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Design and selection criteria for HVDC overhead transmission lines insulators

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SUMMARY

The renewed and growing interest for building HVDC lines which has started to appear in the last five years in several countries shows a deep change in the approach of grid design worldwide compared to trends and construction of the past twenty years. In fact, North America built its last DC lines in the late 1980's and early 90's, around a 500 kV DC concept, while South America completed the Itaipu +/-600 kV DC system in the second half of the 80's. Around the same period, or slightly later, a few projects materialized in Asia, mainly in India and China. Except for these isolated cases, the needs or the funding for bulk transmission lines had almost vanished until the recent development of some projects in India at 500kV DC and more recently in China with UHV projects at the 800 kV DC level. More projects are planned in the near future in India and again Brazil. More recently the decision to expand and upgrade the backbone grids in North America - to better serve increasing demand while reinforcing the network - have started to turn line designers' attention towards DC. Several HVDC projects are presently being studied both in Canada and the USA. The beginning of this new wave of DC projects motivates utilities and consultants to update their technical knowledge and deepen their understanding of overhead line insulators for HVDC applications and its specificities relative to AC insulation.
The fundamental and specific characteristics of dielectric materials for DC insulation are reviewed from a theoretical aspect but also in the light of actual field experience. Monitoring of existing DC lines over the last two decades has shown the necessity to incorporate specific features in DC insulator specifications to prevent premature degradations and ensure good performance over time. Such considerations have been introduced in IEC 61325 standard. It is worthwhile to note that while there is sufficient field experience from several old DC lines using traditional glass or porcelain insulators, the long term field evaluation from DC lines using polymer insulators is quite sparse and is mostly relevant to materials and designs which have since evolved with sometimes significant changes and mostly implemented for AC applications. The question of polymers in DC applications is also raised by the absence of international standards which today cover only glass and porcelain dielectrics.

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The above considerations open the necessary question of long term performance, life cycle costs and return on capital investment, which are especially pertinent for projects which have very high quality of service criteria at stake, and are critical to global grid stability.
In addition to discussing key dielectric and material options, this paper offers also guidance criteria for DC insulator string dimensioning. Typical dimensioning flow chart is presented to help determining the optimum string length. The effects of unidirectional electrostatic field and the requirements for specific consideration for contamination performance and fitting protection against possible electrochemical corrosion are reviewed.

KEYWORDS

DC - Transmission line – Glass insulators – Insulator selection – Pollution - String design – Dimensioning - Insulators

1. INTRODUCTION

String design and insulator selection for HVDC is an exercise which requires specific considerations given the particularity of the application. Insulators for DC lines are made with specific dielectric materials, and this paper presents the key and fundamental attributes of these insulators. Additionally, the string length and characteristics, such as leakage distance, have to be adjusted according to the relevant contamination conditions of the area crossed by the line. Guidance is given in this paper to help understand the process of definition of a string of insulators for a DC application.

2. DIELECTRIC MATERIAL SELECTION

The unidirectional electric field imposed by a DC line has a strong effect on the integrity of dielectric materials traditionally made for AC applications. In the early years of the first DC lines, it became clear that specific dielectrics were needed. This was the case for ceramics, but also in the more recent years for composite insulators.

In fact the lack of global significant experience with composite in DC should be cautiously considered. Recently China started to use composite DC insulators. It is interesting to note that Chinese experts themselves call for caution when considering life time and performance (1) and they are progressively implementing very thorough line inspection procedures (2) which are not compatible with western world practice. Overall, it is critical to realize that no international standard covers composite insulators for DC applications due to the insufficient knowledge of their specific performance over time, and of the ageing mechanisms involved under those specific stress conditions.

The case for ceramics is different. First of all there is a standard, published under reference IEC 61325, describing precisely the minimum requirements for HVDC glass and porcelain insulators. Secondly there is a mine of field experience available under diverse climatic and environmental conditions to help the line design engineer to understand the specifics and major criteria to be taken into consideration.

