HVDC overhead line insulators selection and design update features

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***Abstract*— The increasing number of HVDC projects has raised new interest in the design of components used in various materials dedicated to DC applications. For example, the unidirectional electric field in a dielectric subjected to a DC voltage generates specific stress conditions resulting in unique features making up the design of insulators. Likewise, the impact of polarization in the environment near a DC line requires special attention for airborne contamination which modifies the ability of a string of insulators to withstand the operating voltage under any circumstances.**

This paper will review the main features of DC overhead line insulators with specific details related to the various technologies available. Contamination aspects will also be discussed including the latest developments in IEC 60815 [1] as well as new mitigation methods for severe contamination conditions.

I. Introduction

The unidirectional electric field of DC application generates an ionic migration process inside the bulk dielectric material which can result in either puncture of the material (if it is porcelain), shattering of the glass (in case of toughened glass) but possibly also a progressive tracking internally for polymer insulators (called treeing in the fiberglass rod or interfacial carbonization inside the polymer insulator). As a result, higher resistivity is needed in the material itself to sustain these unique stress conditions. Today only porcelain and toughened glass are described in international standards such as IEC 61325 [2]. There is currently no standard for polymers today despite the Chinese relatively large application

CIGRE, after years of research is initiating again a new round of work to determine which test protocols should apply for selecting silicone materials against erosion under DC stresses, which is the proof that this technology is not yet bullet proof for DC.

Electro corrosion of end fittings is a second particularity of DC applications and field experience has shown that galvanic protection far beyond current IEC recommendation is required. A mandatory use of a zinc sleeve around the pin is a largely accepted concept and quite well described in IEC 61325 [2] but the protection of the base of the cap needs more attention. The case of polymers again is very specific and it is not exceptional to see severe degradations at the triple point with severe corrosion at the edge of the end fittings.

The question of pollution remains central since it defines most likely string length, therefore tower heights and costs. IEC 60815 [1] describes a set of theoretical equations designed to define the USCD (Unified Specific Creepage Distance). Experience is showing that while the concept is interesting much more work is needed to achieve a good correlation between theory and field experience [3]. Proponents of polymers will argue that silicone offers unique benefits capable to reduce dramatically the string length, but as stated by some experts [4] such reduction might increase substantially the ageing of the polymer.

An alternative for heavily polluted environments is the use of silicone coated insulators for which the ultimate reliability is ensured by the glass underneath (unlike fiberglass rods in polymers). Such applications have been used extensively including in China at 800KVDC

II. Ionic Migration and Dielectric Resistivity

Under DC electric field the ions are migrating through the dielectric itself resulting in the electrical breakdown of the material. First generation insulators were made with a dielectric strength and body resistivity compatible with AC stress levels. Higher shattering rates on glass were found as well as large quantities of punctured porcelain discs. An illustration of this problem is shown in Fig. 1 where porcelain discs were used on a 500kV line in Congo with extensive service interruptions, string separations, with in the end a major difficulty to operate at nominal voltage. While some engineers were looking at a variety of possible root causes (including pollution….) the demonstration was made through a large sampling that many insulators were punctured. This goes unseen, which is typical for porcelain (some manufacturers claim that the failure rate of porcelain is around 1/100000 or less, but it is physically impossible to prove unless several hundred thousand of units are tested one by one to produce such statistics, which of course is not practical and at very high costs).

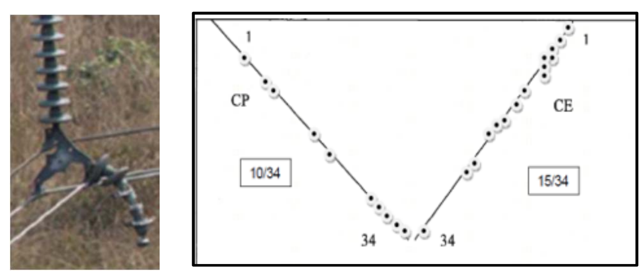

Figure 1. Left: String separation resulting from punctured porcelain. Right: Distribution of punctured discs in a porcelain Vee string in Congo on the 500kV DC Inga-Kolwesi line. Insulators did not have the body resistance required for a DC application. (30% failed units. Round circles show location of punctured discs found during the investigation).

