EVALUATION OF THE PERFORMANCE OF POLLUTED INSULATORS UNDER DC: A STATISTICAL APPROACH

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Abstract: The design of insulators for d.c. applications is generally dominated by the performance under pollution. While specifications for the selection of insulators with regards to pollution in a.c. are already available (IEC 60815 series 1-2 and 3), the work is in progress within IEC TC 36 - WG 11 and CIGRE WG C4-03-03 towards the extension of the specifications to d.c. The main factors influencing the design are analyzed such as the influence of d.c. voltage on contamination deposition, the influence of the type of contamination (e.g. ESDD/ NSDD value, deposit uniformity, etc.), the influence of the insulator characteristics.

In the paper the field experience is analyzed to confirm the greater criticality of the pollution in d.c. with respect to a.c. It is also shown that field experience substantially agrees with laboratory results both for ceramic and composite insulators.

It is pointed out that a simplified design approach, as that suggested in IEC 60815 for a.c. is not suitable for d.c., due to the greater pollution criticality which could largely affect design parameters and system costs,

A design approach based on statistical information on the pollution deposit characteristics and on the insulator strength is presented as a more suitable tool for d.c. insulation design. Applications examples of the statistical approach are given both for ceramic and composite insulators, showing, in particular, the advantages of composites for d.c. application.

1 INTRODUCTION

The a.c. insulation design for EHV and UHV systems is in nearly all cases dominated by the performance requirements under switching overvoltages which determine the arcing distance; the pollution performance requirement is then satisfied by selecting insulators with a suitable creepage factor, CF [1]. On the contrary, in the case of d.c. systems the insulation design is most often dominated by pollution requirements. This is essentially due to the following three reasons:

- the contamination deposit is generally higher on insulators subjected to d.c. voltage than on those subjected to a.c.;
- for the same voltage stress the creepage distance required for d.c. at a given insulator contamination condition is higher than for a.c.;
- the magnitude of switching overvoltages in d.c. systems is much lower than in a.c..

An un-accurate design under pollution condition can thus have a strong impact on the overall system cost. In fact an over-design (leading to extremely long and costly station insulators and huge towers to accommodate long insulator sets) may result in unacceptable investment costs. On the other side, an under-design may lead to unacceptable operating costs (e.g. with the need for costly palliative maintenance measures). It is therefore necessary for the d.c. case to limit, as far as possible, the inaccuracies of the design by following a detailed design approach based on an accurate estimate of the site severity and insulator strength characteristics, combined to a statistically evaluation of the insulator performance.

The approach may be applied both to marine and industrial type environment represented in laboratory by salt fog and solid layer method respectively. However, in the following reference only to the second type of environment is made, usually described in terms of ESDD and NSDD [1].

2 ESTIMATE OF THE SITE SEVERITY IN DC

While for a.c. reference is made to the severity measured on a.c. energized or not energized insulators (more or less accumulating the same pollution), for d.c. reference is to be made to the pollution measured on d.c. energized insulators. In fact, as shown in Figure 1, insulators may accumulate more contaminant in d.c. than in a.c., with a ratio generally ranging from 1 to 3, depending, however, more on the type of contamination condition (e.g. wind condition at the site) than on the site severity, as shown by the quite poor correlation in Figure 1 [2], [3].

The site severity is to be accurately determined before the final design (e.g. by installing experimental stations with energized insulators

having geometrical characteristics similar to the selected ones in representative site conditions. Then it can be defined by a log normal statistical distribution by giving the contamination severity having a 2% probability of being exceeded ($ESDD_{dc2\%}$, $NSDD_{dc2\%}$) and its standard deviation. Typical values for the standard deviation in terms of Ln(ESDD) were found to be between 0,4 and 0,8 [4].
Furthermore, it has to be considered that contamination by itself can not lead to flashover unless the contamination layer is wetted. Therefore it is also necessary to know the number of significant wetting events per year N_t.