The detailed criteria described in this standard are the consequence of extensive R&D studies combined with results from the field. For the dielectric, the necessity to use only high resistivity materials has become a mandatory criterion based on punctures of porcelain bells or shattering of toughened glass as seen in some early applications. Specific corrosion problems leading to severe failures (3) which happened on porcelain discs have also pointed out the need for specific end fitting corrosion protection which so far was only used on glass discs.

The limit of porcelain performance in this field is directly related to the ability of the manufacturer to achieve as much as possible a cohesive structure of crystals with a minimum content of micro cracks, more harmful in DC than they already might be in AC. Specific particle size selection, screening and processing is therefore required. Subcritical crack development can go unseen for quite some time, but ageing is known to be faster in DC than under AC conditions.

The intense R&D work performed during these years by SEDIVER (7) on DC toughened glass has resulted in a combination of design and process innovation [10], totally driven by performance. The high resistivity glass chemistry could only be achieved thanks to specific process details implemented in the factories. An important criteria for glass is the level of purity of the dielectric, (small inclusions can be the reason for some shattering to happen in the first years of service). This has been addressed in very specific ways for DC glass during manufacturing from the glass melting point to the cold end of the production line. Field records from line using this special DC glass have shown excellent results.

a. <u>Dielectric resistivity</u>

High resistivity is required for DC applications. According to IEC 61325 standard, the specificities for dielectric materials can be summarized through two main requirements, both of them of prime importance to prevent harmful consequences on the dielectric:

- Ionic migration
- Thermal runaway

In fact, both are linked together through the resistivity of the dielectric. A continuous transverse current crossing the body of the dielectric (different from the surface leakage current) can generate a temperature increase and subsequently a local decrease of resistivity, inside the head of the insulating bell. The persistence of this phenomenon can bring the dielectric to puncture or shatter through an avalanche phenomenon, which is the visible aspect of a thermal run away (This is even more critical for warm climate countries). In dielectrics such as those used for overhead lines, the ionic current is largely produced by ionic migration of alkalis such as $Na+$. The unidirectional current going through the body of the dielectric can also generate some depletion of the atomic structure of the material, reducing the material's electrical and/or thermo mechanical (as per IEC or ANSI) and electromechanical properties. Therefore, major suppliers for the DC insulators market have significantly increased the electric resistivity of their dielectric materials to provide a correct solution to these particular stress conditions.

The application of these considerations to toughened glass translate into a resistivity of the DC glass body itself (not to be confused with surface leakage currents) about 100 times greater than the AC glass at normal service conditions. The body resistance of the insulator unit is measured at various temperatures (90°C, 120°C and 150°C). The set up for the measurement requires that all leakage currents are eliminated by a screen electrode as shown in figure 1. Typical measured body resistance values are shown in figure 2. These can fluctuate slightly depending upon the size of the dielectric head, directly in relation to the mechanical strength of the insulator. (Mechanical ratings up to 550kN (123kips) are not uncommon in applications above 500kVDC.

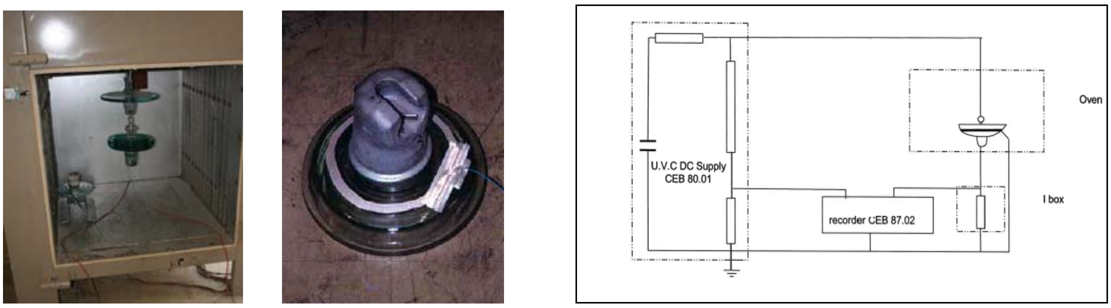


Figure 1: Typical test set up for DC body resistance measurement according to IEC61325 (Sediver laboratory, C.E.B France)

