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Article

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 systematical research on insulator flashover voltage gradient correction involving types of soluble pollution constituents was presented. Taking 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 combining the flashover performance of each soluble constituent, the ESDD contribution of the seven constituents, as well as the saturation performance of $CaSO_4$. The correction was well verified with the flashover test results of insulator polluted by three types of soluble mixture. Research results indicate that the flashover gradient correction method proposed by 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.

Keywords: insulator; pollution flashover; equivalent salt deposit density (ESDD); soluble constituent; flashover voltage gradient

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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 et al [1]. Due to pollution source feature, geographical environment and weather conditions, there are a great diversity of chemical constituents' deposit on insulator surface during contaminating [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 some conductive materials including NaCl, $NaNO_3$, KCl, KNO_3, $Mg(NO_3)_2$, $MgSO_4$, NH_4NO_3, NH_4Cl, $(NH_4)_2SO_4$, $Ca(NO_3)_2$, $CaSO_4$ et al according to the research data in [3-5].

All these constituents must impair their 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]:

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

where U_f is the flashover voltage under a measured ESDD (equivalent salt deposit density), A is a coefficient related to the shape of the insulator, n is a characteristic exponent characterizing the influence of ESDD on U_f. In this formula, ESDD is derived from converting pollution solution conductivity to the amount of NaCl, and A, n is 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.

Viewing 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, the 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:

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

where $U_{LFOV\Sigma}$ is the limiting flashover voltage corresponding to mixture electrolyte solution; U_{LFOVi} is the limiting flashover voltage of single electrolyte solution *i*; $\rho_{ESDD\Sigma}$ stands for the equivalent salt deposit density (ESDD) of the mixture electrolyte solution; ρ_{ESDDi} stands for the ESDD of single electrolyte solution *i*.

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 twelve 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 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 theoretical basis for contamination constituent's effects on insulation property. However, during laboratory artificial tests, pollution degree measurements, as well as field insulation design, NaCl is still used as the only representation for conductive constituent. Moreover, few of the previous works proposed procedure of flashover voltage gradient correction considering 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 constituents and the saturation performance of $CaSO_4$ were analyzed. The corrected flashover gradients were well verified with insulator flashover test results under three types of soluble mixtures. This research is intended for 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. Its technical parameters and profiles of the sample are shown in Table 1, in which *h* is the configuration height, *l* is the leakage distance and *d* is the diameter of insulators.

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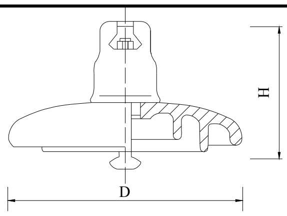
Table 1 Profile parameters of the insulator sample

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

2.2 Experimental setups

The tests were carried out in the multi-function 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 frequent is 50 Hz. The test circuit was shown in Figure 1, where B is the voltage regulator, T is the test transformer, R_0 is the protective resistance (10 k ohms), H is the wall bushing, F is the capacitive voltage divider (1000:1), E is the climate chamber, C is the leakage current measurement system and S is the sample. The setups meet the requirements of pollution flashover test.

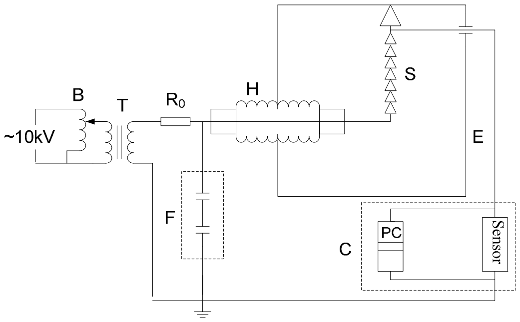


Figure 1. Schematic diagram of the AC test circuit

2.4 Test procedure

2.4.1 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 let to dry naturally indoor to avoid dust or other pollution, and the relative humidity surround was less than 70%RH.

