction of Flashover Gradient Considering Soluble Pollution

4.1. Correction Based on Equivalent Salt Density Contribution Ratio

According to Equation (2) which was provided by literature [7], flashover voltage gradient under a salt mixture can be expressed by:

$$E_{LM} = \frac{\sum\limits_{i=1}^{m} SDD_i \times E_{Li}}{\sum\limits_{i=1}^{m} SDD_i} = (\sum_{i=1}^{m} SDD_i \times E_{Li})/ESDD_M \tag{6}$$

where E_{LM} is the flashover voltage gradient under a pollution mixture composed of *m* kinds soluble constituents, kV/m; $ESDD_M$ stands for the measured equivalent salt deposit density (*ESDD*) of the mixture pollution solution; SDD_i stands for equivalent salt deposit density contributed by soluble constituent *i*, mg/cm^2; and E_{Li} is the flashover voltage gradient corresponding to single soluble constituent *i* under $ESDD_M$.

E_{Li} can be obtained based on the fitting results in Table 5:

$$E_{Li} = A_i \times ESDD_M{}^{-n_i} \tag{7}$$

So, if $ESDD_M$ and SDD_i are determined, Equation (6) can be solved. For a certain pollution mixture, its $ESDD_M$ is directly the measured equivalent salt deposit density of the mixture solution. However, SDD_i of each soluble constituent in the given pollution mixture is uncertain, because the existing chemical test techniques can only determine the ion component and weight of each chemical constituent in the soluble mixture [16–18].

Suppose β_i is the weight percentage of soluble constituent *i* in the pollution mixture, α_i is the contribution ratio of a certain weight of constituent *i* to equivalent salt deposit density, and W_M is the total weight of the soluble mixture:

$$SDD_i = \alpha_i \times \beta_i \times W_M \tag{8}$$

With Equation (8), Equation (6) can be simplified and rewritten as:

$$E_{LM} = \frac{\sum\limits_{i=1}^{m} \left(\alpha_i \beta_i \times A_i \times ESDD_M^{-n_i}\right)}{\sum\limits_{i=1}^{m} \alpha_i \beta_i} = \sum\limits_{i=1}^{m} \left(\eta_i \times A_i \times ESDD_M^{-n_i}\right)$$

$$\eta_i = \frac{SDD_i}{ESDD_M} = \frac{\alpha_i \beta_i}{\sum\limits_{i=1}^{m} \alpha_i \beta_i}$$

(9)

where η_i stands for the *ESDD* percentage of soluble constituent *i*. It can be seen from Equation (9) that if α_i and β_i corresponding to each soluble constituent are determined, the flashover voltage gradient can be solved.

Equivalent salt density is basically derived from the conductivity of a certain solution, thus, soluble constituent conductivity tests were carried out. During the tests, the volume conductivity of each electrolyte solution under different concentrations was measured, and then the results were converted to the standard temperature (20 °C), as shown in Figure 4:
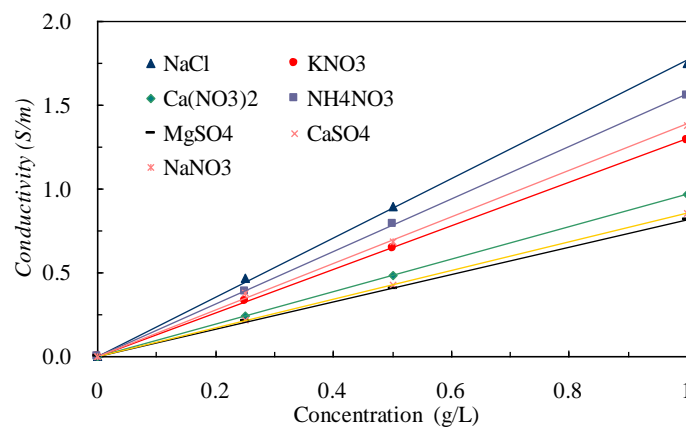

Figure 4. Different soluble constituent volume conductivity performance.

