

The Reliability Study of the Statistical Method on Insulator Dimensioning of (U)HVDC Lines with Regard to Pollution Conditions

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Abstract--The reliability of DC lines is critical for the reliability of Ultra High Voltage (UHV) DC system operation. Being the main factor in determining the reliability of DC lines, the external insulation is designed mainly with the consideration of the pollution performance of DC insulators at the operating voltage in contaminated areas. Among the approaches for external insulation design, the statistical method would be a good candidate with the consideration of the statistical nature of the input variables. In order to use the statistical method with reasonable confidence for (U)HVDC projects, the influences of various potential inputs on the dimensioning results with statistical principles are studied and evaluated in a cooperative project between ABB and China EPRI. The results demonstrate that the interpretation from the natural conditions to artificial conditions or vice versa is most important for the reliability of the insulator dimensioning in the statistical method because it affects the insulator performance and consequently the dimensioning results significantly. It also shows that the different parameters have different effects on the design result. The study is the important step for input preparation for the statistical dimensioning of insulators with regard to pollution conditions on (U)HVDC lines.

Index Terms—Insulator Dimensioning, Pollution, Statistical Method, DC Lines, (U)HVDC, Reliability.

I. INTRODUCTION

Large-capacity HVDCs have been the popular solutions for power transmissions in various countries. The reliability of DC lines is critical for the reliability of (U)HVDC system operation, and the external insulation design with regard to pollution performance is the determining factor for the reliability of DC lines in the contaminated environment [1]. With the coming UHVDC project in China, the higher requirements are needed for external insulation, and more investigations are thereby motivated.

The approaches for insulator dimensioning generally can be classified into the deterministic method and statistical method. The statistical method would be a promising candidate since it is applied for insulation dimensioning with

the consideration of the statistical nature of the input variables. However, the approach is rarely accepted by the designers so far because more detailed and reliable input data is needed to describe the variables, most of which are often difficult to be available [1]. In spite of this, new efforts have been made recently to develop software applications with the statistical principles, in an attempt to help the designers with the line design or line performance assessment [2-4]. It is important to validate the applications with the existing projects. However, up to now, there is lack of clear guidance about the numerous and complicated inputs for the users. And it is not well known yet how and how much all variables have influences on the reliability of the dimensioning results. The preparation of the input data therefore becomes important for the reliability of benchmark, and also one of the important works before the statistical method can be used with reasonable confidence.

In a cooperative project between ABB and China Electrical Power Research Institute (CEPRI), the influence of various parameters are studied and evaluated on the dimensioning results based on statistical principles. The results can be used as a reference/guide to inputs preparation for benchmark with existing HVDC projects. It is also one of the important steps in the reliability of the outdoor insulation design or assessment for (U)HVDC projects with statistical principles.

II. SOLUTION AND METHODOLOGY

A. Principles

The optimal dimensioning results with statistical principles are obtained by the calculation of the line's risk-of-failure to an acceptable value at the specific operating voltage. The equation is given as follows [5-6].

$$R = M \int_{-\infty}^{\infty} f(x)P(x)dx \quad (1)$$

In which $f(x)$ is probability density function of site severity at the start of a wetting event, $P(x)$ is the cumulative function of insulator flashover probability, x is the site severity (Equivalent Salt Deposit Density (ESDD)), M is the number of wetting events in the calculated period, and R is the line's risk-of-failure.

When the insulation with the higher strength is selected,

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the probabilistic flashover curve moves towards the right of the distribution function of ESDD, so that the risk-of-failure decreases, as shown in Figure 1 [1, 6-7].

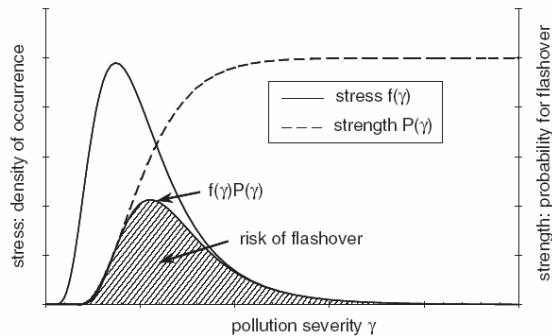


Fig. 1 The principle of the statistical method

B. Influencing factors

According to the figure 1, both the pollution performance of DC insulators and the pollution severity in the areas where HVDC lines pass through are decisive factors for insulation design. However, the pollution performance, $P(x)$, is obtained in laboratory tests under typical conditions; while the distribution function of pollution severity density is derived from the natural conditions. It has been recognized that there are significant differences in the behavior of insulators under these two conditions [1]. In order to make correctly use of the data from these two different sources, correction factors are needed for the conversion and unification. Such correction factors have mostly been obtained from artificial tests. As an example, Table 1 summarizes the major differences between natural conditions and laboratory test conditions (solid layer method) for the line insulators [8].