2.4.2 Polluting

Dipping method was applied to pollute the sample. The pollution solution was made strictly referring to standards [14-15]: firstly, add the soluble constituent until the volume conductivity reaches a predetermined value, and then add kaolin 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 surface.

After each dipping procedure, select three pieces of the samples randomly and measure the average value of their equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD), as the ESDD and NSDD of the soaked samples. When measuring the ESDD of the polluted samples, use 300 ml deionized water basing on IEC standard to wipe off the contaminants.

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

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2.4.3 Flashover test

The polluted insulators were firstly pre-charged by a predicted voltage level and then wetted by steam fog. The fog was generated by a 1.5 t/h boiler, of which the rate was 0.05 ± 0.01kg/h·m³. During flashover test, the temperature in the chamber was controlled between 30 ºC and 35 ºC through the refrigeration system and the atmospheric pressure is 98.6 kPa in all the experiments.

In the tests, up-and-down method was adopted to get the 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 according to the up-and-down method. 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, apply a small voltage on the suspended samples, and then open the steam fog; the wetting condition of the surface is judged by observing the surface water film situation as well as the variation of recorded leakage current waveform. When the surface water films are formed and connected with each other, or the leakage current reaches a high value and appears a decreasing, the insulator pollution surface can be treated as wholly wetted. Then lift the voltage till flashover. The final voltage value is the predicted flashover voltage.

When testing, the polluted insulators were firstly pre-charged by a predicted flashover voltage level, and then open the steam fog. If flashover occurs, the voltage applied in the next test was set 5% lower; but if the current recorded peaks have decreased to values permanently lower than 70% of the maximum peak [14], the withstand of the insulator is definitive and the test can be 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, and N is the total number of "valid" tests, σ is the relative standard deviation.

3 Test results and analysis

Insulator flashover voltage gradient can be expressed by:

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

where L is the total creepage distance, E_L is the flashover voltage gradient, kV/m.

Table 2. Test results of insulator strings polluted with different soluble constituents

Soluble constituent	Flashover Parameters	Test results		
NaCl	*ESDD* (mg/cm²)	0.027	0.045	0.078
	NSDD (mg/cm²)	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/cm²)	0.032	0.055	0.072
	NSDD (mg/cm²)	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/cm²)	0.024	0.039	0.073

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	NSDD (mg/cm²)	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/cm²)	0.031	0.056	0.100
	NSDD (mg/cm²)	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/cm²)	0.026	0.051	0.109
	NSDD (mg/cm²)	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/cm²)	0.049	0.082	0.160
	NSDD (mg/cm²)	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/cm²)	0.055	0.145	0.028
	NSDD (mg/cm²)	0.092	0.088	0.079
	E_L (kV/m)	65.3	56.9	72.8
	σ (%)	5.1	5.6	5.3

It can be seen from Table 2 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/cm² through 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/cm², insulator E_L is 55.5 kV/m; but when the soluble constituent is $MgSO_4$ and ESDD increase to 0.049 mg/cm², the E_L increase to 57.3 kV/m. A higher ESDD value does not always mean a lower flashover voltage when the soluble constituent is different.

(3) Use the negative exponent function in Eq.(1) to fit the data in Table 1, the results were shown in Fig.2.

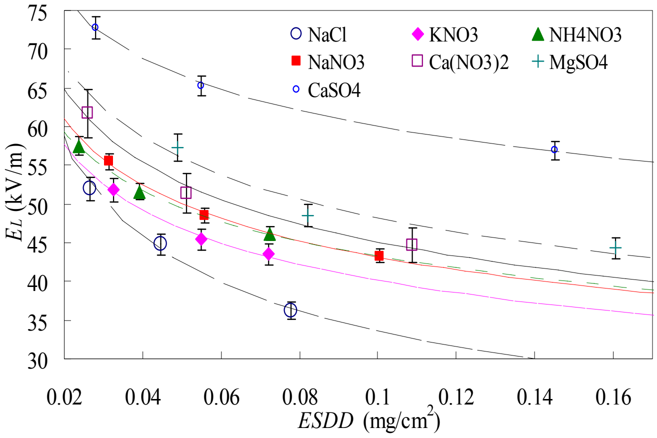

Figure2. Fitting curves of each soluble constituent using nagative expoent function

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

Fitting results of coefficients *A* and *n* were shown in Table 3.