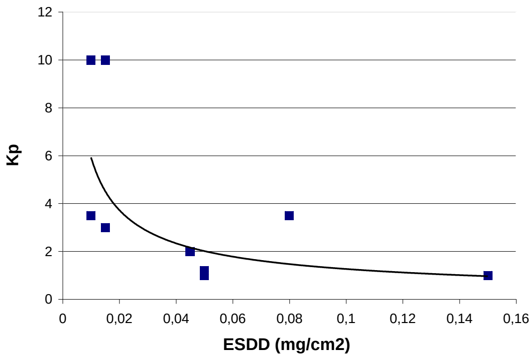


Figure 1: Ratio between the contamination measured on insulators energised under d.c. voltage versus the contamination measured on insulators energised in a.c. or not energised,

However, often for preliminary design only information on a.c. energized or not energized insulators of a given type are available. In these case it is necessary to "translate" the available data to the d.c. conditions. In particular, a set of coefficients is to be established to "translate" the site contamination severity in a.c. (e.g. $ESDD_{ac}$, $NSDD_{ac}$ [1]) to the corresponding value in d.c. for the specific insulator selected [5]:

$$ESDD_{dc2\%} = ESDD_{ac2\%} \cdot K_s \cdot K_p \cdot K_d \quad \text{where:}$$

- K_s takes into account the difference in contamination of the different insulators if the measurements are not made on the specific insulator selected (e.g. translation of the measurement from a standard to an anti-fog insulator)
- K_p takes into account that d.c. energized insulators may collect more contamination than a.c. energized insulators, in the same environment, as shown in Fig. 1.
- K_d takes into account that insulators with a large diameter collect less pollution than insulators with a small diameter

The same approach can be applied to evaluate $NSDD_{dc2\%}$..

It has to be pointed out that the above coefficients are generally subjected to a high degree of uncertainty and that as far as possible reference to measurements on energized insulators of the specific type should be preferred.

$ESDD_{dc}$ and $NSDD_{dc}$ values could be directly used to assess the performance of the insulators in the laboratory by not-standardized testing, by simulating as close as possible the site contamination.

If the standardized solid layer method is used, it has to be taken into account that in the standardized laboratory tests reference is made to a nearly uniform pollution layer and to a fixed value of NSDD (corresponding to about 0,1 mg/cm^2). Thus the equivalent laboratory SDD value can be evaluated by the following equation [5]:

$$SDD = ESDD_{dc} \cdot K_n \cdot K_t \quad \text{where}$$

- K_n takes into account that the site contamination material can differ remarkably from that used in standardized tests: in particular, the inert content in the field may be much higher than in standardized testing. This can influence the insulator performance, thus requiring to correct the site severity.
- K_t takes into account that the distribution of the contaminant along the insulator length can be quite different from that typical of standardized tests. In particular it takes into account the fact that the contamination on the bottom of the insulator can be different from the contamination on the top, as given by the ratio B/T.

Then the statistical SDD_w may be determined as the value at which the withstand of the insulator is to be verified in laboratory tests. The determination of this value is to be made by following a statistical procedure taking into account, among others:

- the number of insulator in parallel: N_{ins}
- the number of events per year: N_t
- the number of flashovers per year considered as acceptable

3 ESTIMATE OF THE DC INSULATOR PERFORMANCE BY LABORATORY TESTS

The USCD [1] at withstand for cap and pin insulators of standard and anti-fog profiles obtained with the standardized solid layer procedure are reported in Figure 2 [2]. The curve averaging the USCD values may be given by the following equations [4]:

$$USCD = 100 \cdot SDD^{0,33} \text{ (mm/kV, mg/cm}^2\text{)}$$

The results are however rather spread (even if masked at some extent by the logarithmic scale), depending on the insulator geometry. In particular the efficiency of the profile for cap and pin insulators decreases as far as the creepage factor [1] increases as shown in Figure 3 [6], [7], [8] such as that there is not any benefit in terms of flashover voltage when increasing CF above a value of about 3.3 for cap and pin insulators and about 3.8 for composites.