It can be seen that the volume conductivity presents an almost linear relationship with the increment of electrolyte concentration. It is known that *ESDD* is calculated based on the NaCl conductivity-weight relationship:

$$ESDD = \frac{S_a V}{A}$$

(10)

S_a can be calculated by volume conductivity, expressed as:

$$S_a = \left(5.7\sigma_{20}\right)^{1.03}$$

(11)

It can be seen that *ESDD* is almost linear with the volume conductivity. So, the contribution ratio of soluble constituents to *ESDD* can be obtained through comparing the conductivity curves' slopes to the NaCl conductivity curve slope, as shown in Table 8.

Table 8. Equivalent salt deposit density (*ESDD*) contribution ratio of soluble constituents.

Salt	NaCl	NH$_4$NO$_3$	KNO$_3$	Ca(NO$_3$)$_2$	CaSO$_4$	MgSO$_4$	NaNO$_3$
α_i	1.000	0.885	0.733	0.550	0.485	0.462	0.784

With Table 8 and the weight percentage of each constituent given in 6, Equation (9) can be solved, as is shown in Table 9.

Table 9. Flashover voltage gradient correction considering each constituent's contribution to *ESDD*.

Mixture Type	*ESDD* (mg/cm^2)	Calculated E_{LM} Using Equation (9) (kV/m)	Relative Error Δ (%)
Type I	0.081	49.9	1.5
Type II	0.082	51.0	−7.0
Type III	0.251	39.5	−20.4
Δ (%) = $(E_L - E_{LM})/E_L \times 100\%$			

It can be seen from the table that when considering the equivalent salt density of each soluble constituent, the relative errors between calculated and tested values decreased a lot. Two of the errors were already within 7%, which is acceptable for the prospective of practical engineering.

However, when it comes to a Type III pollution mixture, the relative error is still not acceptable. For Type III pollution, the amount of $CaSO_4$ makes up to 60%, and the *ESDD* reaches 0.251 mg/cm^2. In this circumstance, a large amount of $CaSO_4$ cannot be dissolved during the insulator wetting process, which means the *ESDD* contribution ratio of $CaSO_4$ needs to be reconsidered, given its easy saturation feature.

4.2. Correction Based on Calcium Sulfate's Slight Solubility

The contribution of $CaSO_4$ to *ESDD* is different from other soluble constituents, of which the solubilities are much higher, and the volume conductivities are linear with concentration. $CaSO_4$ is slightly soluble, with a solubility of about 2 g/L at 20 °C. The $CaSO_4$ on the surface of an insulator cannot dissolve sufficiently during the actual insulator wetting process in a steam chamber.

Under normal circumstances, one standard suspension insulator unit can only be coated by approximately 20 mL water [13], and this volume is much smaller than the 300 mL water used when measuring the *ESDD*. This fact will not affect the contribution of good diffluent constituents, but does bring obvious error when hard-to-dissolve salt $CaSO_4$ makes up a large part of the pollution mixture, because in this case a greater portion of the $CaSO_4$ does not act as conductive electrolyte if the insulator surface is wetted by just 20 mL water.

Considering this, the conductivity performance of high concentration $CaSO_4$ solution was measured, and then a comparison was made between the *ESDD* contribution of $CaSO_4$ in 20 mL solution and in 300 mL solution, as shown in Figure 5.
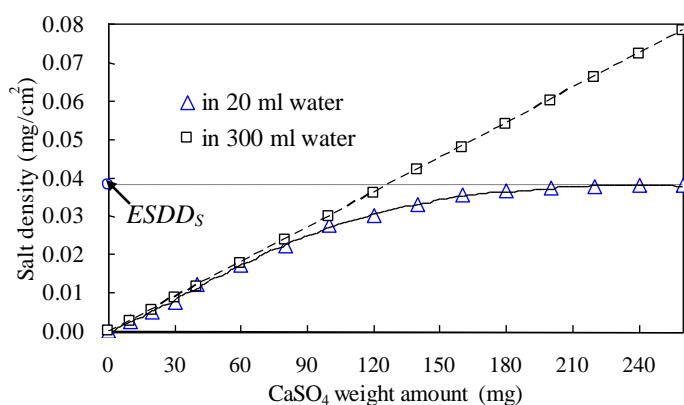
Figure 5. The *ESDD* contribution of $CaSO_4$, considering different amounts of water.