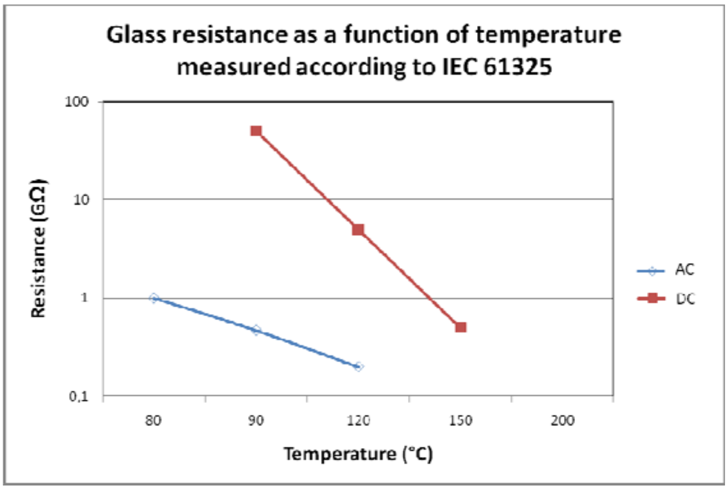


Figure 2: Example of comparative body resistance between AC and DC toughened glass insulators. (SEDIVER data)

b. Verification of the ionic migration strength

Compliance with ionic migration performance test requires firstly an appropriate resistivity value but also excellent purity and homogeneity of the dielectric materials.

The samples for testing are energized at a temperature allowing in a reasonable period of time to accumulate an electric charge quantity (Q_{50} in Coulomb) corresponding to 50 years of service. This charge quantity is calculated from the initial measurement of the body resistance according to the relation from IEC 61325 (4) below:

$$Q_{50} = V \sum_{-15^{\circ}C}^{+65^{\circ}C} \frac{t(\theta)}{R(\theta)} \qquad (4)$$

with V the applied voltage, t the time at a given temperature (normal distribution) and R the resistance of the dielectric at that temperature.

The time duration in days of the ionic migration test is defined by:

$$D = \frac{Q_{50} \times R(\theta_{test})}{3600 \times 24 \times V_{test}} \qquad (4)$$

The test is concluded positively if at the end of the defined test period there has been neither puncture nor shattering on a population of 50 units. An example of test set up is shown in figure 3. Note that the leakage current is not to be taken into account in this test, all skirts being grounded to ensure that the ionic current is only through the head of the dielectric.

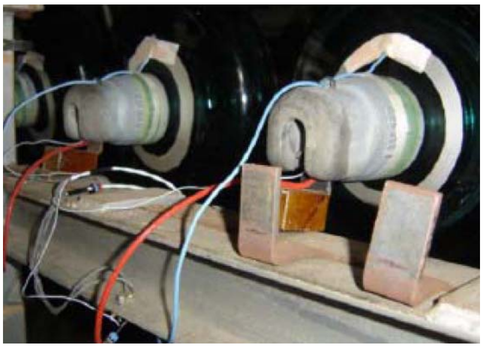



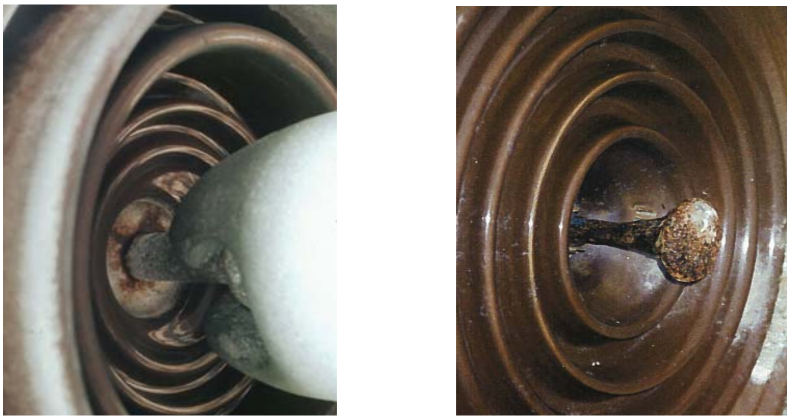
Figure 3: Ionic migration chamber. (CEB Bazet laboratory, Sediver France)
Left: general view of the chamber. Right: detail of current measurement