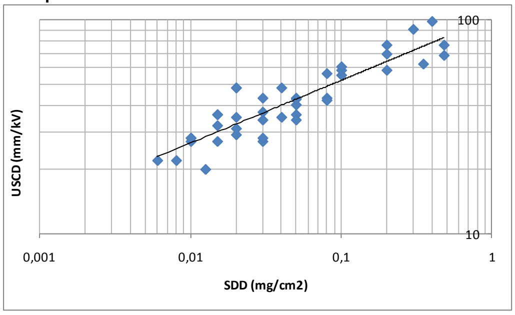
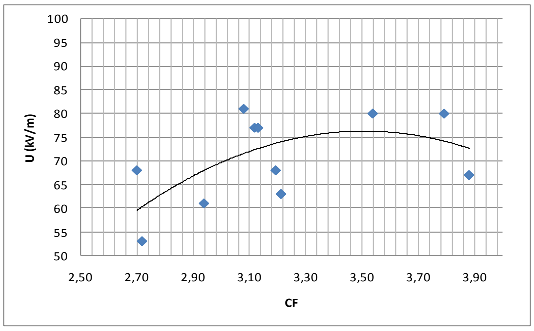
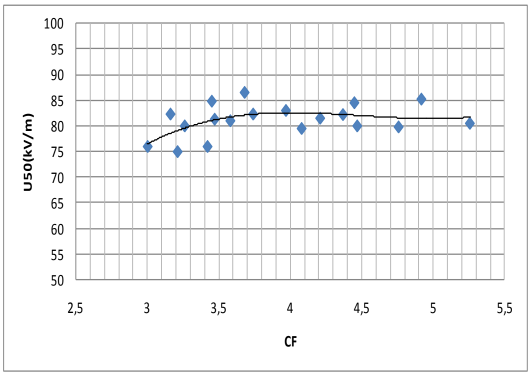


Figure 2: Solid layer tests – Results on cap and pin insulators (standard and anti-fog). Fitting of average values



a) Ceramic cap and pin insulators



b) Composite insulators

Figure 3: Line insulators. Solid layer method. USCD versus creepage factor for various values of SDD

When considering station insulators the diameter is another important influencing factor. Extrapolating experimental results a rough average indication of the diameter influence can be obtained by the following equation for ceramic insulators:

$$USCD_D = USCD \cdot (D / D_o)^{0,30}$$

where D_0 = 250 mm and D is the average diameter in mm.

The required creepage distance for insulators with HTM (hydrophobicity transfer material) properties (e.g. composite insulators) is lower than for ceramic ones for a given ESDD., as shown in Fig.4 based also on field experience [3], [5], For composite insulators the following conservative equation is proposed for an average estimate of USCD under solid layer method:

$$USCD = 65 \cdot SDD^{0,27} \text{ (mm/kV, mg/cm}^2\text{)}.$$

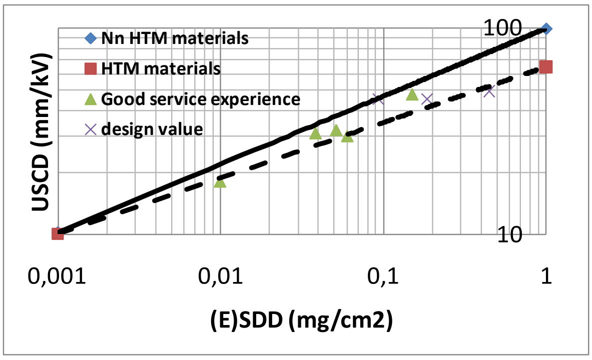


Figure 4 Comparison of field and laboratory experience resulting from ongoing analysis within CIGRE WG C4.03.03 [3], [5].

Furthermore, for HTM materials the diameter influence is less than that for non-HTM materials.

The standard deviation of USCD is of the order of 8%. When given in terms of pollution severity it corresponds to a standard deviation of about 25% for ceramic insulators and about 37% for composite insulators (different because of the difference of the slope in Fig. 4).