It can be seen from Figure 4 that the *ESDD* contribution of $CaSO_4$ is overrated, considering the limited volume of insulator surface water absorbed. The saturated *ESDD* contribution ($ESDD_S$, as shown Figure 5) of $CaSO_4$ is only equal to 0.038 mg/cm^2 if the water volume is 20 mL, which is much lower than the *ESDD* contribution for a volume of 300 mL.

The *ESDD* contribution of $CaSO_4$ under 300 mL solution ($ESDD_i{}^{300}$) can be calculated using the measured $ESDD_M$, based on Equation (9):

$$ESDD_i{}^{300} = \eta_i \times ESDD_M \quad i = CaSO_4 \tag{12}$$

Then, according to Figure 5, the corrected $CaSO_4$ *ESDD* contribution, considering slight solubility and limited wetting amount, can be expressed as follows:

$$ESDD_i^{20} = \begin{cases} ESDD_i^{300}, ESDD_i^{300} < ESDD_S \\ ESDD_s, ESDD_i > ESDD_S \end{cases} \tag{13}$$
$$i = CaSO_4, ESDD_S = 0.038 mg/cm^2$$

where $ESDD_i^{20}$ is the corrected value, assuming the largest surface-coated volume of water is 20 mL. The measured *ESDD* value of the pollution mixture should also be corrected to the 20 mL situation:

$$ESDD_M^* = ESDD - ESDD_i^{300} + ESDD_i^{20} \tag{14}$$
$$i = CaSO_4$$

Then, the *ESDD* percentage of each constituent should be modified:

$$\eta_i^* = \begin{cases} \dfrac{\eta_i \times ESDD_M}{ESDD_M^*} & i \neq CaSO_4 \\ ESDD_i^{20}/ESDD_M^* & i = CaSO_4 \end{cases} \tag{15}$$

Considering the slight solubility of $CaSO_4$, and using Equations (14) and (15) to correct the measured equivalent salt deposit density ($ESDD_M$) and *ESDD* percentage (η_i) of each constituent, the results are as shown in Table 10.

Table 10. Correction of measured equivalent salt deposit density and *ESDD* percentage of each soluble constituent.

Pollution Type	Type I		Type II		Type III	
$ESDD_M$ correction	$ESDD_M$ 0.081	$ESDD_M{}^*$ 0.081	$ESDD_M$ 0.082	$ESDD_M{}^*$ 0.082	$ESDD_M$ 0.251	$ESDD_M{}^*$ 0.164
η_i correction	η_i	$\eta_i{}^*$	η_i	$\eta_i{}^*$	η_i	$\eta_i{}^*$
$CaSO_4$	0.451	0.451	0.468	0.468	0.503	0.232
NaCl	0.212	0.212	0.183	0.183	0.237	0.363
KNO_3	0.107	0.107	0.082	0.082	0.122	0.186
$NaNO_3$	0.110	0.110	0.031	0.031	0.000	0.000
NH_4NO_3	0.092	0.092	0.000	0.000	0.000	0.000
$MgSO_4$	0.028	0.028	0.034	0.034	0.064	0.097
$Ca(NO_3)_2$	0.000	0.000	0.202	0.202	0.075	0.115

It can be seen from the table that for the Type III pollution mixture, its actual equivalent salt deposit density and constituent *ESDD* percentage are changed obviously after correction. This is because the weight of $CaSO_4$ in the Type III pollution mixture is much greater than those in the other two types.

As the table shows, for the Type III pollution mixture, its actual equivalent salt deposit density should be 0.164 mg/cm^2, decreased by 34.6% compared to the measured value using 300 mL water; the *ESDD* percentage of $CaSO_4$ should be 0.232, decreased by 54% compared to the measured value using 300 mL; and for other soluble constituents, their *ESDD* percentage increased a bit. This indicates that the traditional method of measuring *ESDD* will overrate the influence of slightly soluble constituents on flashover voltage.