Today specific DC materials are defined by their body resistance as per IEC 61325 [2] which describes an ionic migration test and a body resistance test. These procedures offer a methodology for testing under DC conditions the ability of a material to sustain an ionic environment. The body resistance is measured at 3 different temperatures (90°C, 120°C and 150°C). Experience is showing that high resistivity discs will solve the question of thermal runaway. An example

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of such values on glass insulators is shown in Fig. 2. A resistance value around 3 GΩ measured as per IEC 61325 at 120°C is a good reference.

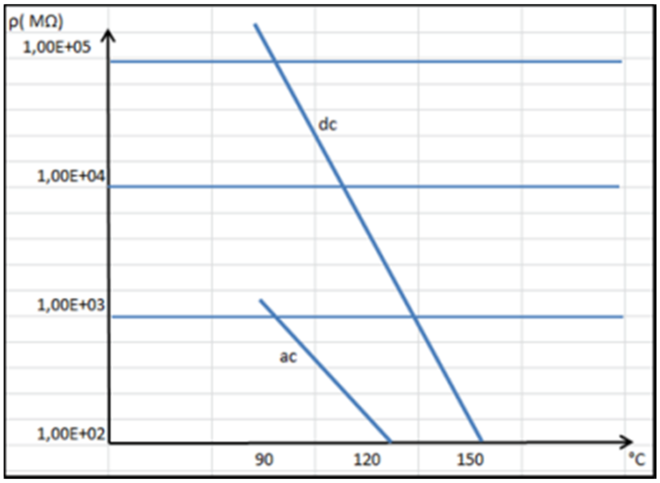


Figure 2. Comparative AC and DC body resistance of toughened glass insulators (ref. Sediver)

It is also interesting to note that the heterogeneous nature of porcelain (compared to the amorphous nature of glass) has an influence on the stability of the body resistance as a function of mechanical rating. In fact, the higher the mechanical rating, the bigger the head of the insulator and higher is the probability to have micro structural defects though the thickness of the porcelain material. Fig. 3 shows the evolution of DC porcelain body resistance as a function of mechanical rating.

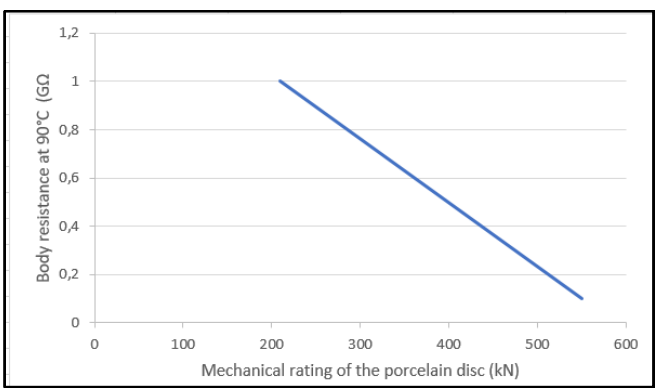


Figure 3: influence of the thickness of the porcelain head (mechanical rating of the insulator) on the body resistance of porcelain insulators measured at 90°C

III. Corrosion of End Fittings in DC

As stated earlier, DC stresses accelerate the possible corrosion of the metal end fittings. IEC 61325 [2] explains the design of the zinc sleeve for the protection of the pin, and experience shows the benefits of this design. [6]. The cap on the other side needs also special care. Some older insulators (like in the 600KVDC bipole Itaipu 1, Brazil shown in Fig. 4) have some corrosion at the base of the cap [7]. The corrective action for Itaipu 2 was immediately implemented by adding a large zinc collar at the base of the cap. Fig. 4 shows an insulator with this feature which is not correctly described in the current version of IEC 61325 [2].