4 STATISTICAL DESIGN APPROACH

A computer program for design of insulators according to the statistical approach, schematically illustrated in Figure 5, has been developed.

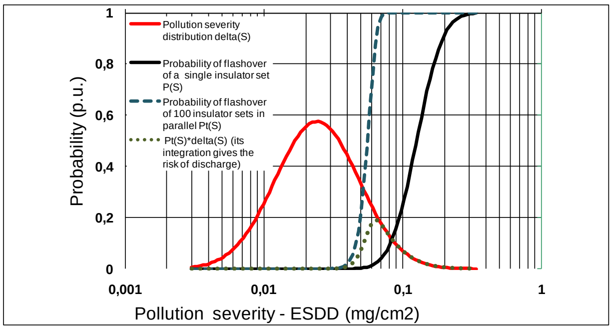
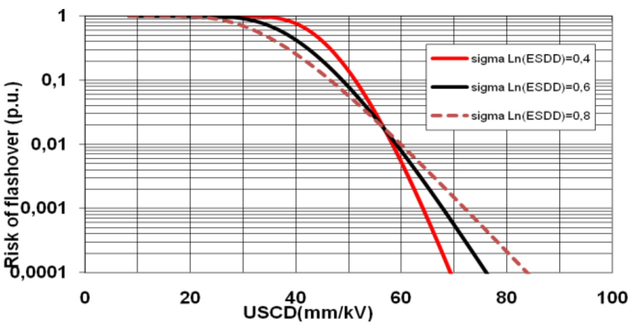


Figure 5: Schematic representation of the parameters necessary for the risk evaluation

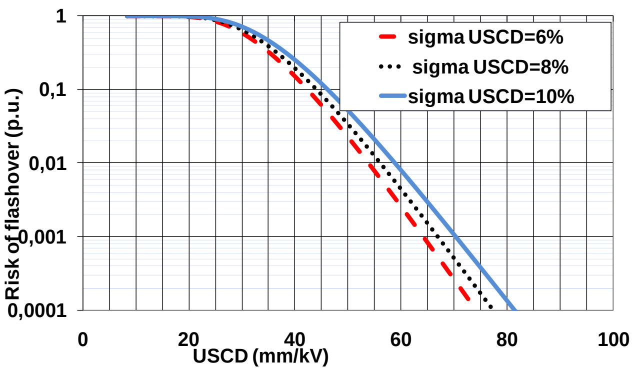
In the following the method is applied to show the importance of some of the main design parameters. Some reference average values of these parameters are assumed and then the effect of the variation of each parameter at time around these average values is analyzed. To reduce the number of cases it has been assumed that the contamination severity values are obtained by measurements made on the d.c. energized specific insulator to be adopted (K_p=1, K_s=1, K_d=1). However it important to stress that K_p is the most important parameter among the three, which can lead to important increase of the ESDD to be considered if reference is made to the a.c. value.

The evaluation is made in the following, assuming that the selected insulator has a withstand curve as in Fig.4. The evaluation is made for one wetting event. The risk is then to be multiplied for the number of events to obtain the total risk.

The sensitivity to the standard deviation values is shown in Fig. 6: an increase of the standard deviation increases the insulation requirements at least for the lowest values of acceptable risk of flashover, of major interest for the design.



a) σUSCD=8%. Influence of σln(ESDD)



b) σln(ESDD)= 0.7. Influence of σUSCD

Figure 6: Cap and pin insulators. $ESDD_{2\%}$=$NSDD_{2\%}$=0.1 mg/cm^2. Nins=100, Tb/Tt=1

The other examples in the following are all made assuming σln(ESDD)=0.7, σ USCD=8%.

The risk is significantly influenced also by the number of insulators in parallel, Nins, as shown in Fig, 7.