Using the corrected data of Table 10 to correct the E_{LM} value:

$$E_{LM}^* = \sum_{i=1}^{m} \left(\eta_i^* \times A_i \times ESDD_M^{*-n_i} \right) \tag{16}$$

The corrected flashover voltage gradient values and corresponding relative errors are as shown in Table 11.

Table 11. Flashover voltage gradient correction, considering the slight solubility of $CaSO_4$.

Pollution Mixture Type	*ESDD* (mg/cm²)	Calculated $E_{LM}{}^*$ Use Equation (9) (kV/m)	Relative Error Δ (%)
Type I	0.081	49.9	1.5
Type II	0.082	51.0	−7.0
Type III	0.251	34.3	−4.4
$\Delta = (E_L - E_{LM}{}^*)/E_L \times 100\%$			

It can be seen obviously that the relative error for the Type III pollution mixture decreases from −20.4% to −4.4%, which means the correction, when considering the slight solubility of $CaSO_4$, does lower the calculated error, making the flashover voltage gradient calculation more accurate and scientific.

5. Discussion

The flashover tests in a laboratory climate chamber cannot actually reflect the real flashover of a natural polluted insulator, making the voltage calculating error inevitable. However, through the correction process proposed in this paper, the error can be significantly reduced. It is important to calculate the *ESDD* contribution ratio of each soluble constituent when predicting flashover voltage of natural polluted insulator, because different soluble constituents on an insulator surface correspond to different flashover performances. Also, consideration of $CaSO_4$ saturation performance is a necessary step due to $CaSO_4$ always occupies the largest proportion of natural contaminants.

Currently, the effects of pollution constituents have been brought to the attention of relative research institutes. They conducted plenty of measurements on field insulator surface chemical components, and the most commonly used method is IC (ion chromatograph) analysis [4,16–18]. This method provides accurate categorization of negative and positive ions, as well as their mass percentage in the pollution solution. Then, the soluble constituents and their weights in the pollution solution can be easily determined by pairing the ions. Based on this, the flashover gradient of an insulator under natural pollution conditions can be better determined through a systematical correction procedure shown in Figure 6.
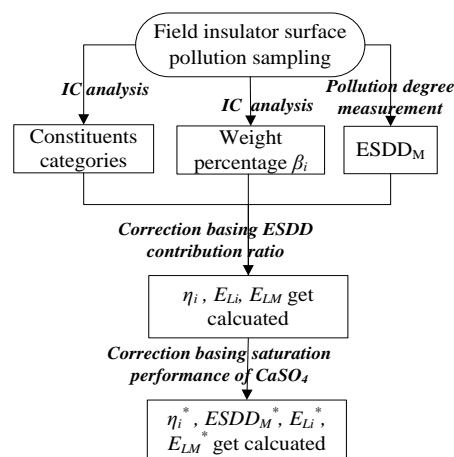

Figure 6. Flashover voltage gradient correction procedure for natural polluted insulator.

This procedure remedies the deficiency of the traditional *ESDD* method by considering the soluble constituents of insulator surface contaminants, and it is easy to implement in engineering practice.

6. Conclusions

In this paper, a systematic study on insulator flashover gradient correction involving different soluble pollution constituents was presented, and the conclusions are as follows.

(1) Insulator flashover performance is quite different with differently soluble constituents. A higher *ESDD* value does not always mean a lower flashover voltage when the soluble constituent is different.

(2) For the seven kinds constituents with different solubilities presented in this paper, the *A* value of the insulator sample varies within 15.5–36.2 and *n* varies within 0.19–0.34. Different solubilities of constituents correspond to very different E_L-*ESDD* relationships.

(3) The proposed flashover gradient correction method, which considers a soluble constituent's *ESDD* contribution and $CaSO_4$ saturation characteristic, performs well for reducing the calculating error. It is recommended to carry out component measurements and flashover gradient correction to better select outdoor insulation configuration.

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