c. Other material considerations

Among other characteristics, the risk of electrochemical corrosion needs to be considered with care. The effect of airborne particles attracted by unidirectional electric field will generated a "background" pollution level, irrespective of specific contamination factors from the environment. The metal end fittings can be severely degraded from the resulting unidirectional electric activity on the surface of the insulator in the direct vicinity of the fittings. This phenomenon is also known in AC but mostly when severe or extreme pollution is present. The pins will suffer most (figure 4), and today all DC insulators are equipped with a sacrificial zinc sleeve at the pin (figure 7). Areas where such device was not used have encountered failures (3) and line drops.

The cast iron cap itself can also suffer of corrosion. The time for significant corrosion of the cap to reveal itself is longer than for the pins. In the past DC insulators were assembled with normal caps, (figure 5) and while the corrosion itself has no influence on the mechanical strength of the unit, it can occasionally leach some rust over the dielectric, with possible negative impact on the leakage currents and flashover performance. This is even more critical for composite insulators under contaminated environments as shown in figure 6. In this case, a major risk of erosion will jeopardize the integrity of the housing.

Today, state of the art design of HVDC insulators uses corrosion protection both on the pin as well as on the cap side (figure7). Various shapes of zinc sleeve are available depending upon severity of the expected contamination. Corrosion protection devices are also described in IEC61325.



<u>Figure 4</u>: Example of pin corrosion in a case where there is no zinc sleeve and high electric activity.

<u>Figure 5</u>: Rust leaching on the surface of the dielectric when the cap is not protected against corrosion.

<u>Figure 6</u>: DC corrosion of composite end fitting with heavy rust on the rubber housing

<u>Figure 7</u> : State of the art HVDC insulator with corrosion protective sacrificial zinc sleeves on cap and pin. <u>Left to right</u>: zinc collar on cap – zinc sleeve on pin side – zinc sleeve on pin from Itaipu 600kVDC after 20 years – difference of behaviour between pin without and with zinc sleeve under extreme pollution.

3. STRING DIMENSIONING

Several factors have to be taken into consideration for the design of a HVDC insulator string.

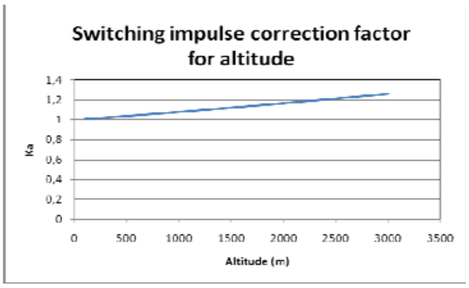
- Maximum Voltage level of the line
- Altitude of the path of the line
- Contamination conditions

3.1 Factors not related to contamination

The level to consider for the maximum voltage of the DC line is defined by the converting station and initial decisions taken in the insulation coordination of the line. This figure is necessary when determining the string length. Typical values found in the field are in a range around 3% to 6% above the nominal voltage of the line. For example, for a 500kVDC line a reference value would be 515kV. For a 600kVDC line it could be 620kV or 630KV.

Related to this first point is the question of insulation coordination, mostly for impulse values such as the switching impulse withstand level. Minimum clearances, air gaps required by line design criteria are typically defined by the utility in close relation to the converter station design. The air gap length required for a string in DC is usually not the driver. String length is most likely to be determined by contamination considerations rather than switching impulse requirements.

Altitude can be a sensitive question. It is not uncommon, given the length of DC lines, to have a line crossing high altitude areas, for which a careful evaluation of the air density influence is required. IEC 60071-2 provides correction factors (5), one of the most important to consider in this case being the positive switching impulse flashover value. Figure 8 shows an estimate of correction factor *Ka* for switching in the case of a 500kV DC line in a clean area. In this example if a switching value of 1100kV is considered at normal sea level, this would result in a value of 1386kV at an altitude of 3000m.



$Ka = e^{(m \times H/8150)}$
With m=0.63 for switching impulse flashover and H the altitude in meters

$U_{alt} = Un / Ka$
With Un being the flashover voltage measured in normal conditions below 1000m elevation, and U_{alt} the flashover voltage at the corrected altitude.