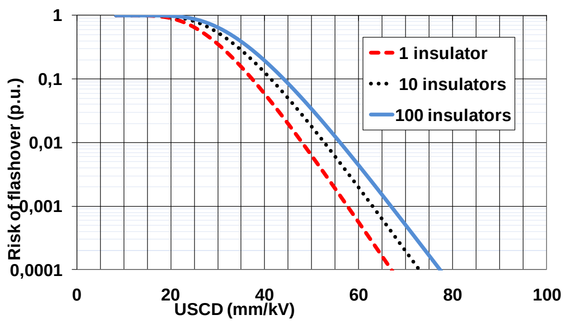


Figure 7: Ceramic insulators. Influence of the number of insulator sets in parallel. σln(ESDD)=0.7, σ USCD=8%

The other examples in the following are made with reference to Nins=100.

The sensitivity to the type of contaminant and of the contaminant uniformity is shown in Figure 8. The Figure stresses in particular the influence of NSDD. With the same ESDD the risk can be much higher if NSDD is increased (in the examined case 5 times ESDD).

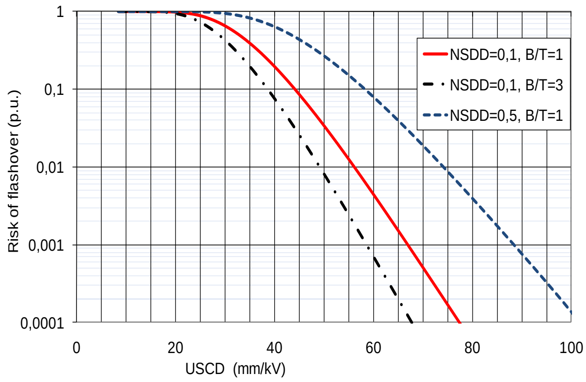


Figure 8: Cap and pin insulators. $ESDD_{2\%}$=0.1 mg/cm^2. Influence of contamination uniformity (B/T) and of NSDD

The sensitivity to ESDD is shown in Fig. 9.

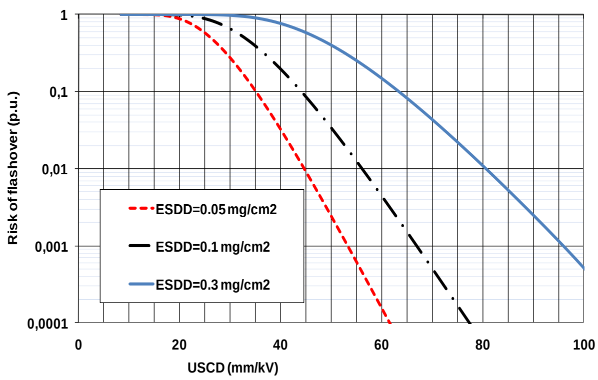
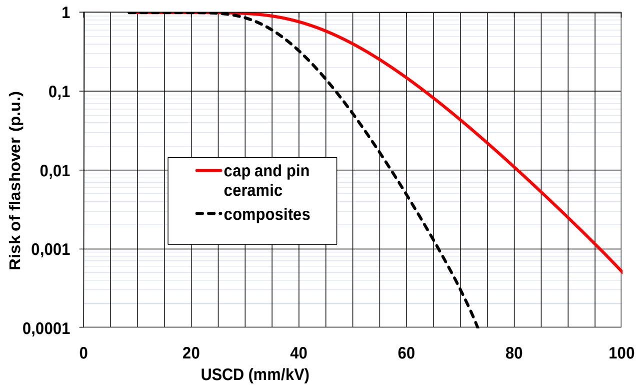


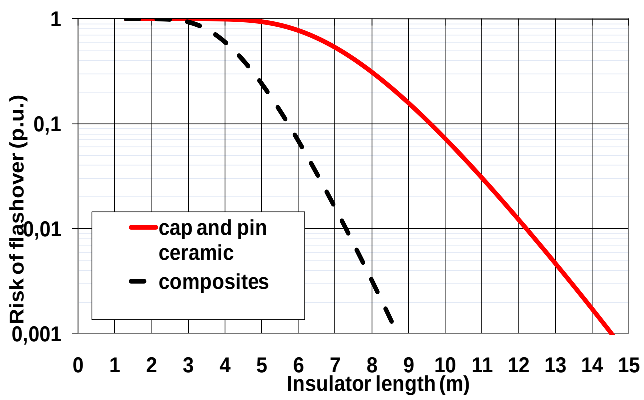
Figure 9: Cap and pin insulators. Influence of ESDD (NSDD=0,1 mg/cm^2)