Table 3. 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. 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 paper three types of pollution mixture were simulated, which represented highway area, chemical plan area and seaside respectively. Test results were shown in Table 4.

Table 4. 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)	0.081
	NSDD (mg/cm^2)	0.117
	E_L (kV/m)	50.6
	σ (%)	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)	0.082
	NSDD (mg/cm^2)	0.128
	E_L (kV/m)	47.8
	σ (%)	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)	0.251
	NSDD (mg/cm^2)	0.112
	E_L (kV/m)	32.8
	σ (%)	4.6

It can be seen from Table 3 that, under different types of pollution mixtures, the flashover performance is different. For example when ESDD is 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, decreased by 6%.

Use the traditional method, which is only based on insulator flashover performance under NaCl (shown in Eq.(1)), to calculate the flashover voltage gradient under pollution mixture. Calculation results and relative errors are shown as follows:

Table 5. Test results of insulator strings polluted with three types of soluble constituents mixture

Mixture Type	***ESDD* (mg/cm^2)**	**Calculated 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 gets 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 as well as to optimize the flashover voltage calculation results.

4 Correction of flashover gradient considering soluble pollution

4.1 Correction basing equivalent salt density contribution ratio

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

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

where E_{LM} is the flashover voltage gradient under mixture pollution 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/cm²; E_{Li} is the flashover voltage gradient of single soluble constituent *i* at the ESDD equal to $ESDD_M$.

E_{Li} can be obtained based on the fitting results in Table 3:

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

where *i* stands for a certain soluble constituent, A_i and n_i are as presented in Table 3.

So if $\mathrm{ESDD_M}$, SDD_i are determined, Eq.(6) can be solved. For certain mixture pollution, its $\mathrm{ESDD_M}$ is directly the measured equivalent salt deposit density of mixture solution. However SDD_i is uncertain for a given insulator surface pollution sample, because current chemical test techniques can only determine the ion component and weight amount of each chemical constituent in soluble pollution mixture [16-18].

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

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

With Eq.(8), Eq.(6) can get simplified and rewritten to :

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

$$\eta_i = \frac{SDD_i}{ESDD_M} = \frac{\alpha_i \beta_i}{\sum_{i=1}^{m} \alpha_i \beta_i} \tag{9}$$

where η_i stands for the ESDD percentage of soluble constituent *i*. It can be indicated from Eq.(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 (20ºC), as shown in Figure 3:

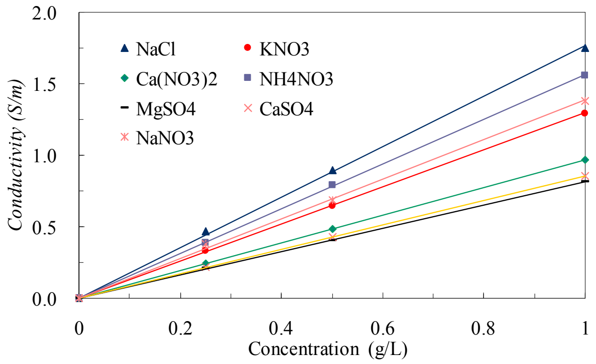

Figure 3. Different soluble constituent volume conductivity performance

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 basing on NaCl conductivity-weight relationship:

$$ESDD=\frac{S_a V}{A} \tag{10}$$

where V is the volume of the suspension (cm^2), 300 ml in this paper; A is the area of the cleaned surface (cm^2); S_a is the salinity (kg/m^3). S_a can be calculated by volume conductivity, as is expressed:

$$S_\mathrm{a}=\left(5.7\sigma_{20}\right)^{1.03} \tag{11}$$

where σ_{20} is the volume conductivity at a temperature of 20 ºC (S/m). It can be seen that ESDD is almost linear with the volume conductivity. So the contribution ratio of other soluble constituents to ESDD can be obtained through comparing the conductivity curves' slopes, as shown in Table 6:

Table 6. ESDD Contribution ratio of other soluble constituents

Salt	NaCl	NH_4NO_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 6 and the weight percentage of each constituent given in Table 3, Eq.(9) can get solved, as is shown in Table 7:

Table 7. Flashover voltage gradient correction considering each constituent's contribution to ESDD

Mixture Type	*ESDD* (mg/cm^2)	Calculated E_{LM} use Eq. (9) (kV/m)	Relative error △ (%)
Type I	0.081	49.9	1.5
Type II	0.082	51.0	-7.0
Type III	0.251	39.5	-20.4
△ (%)=(E_L−E_{LM})/E_L×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 Type III pollution mixture, the relative error is still not acceptable. For Type III pollution, the amount of $CaSO_4$ takes up to 60%, and the ESDD reaches 0.251 mg/cm^2. Under this circumstance, large amount of $CaSO_4$ can not get 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 basing calcium sulfate slight solubility

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

Under normal circumstances one standard suspension insulator unit can only be coated by approximately 20 ml water [13], and this amount is much smaller than the 300 ml water used when measuring the ESDD. This fact will not effect the contribution of good diffluent constituents, but does bring obvious error when hard-to-dissolve salt $CaSO_4$ takes large part of the pollution mixture, because under this case much more of the $CaSO_4$ did not act as conductive electrolyte if insulator surface was wetted by just 20 ml water.

Viewing this, measure the conductivity performance of high concentration $CaSO_4$ solution, and then compare the ESDD contribution of $CaSO_4$ under 20 ml and under 300 ml, as shown in Figure 4.

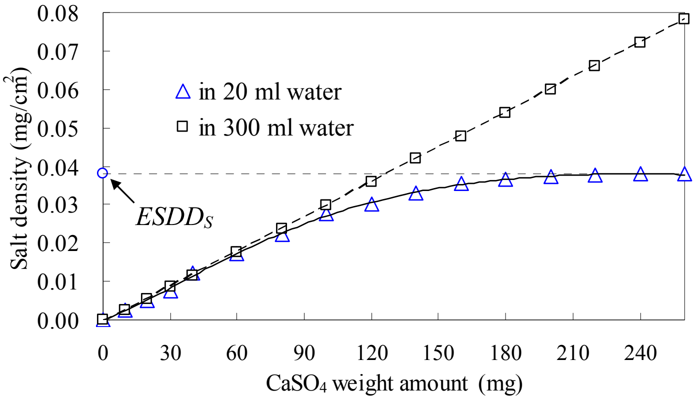

Figure 4. The ESDD contribution of caso4 considering different water amount

It can be seen from Figure 4 that, the ESDD contribution of $CaSO_4$ is overrated considering limited insulator surface water absorption amount. The saturated ESDD contribution (*$ESDD_S$*, as shown Figure 4) of $CaSO_4$ is only equal to 0.038 mg/cm² if the water amount is 20 ml, which is much lower than that under 300 ml.

The ESDD contribution of $CaSO_4$ under 300 ml ($ESDD_i^{300}$) can be calculated using the measured $ESDD_M$ basing Eq.(9):

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

Then according to Figure 4, the corrected $CaSO_4$ ESDD contribution considering slight solubility and limited wetting amount can be expressed as follows:

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

where $ESDD_i^{20}$ is the corrected value assuming the largest surface coated water amount is 20 ml.