Figure 8: correction factor for switching flashover values.

Work done for UHV projects in China has shown that IEC60071-2 was optimum for altitude correction factors even at altitudes of 4000m and above. Correlation with actual full string testing was achieved in high altitude test sites (6).

String length in altitude is defined by air gaps, and is not related to the type of insulator or material. If composite insulators are used in high altitude, special care should be taken to prevent the possible existence of corona on or near the housing material. Corona inception voltage is decreasing at high altitude, and it is well known that corona has the ability to develop nitric acid through ozone, which is extremely harmful for the polymer itself. To reduce the risk of corona, it becomes necessary to develop specific additional grading devices. In some recent applications, multiple grading rings at each end have been implemented to counter the excessive risk of accelerated ageing. Finally, the gain in string length commonly promoted for composite insulators is substantially reduced by the presence of these devices not mentioning the still present risk of polymer degradation.

3.2 Contaminated environments and string determination

Pollution withstand characteristics have to be clearly defined when crossing a severe environment. The usual differentiation should be made when dealing with contamination, between coastal and desertic conditions, obviously paying attention to possible mixed conditions.

The evaluation of the string length based on leakage distance requirements for any given pollution level can be established according to the method described below and summarized in the appendix.

Necessary entry parameters are:

- Top and bottom surface of the dielectric shell for a given insulator (data from suppliers)

- Overall ESDD level expected on the insulator: this value is necessary including an estimate of the ESDD Top and Bottom ratio for a given shape (typical fog type is usually used in DC, but not necessarily always). Insulators are collecting more contamination in the underskirt given the presence of ribs, than the upper skirt. Therefore T/B ratios are important to consider for the evaluation.

  CUR= ESDD Top / ESDD Bottom

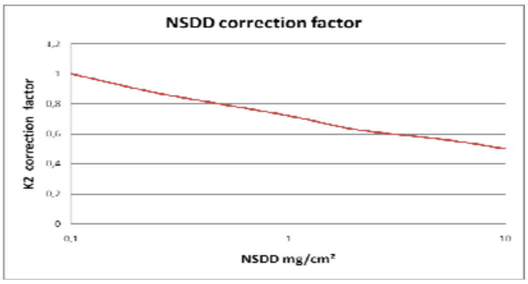
- U50 flashover value of a given insulator in kV/unit for the given ESDD with CUR=1 for an NSDD=0.1mg/cm².

  At this stage, it is possible to calculate the correction factor to theU50 flashover value impacted by the ESDD and the unbalanced *CUR= T/B* ratio:

  $K1 = 1 - W \times \log(CUR)$ — *W* is usually taken from a range 0.35< W < 0.45; *W=0.38* is a practical value (11)

- NSDD level expected on the insulator: This value is given by the non soluble contaminants. Overall NSDD value is considered for the following calculation.

The value of the correction factor K2 related to the influence of the non soluble part of the contamination (NSDD) is given in figure 8. This correction factor is based on existing test data and has been empirically validated for many years now. As always in such matter, fine tuning of this equation is still of interest and ongoing studies and tests are still in progress.



$$K2 = (NSDD/0.1)^{-0.15}$$

Figure 8: K2 correction factor for NSDD

The corrected value of U50 of the given insulator unit can be calculated with the following relation:

$$U50corr = U50 \times K1 \times K2$$

This is an estimated value of a flashover of a given unit. The next step is related to the evaluation of the risk to have a flashover for the insulator string under consideration.
If we call *Vdc* the maximum voltage of the line, and we take, as it is traditionally the case, a probability of 98% of withstand, with a standard deviation of 7%. The string should have a flashover value not less than *U50string* defined as:

$$U50\ string = Vdc/(1-n\sigma) \quad \text{where } n=2.15 \text{ and } \sigma = 0.07$$

For the line under consideration, the correct number of units to place in a string for the given pollution condition and the selected insulator would be defined by:

$$Nb\ insulator = U50string \ / \ U50corr$$

Note: The value *U50* for a given ESDD level is taken from manufacturers data, and provided typically from standard test data, usually with a NSDD=0.1mg/cm². Pollution tests with solid layer and clean fog are performed with a pre-deposit of some types of contaminant. Normally, the pollutant used for this test is a Kaolin mix. However, some tests are performed with Tonoko. If Tonoko is being used, the results can be higher by up to 20% compared to the same test performed with kaolin (9). Only results from similar pollutants should be considered.