The influence of the type of insulator (ceramic or composite) is examined in Figure 10 for a ESDD value of 0,3 mg/cm^2 to emphasize the insulator type effect. The advantage of composite insulators it is to be mentioned that the advantage can be higher than that shown in Figure 10 a) because of different limits for the creepage factor efficiency, assumed in the example of 3.8 for composites against a value of 3.3 for cap and pin insulators (see Fig. 10 b).

As a general comment, all the above Figures indicate that the risk of flashover is a function of many parameters and that the specific creepage distance to be adopted varies remarkably depending on the risk level considered acceptable. A simplified approach as in a.c., assuming a unique reference value for USCD as a function of the pollution class may lead to very inaccurate design.



a) Risk as function of USCD



b) Risk as a function of insulator length

Figure 10: 500 kV d.c. line. SDD=0,3 mg/cm^2, NSDD=0,1 mg/cm^2 . Comparison between ceramic and composite insulators requirements.

5 COMPARISON OF CALCULATION AND FIELD EXPERIENCE

Unfortunately there is not much detailed information in the literature to make a direct comparison between model prediction and field experience.

A good piece of information, relevant to ±500kV HVDC Rihand-Dadri Line in India, is reported in [9]. The line has been designed assuming light to medium pollution (ESDD of 0.045 mg/cm^2). The selected creepage distance of 41.6 mm/kV is in line with the preliminary estimation which can be obtained from Fig. 4 .and leads to an insulator length (V string type) of about 6.5 m.

Unfortunately the actual contamination conditions was found much higher, reaching extreme values (ESDD max=0,81 mg/cm^2, NSDD max= 3,62 mg/cm^2) in 1999. In this conditions practically all the wetting events caused by high humidity/fog during late evening, early morning and night, especially in the winter months led to frequent flashovers. Being the required USCD much higher than the selected one, the number of wetting events can be assumed equal to the trip-outs obsrved (about 100 per year).
However, a high rate of flashover was present also at lower level of contamination (1997 data): 55 trip-outs were found corresponding to a contamination conditions characterized by the following values: ESDD max=0,068 mg/cm^2, NSDD max=0,69 mg/cm^2.

The experimental observation are in good agreement with the calculations as shown in Figure. 11, evaluated considering a number of wetting events equal to 100.

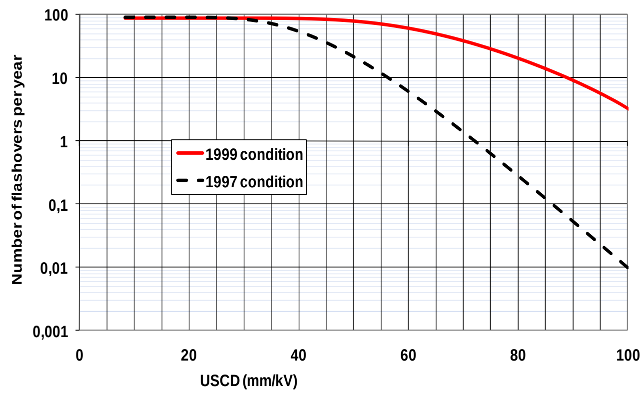


Figure 11: HVDC Rihand-Dadri Line. Estimate of the number of flashovers to be expected at the pollution severity levels observed in 1997 and 1999 as a function of the USCD

An exercise is also made to check the number of trip-outs to be expected in case composite insulators should be used with reference to the 1997 condition. The comparison of ceramic and composite is made in terms of insulator string length, since for composite a CF of 3.8 is taken against 3.2 for ceramic.
It is evident that a much lower number of trip-outs could be expected for composite insulators in correspondence to the selected insulator length of about 6.5 m.