The measured ESDD value of pollution mixture should also be corrected to the 20 ml situation:

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

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 Eq.(14) and (15) to correct the measured equivalent salt deposit density ($ESDD_M$) and ESDD percentage (η_i) of each constituent, the results were as shown in Table 8:

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Table 8. 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	$ESDD_M$	$ESDD_M^*$	$ESDD_M$	$ESDD_M^*$	$ESDD_M$	$ESDD_M^*$
	0.081	0.081	0.082	0.082	0.251	0.164
η_i correction	η_i	η_i^*	η_i	η_i^*	η_i	η_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 Type III pollution mixture, its actual equivalent salt deposit density and constituent ESDD percentage get changed obviously after correction. It is because the weight amount of $CaSO_4$ in Type III pollution mixture was extremely larger than those in other two types.

As the table shown, for Type III pollution mixture, its actual equivalent salt deposit density should be 0.164 mg/cm², decreased by 34.6% as the measured value using 300 ml; the ESDD percentage of $CaSO_4$ should be 0.232, decreased by 54% as the measured value using 300 ml; and for other soluble constituents, their ESDD percentage increased a bit. This well indicated that the traditional method of measuring ESDD will overrate the influence of slightly soluble constituent on flashover voltage.

Using the corrected data of Table 7 to correct the E_{LM} value:

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

The corrected flashover voltage gradient values and corresponding relative errors are as shown in Table 9:

Table 9. **Flashover voltage gradient correction considering slight solubility of $CaSO_4$**

Pollution mixture Type	*ESDD* (mg/cm²)	Calculated E_{LM}^* use Eq.(9) (kV/m)	Relative error △ (%)
Type I	0.081	49.9	1.5
Type II	0.082	51.0	-7.0
Type III	0.251	34.3	-4.4

$△=(E_L-E_{LM}^*)/E_L\times 100\%$

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

5 Discussion

The flashover tests in laboratory climate chamber cannot actually reflect the real flashover of natural polluted insulator, making the voltage calculating error inevitable. However, through the correction process proposed by this paper, the error can get 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 constituent on insulator surface corresponds to different flashover performance. Also, consideration of $CaSO_4$ saturation performance is a necessary step due to $CaSO_4$ always takes the largest part of the natural contaminants.

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Currently, the effects of pollution constituents have 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 [16-19]. This method provides accurate categories of negative and positive ions, as well as their mass percentage in the pollution solution. Then the soluble constituents and their weight amount in the pollution solution can get easily determined through pairing the ions. Based on this, the flashover gradient of insulator under natural pollution can get better determined through a systematical correction procedure shown as follows:

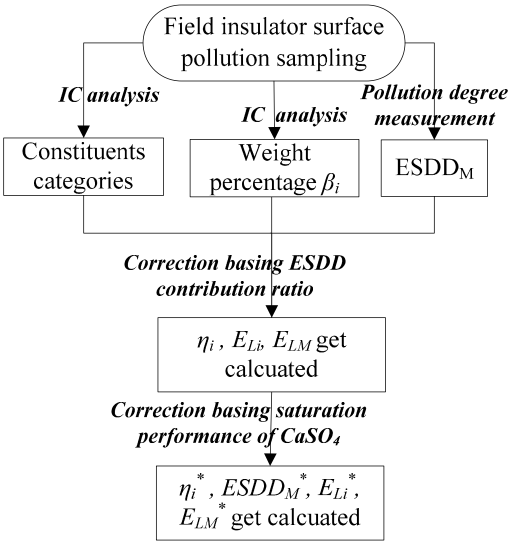

Figure 5. Flashover voltage gradient correction procedure for natural polluted insulator

This procedure does remedy the deficiency of traditional ESDD method in considering the soluble constituents of insulator surface contaminants, and it is easy to get implemented in engineering practice.

6 Conclusion

In this paper, a systematical research on insulator flashover gradient correction involving different soluble pollution constituents was presented, conclusions are as follows:

(1) Insulator flashover performance is quite different under different 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 soluble constituents in this paper, the A value of the insulator sample varies within 15.5 – 36.2, n varies within 0.19 – 0.34. Different soluble constituent corresponds to very different E_L-ESDD relationship.

(3) The proposed flashover gradient correction method, which considers soluble constituent's ESDD contribution and $CaSO_4$ saturation characteristic, 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.

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