Without going into details related to the testing protocol, the deposit process of the contaminant is of importance, some laboratories are using a paint brush while others are using a dipping method or a spray technique.

3.3 Examples

- The first example is a 500kVDC project using a 160kN fog type insulator (leakage distance 545 mm) with pollution parameters described in the table below. Maximum line voltage is taken at +/-515kV, and withstand probability is at 98%. The determination of the string length is given below with the methodology described in the upper section of this paper.

ESDD (mg/cm²	0,03	0,05	0,08	0,15
CUR	1/3	1/5	1/8	1/10
NSDD (mg/cm²)	0,18	0,3	0,48	0,9
U50 (kV/unit)	17	13,6	11,1	8,8
K1	1,181	1,265	1,343	1,38
K2	0,916	0,848	0,79	0,719
U50corr (kV/unit)	18,4	14,6	11,8	8,7
Nb of units per string	33	42	52	70

- A second example could be a 450kV DC line with relatively clean conditions and no NSDD problem to report. If we take the hypothetic level of ESDD=0.03, and a top to bottom ratio of 1/3, again on a fog type insulator of the same shape as above, the result would be:

$$U50corr = U50 \times K1 = 17 \times 1.181 = 20$$

Under such conditions, and taking similar probalistic parameters as previously, taking the maximum line voltage at 105% of 450kV, we would have:

$$472.5 / 20 = 24 \text{ units in the string}$$

This example is interesting, since we can compare it with the 450kV line from Hydro Quebec, using precisely 24 units per leg of their V strings equipped with toughened glass. It is also interesting to note that in this application, the designer took into consideration disc profile efficiency. The difference in shape of the disc, mostly in the location of the ribs under the skirt, can influence partial arcing and interib bridging under polluted condition especially in DC. Also, dirt accumulation is easier when ribs are closer. Therefore, the line designer had specified 10% more units if using a specific shape of porcelain discs. The reasoning can be appreciated from the shape comparison described in figure 9. Similar results had already been pointed out by EPRI in the 1980's.

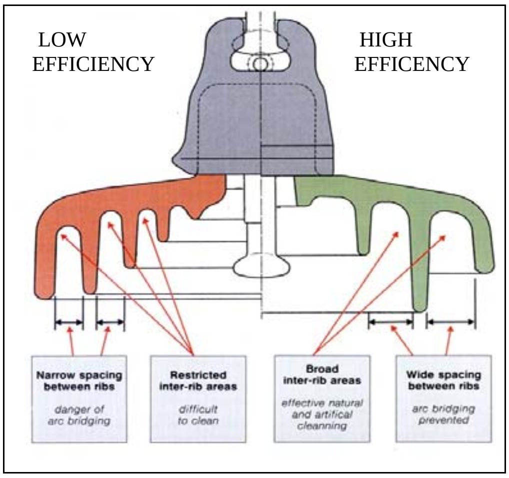


Figure 9: Rib distribution depending upon dielectric material processing.

4. CONCLUSION

HVDC requires special care in string design and insulator selection: attention must be paid to the materials being used, the specific stress conditions on the dielectric but also the metal end fittings design. Field experience and servicing considerations are in favour of traditional insulators rather than polymers for which sufficient service life with a well identified design and ageing mechanism understanding are not yet attained in DC.

Various parameters have been defined for the evaluation of the string length of a DC line, when submitted to environmental conditions such as high altitude, but also under contaminated conditions for which special care is required in the string parameters calculation.

Toughened glass insulators provide a mature design, well recognized through a vast compilation of field experience over the last 30 years, and proven to be stable over time (8). The same benefits and attributes recognized for easy and safe line inspection, live line work on AC lines apply to the SEDIVER DC toughened glass design.

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APPENDIX
DC insulator selection and string length flow chart