In addition to the factors listed in Table 1, there are some other differences between the natural conditions and test conditions, e.g. wetting method and intensity [1]. For insulator dimensioning with statistical principles, more parameters, e.g. the standard deviation of the probability density distribution of pollution severity (e.g., lognormal distribution, $\text{Ln}(\text{ESDD})$), the standard deviation of insulator performance, number of strings in parallel and number of wetting events also have influences on insulator design.

C. Equations and basic conditions

A bind of equations for insulator dimensioning of DC lines in respect of polluted conditions is proposed to be evaluated with the operational data of the existing HVDC projects. To date, many studies have been conducted and reported on DC flashover voltages at various laboratories under different test conditions, e.g. different inert materials and different quantities [16-22]. Based on the results of literatures, the following equations are obtained by analyzing the data in numerical statistical way.

- The flashover characteristics as function of pollution severity (Salt Deposit Density (SDD)), under 0.1 mg/cm^2 of NSDD (Roger's Kaolin) and uniform distribution, for the DC porcelain insulators

- The conversion between SDD and ESDD with the consideration of calcium ion proportion in natural contamination
- The conversion between SDD and ESDD with the consideration of the organic component in natural contamination
- The correction of the type of NSDD
- The correction of the quantity of NSDD
- The correction of the contaminant distribution on the surface between the top and the bottom of the insulator

The dimensioning results by the equations are then tested by the design data [16,17], and the maximum errors of the required number are 3% and 5% separately.

In addition to the equations aforementioned, there are some assumed conditions used for the study in Section III as shown in Table 2.

TABLE 1 THE DIFFERENCES BETWEEN NATURAL CONDITIONS AND STANDARD POLLUTION TEST CONDITIONS FOR PORCELAIN INSULATORS.

Factors	Natural conditions	Test conditions	Empirical correction
Different in shed profiles	Often different in pollution accumulation	Same uniform pollution for all type of sheds	None
Top/bottom surface of a shed	Often non-uniformly polluted	Uniform	Available [9-12]
Along the insulator	Often non-uniformly polluted	Uniform	Available [12]
Type of salt	Different and site dependent	Sodium Chloride (NaCl)	Available for some cases [10,11,13]
Type of Non-Soluble Deposit Density (NSDD)	Can be various types and site dependent	Kaolin or Tonoko	Available between a few types used in artificial tests [9,12,14,20]
Quantity of NSDD	Site dependent	40g in 1000g water	Available [9-10,12-15]
Installation in a non-vertical position	Often accumulate less pollution	Often not being considered	None

TABLE 2 THE SPECIFIED VALUES FOR THE PARAMETERS IN STUDY

Conditions	Values and References
Insulator type	The specified DC porcelain insulator
Line length	100km
Number of strings	500
The maximum system operating voltage	515kV

Acceptable risk-of-failure	0.02/(100km.yr)
The standard deviation for Ln(ESDD)	0.45 or 0.3-0.8 [5,23]
Calcium ion proportion	70%-90%, according to the measurements along Gezhouba-Nanqiao HVDC lines [10]
NSDD/ESDD	4-6 [10]
Top to bottom ratio	1/3 when ESDD=0.03mg/cm ² 1/5 when ESDD=0.05mg/cm ² 1/8 when ESDD=0.08mg/cm ² 1/10 when ESDD≥0.1mg/cm ² [10]
The number of wetting events	10-100, estimated according to the regional navigation information along Yangtse River

III. SENSITIVITY STUDY

A. Calcium ion

The influence of the calcium salt on the dimensioning results is studied and the results are shown as in Figure 2.

It shows that the dimensioning results are affected significantly by the calcium ion proportion. The required number estimated without consideration of the correction is over 10 pieces more than the estimation with 70% of calcium ion proportion. And the difference of the results between 70% and 80% of the calcium ion proportion is about 5-7 pieces. It is evident that the design needs to be optimized with the consideration of the salt type of ESDD. The salt type and proportion, e.g. the calcium ion proportion, should be measured and estimated.

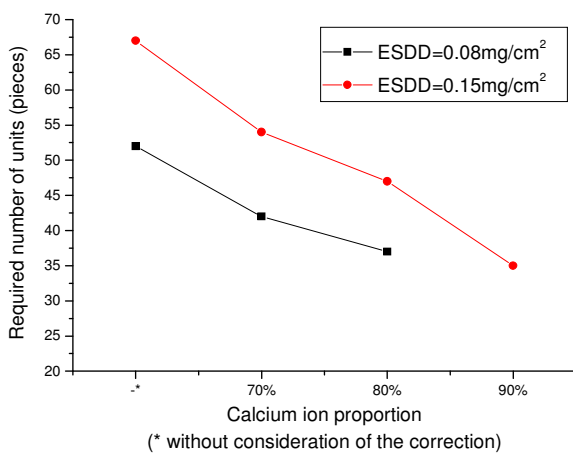


Fig. 2 The influence of calcium ion proportion on insulator dimensioning of DC lines (The number of wetting events is 1)