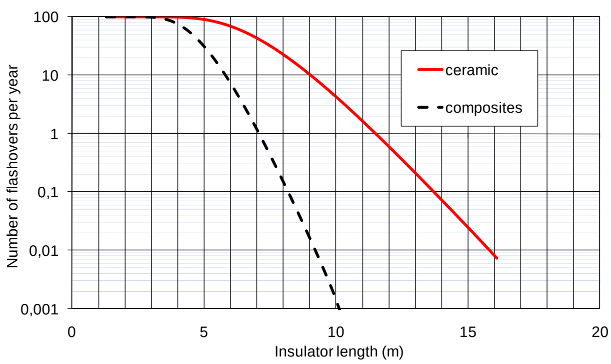


Figure 12: HVDC Rihand-Dadri Line. Estimate of the number of flashovers to be expected as a function of the insulator length at the pollution severity levels observed in 1997

6 CONCLUSIONS

- Pollution generally dominates the design for external insulation in d.c. Being pollution very demanding in terms of insulator length, an extremely accurate design approach is to be followed, based on an accurate determination of the pollution severity and of the insulator strength.
- Reference to the contamination on energized insulators is to be made in d.c., due to the influence of the d.c. stress on contamination. The degree of contamination in d.c. can thus remarkably differ from the contamination observed in a.c. Correction factors are proposed to translate the pollution severity measured on one insulator type under a.c. to d.c.. However, the accuracy of the procedure can be low when use is made of correction factors. Ideally, the statistical distribution of the contamination should be obtained by means of long term measurements on d.c. energised insulators, possibly of the same type of those selected.
- The performance of polluted insulators under d.c. may depend remarkably on insulator geometry and material. Reference to average curves, derived by past experience, may be useful for a preliminary design. However, an accurate design should make use of statistical data about the performance of the specific insulator considered under representative test conditions.
- Once statistical information about the pollution severity and insulator strength should be available, the risk of flashover can be evaluated and the insulator length can be established on the basis of the acceptable risk level.
- Making use of a computer program set up, the influence of various parameters on the flashover risk is examined in the paper , showing among others, the benefits of composites.
- A specific case is examined showing that the approach proposed may predict quite closely the observed line performance.

7 REFERENCES

[1] IEC/TS 60815 Edition 1.0 2008-10 “Selection and dimensioning of high-voltage insulators intended for use in polluted conditions –Part 1,2 and 3
[2] A. Pigini, A.C Britten, C. Engelbrecht “Development of guidelines for the selection of insulators with respect to pollution for EHV-UHV DC: state of the art and research needs” Cigre general session 2008 paper C4-101
[3] A. Pigini, R. Cortina “Insulation Challenges when Uprating EHV AC Lines or Converting EHVAC Lines to EHVDC Lines” INMR Congress Seoul 2011
[4] C. S. Engelbrecht, I. Gutman, and R. Hartings, “A Practical Implementation of Statistical Principles to Select Insulators with Respect to Polluted Conditions on Overhead a.c. Lines” IEEE PowerTech 2005 paper 129
[5] CIGRE WGC4.03.03 “Outdoor insulation in polluted conditions: Guidelines for selection and dimensioning. Part 2:the DC Case” Draft March April 2010
[6] T. Kimoto, T. Fujimura, K. Naito “ Performance of insulators for direct current transmission lines under contamination conditions “ IEEE Trans. On PAS 92 1973
[7] EPRI TR 102764 1993 “ HVDC Transmission line reference book”
[8] Fuzeng Zhang, Xiaolin Li, Bing Luo, Liming Wang, Zhicheng Guan “Influence of composite insulator shed design on flashover voltage” CEIDP 2010
[9] L.N.Agrawal, K.Kapurm, L.Sachdeva “Insulation Performance of ±500kV HVDC Rihand-Dadri Line In India” Cigre 2000 general session