B. NSDD

The influence of different quantity of NSDD on dimensioning results is shown as in Figure 3. According to the results, there is a remarkable difference between the result with and without the correction of NSDD by 17% of the

average difference. The ratio of NSDD to ESDD does not have a significant effect on the results. For instance, at 0.08mg/cm², the required number is 49 and 52 for the ratio of 4 and 6 respectively. The difference is not influenced significantly by the wetting events. One ratio reasonably estimated from on site measurement, e.g. 5, can be adopted.

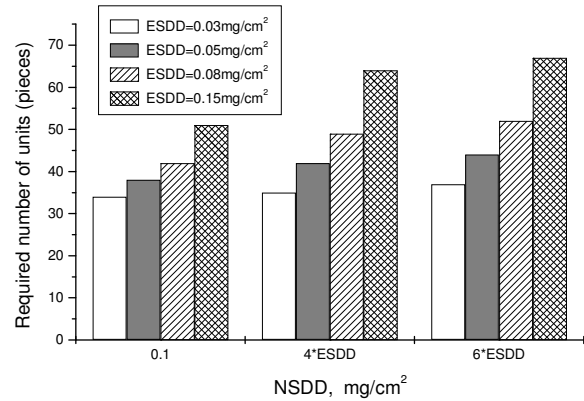


Fig. 3 The influence of NSDD quantity on the estimation of dimensioning (The number of wetting events is 1)

C. Non-uniform distribution

Figure 4 shows the influence of non-uniform distribution between the top and bottom of the insulator's surface. The results differ remarkably between with uniform distribution (1/1) and non-uniform distribution (1/10). The average difference is larger than 20%. However, the difference is not significant between 1/10 of the top to bottom ratio and the values given in Table 2, especially at moderate and heavy pollution levels. The non-uniform distribution on the surface of insulators should be considered in design. Typical value, e.g. 1/10, can be used.

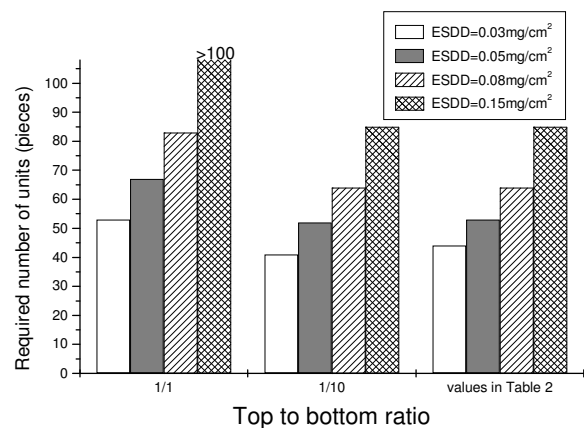


Fig. 4 The influence of the non-uniformity distribution on the estimation of dimensioning (The number of wetting events is 30)

D. Standard deviation of probability density distribution of pollution severity

Usually, lognormal/normal distribution function is used to describe the pollution accumulation. Both the mean and variance are derived by the measurement. The influence of

different standard deviations of $\text{Ln}(\text{ESDD})$ on insulation dimensions is shown in Figure 5 for 30 of the number of wetting events. The results are affected by the standard deviation remarkably by about 2 pieces and 4 pieces per 10% increase of the standard deviation, at 0.03 and 0.08 mg/cm^2 respectively. The standard deviation of $\text{Ln}(\text{ESDD})$ has more influence on the results under the heavier pollution condition.

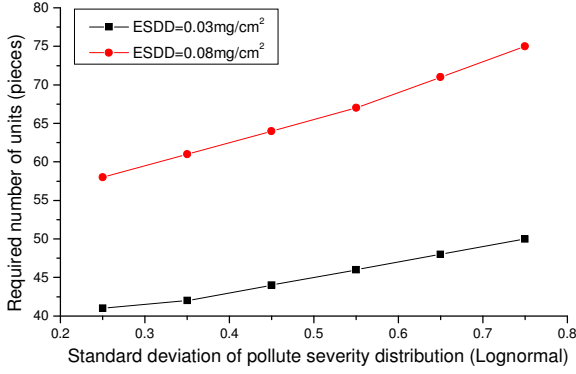


Fig. 5 The influence of standard deviations of pollution severity distribution on the dimensioning results (pollution severity as lognormal distribution with design ESDD as 2% maximum value)

E. Standard deviation of insulator performance

According to the results in Figure 6, the influence of the variance of flashover voltages on the dimensioning results is remarkable and the dimensioning results increase with the increase of standard deviation by about 2 pieces per 1% of the deviation change.

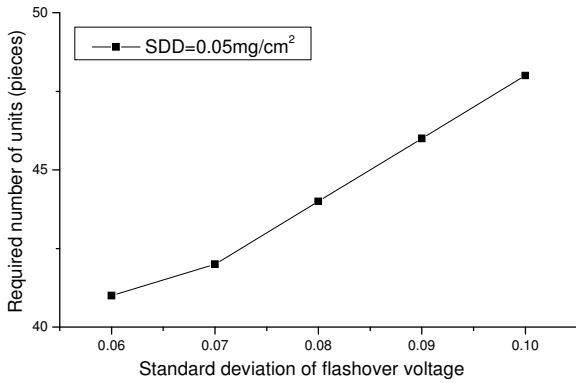


Fig. 6 The influence of standard deviations of flashover performance on the dimensioning results

F. Number of strings

The study with different number of strings in parallel shows that the results are not sensitive to the string number if the number is greater than 100 (Figure 7). Since the number of strings is often more than 100 for a line section longer than 25km. A typical value between 100 and 1000 can be used in design, without leading to a significant difference. With the shorter line section, the actual number should be adopted, in particular at the moderate and heavy pollution areas.

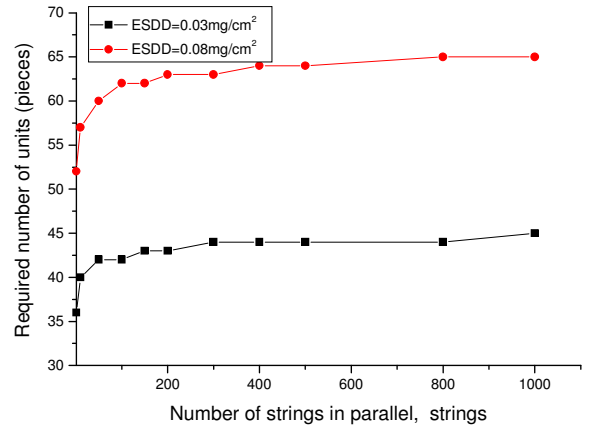


Fig. 7 The influence of strings in parallel on dimensioning estimation

G. Number of events

As shown in Figure 8, the number of wetting events has a significant influence on the dimensioning results when the number is below 50. The effects of the number of wetting events are involved with other parameters, e.g. pollution level, the standard deviation of pollution severity distribution. The joint effect of the wetting events with other parameters are not described in detailed in the paper.

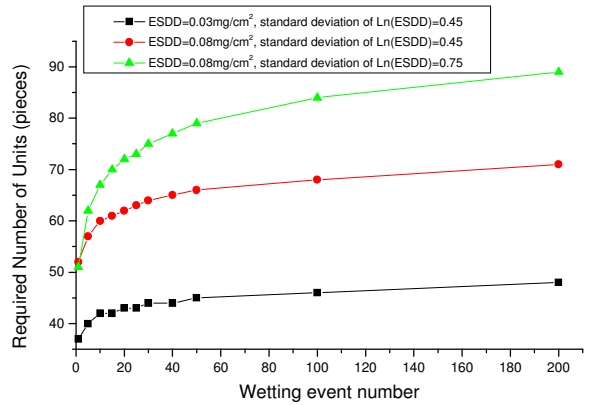


Figure 8 The influence of wetting event number on dimensioning estimation

H. Other parameters

Other parameters, which may have an impact on insulator dimensioning, are not included in the paper and need to be further studied.

IV. DISCUSSION AND CONCLUSION

To apply the statistical method in (U)HVDC projects, the selection of the inputs has significant influences on the reliability of the results. In order to make proper preparation of the inputs, the sensitivity of the dimensioning results to the inputs are investigated and analyzed. The results are summarized as follows.

(1) It is critical for the reliability of the insulator dimensioning to convert and unify the data from both natural

and artificial conditions into the same working reference. The correction factors have significant influences on the insulator performance, consequently affect the design results remarkably.

(2) The salt type and proportion should be measured and estimated carefully, since significant deviations may be caused.

(3) The quantity of NSDD needs to be considered in the design.

(4) The correction of non-uniform of pollution distribution on the insulator should be applied.

(5) The standard deviation of probability density distribution of pollution severity has a significant influence on the dimensioning results, especially at the moderate and heavy pollution level.

(6) The standard deviation of flashover voltage has an impact on the design results.

(7) The influence of the number of strings in parallel is not significant on the insulator dimensioning when it is greater than 100. A typical value between 100 and 1000 can be used in the design.

(8) The influence of the number of wetting events is remarkable on the insulator dimensioning when it is low, e.g. below 50. The influence of the wetting events is involved with other parameters, which should be further studied.

The study provides some guidance for the input preparation for the insulator dimensioning in statistical method. There is still a need for the further research work on these and other parameters.

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