Figure 4. Left: Corrosion at the base of a cap without large zinc ring protection (Itaipu 1) - Right: Optimum design using a large zinc collar at the base of the cap

The standard only calls for 5g of zinc which in fact correspond barely to a galvanization thickness of 110µm…this simply does not work and more stringent criteria are required for an effective protection. Field experience is showing clearly that an optimum protection is achieved with at least 100g of zinc distributed at the base of the cap as shown in Fig. 5. Another approach can be based on the contact surface between the casting of the cap and the zinc ring. In this approach a cross section of at least 40mm² is a good reference.

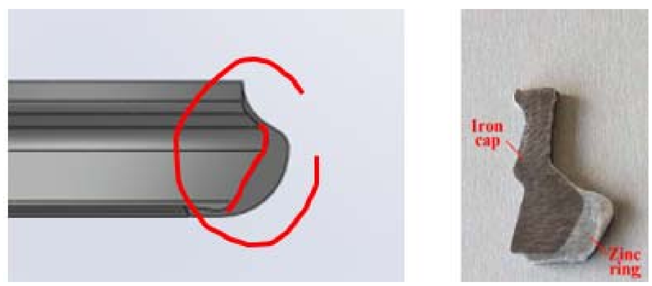


Figure 5. Detail of the zinc collar at the base of the cap

Directly connected to this topic is the quality of the assembly. The gap between the dielectric and the base of the cap can generate discharges and severe risks of corrosion. Ideally the contact should be direct as shown in Fig. 6. Some manufacturers are using plastic seals which don't last (thermal stability). The presence of a gap at the base of the cap as shown in Fig. 7 is known to be critical up to a point where the dielectric can be damaged (Fig. 8 with damaged glaze and crack underneath of the porcelain itself). This has been a reason for taking down more than 20000 porcelain insulators after about 3 years in China [8]. Such degradations are expected to occur faster in high temperature, humidity and elevation.

Polymer insulators are at risk as well. The idea of promoting composite insulators because there are only 2 fittings is not correct. In fact, the risk of corrosion at the fittings is the same with the additional risk of degrading the triple point and destroying the seal (if any) as seen in Fig. 9.

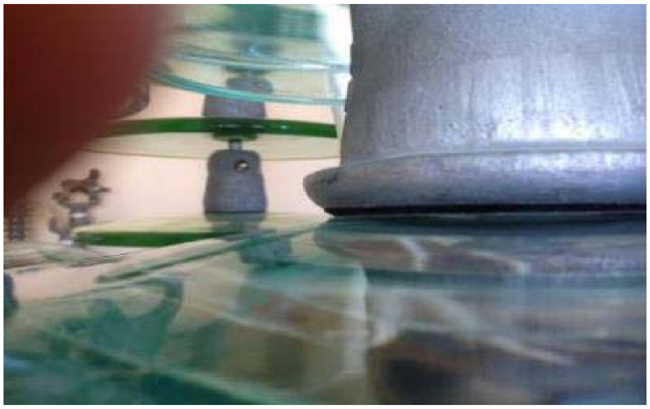


Figure 6. Ideal junction between dielectric and cap

Figure 7. Typical gap between the cap and the dielectric in porcelain designs

Figure 8. Damaged porcelain insulator resulting from the lack of zinc collar and excessive gap.

Figure 9. Corrosion and degradation of the seal of a polymer insulator at the triple point resulting in moisture ingress and major risk of failure. (removed from service after a decade)

IV. CONTAMINATION CONSIDERATIONS

The ionized surroundings of a DC line are prone to attract airborne dust and increase the pollution level on the insulators. A DC line built in the same path as an AC line will therefore collect more dust and requires a different approach to the management of pollution and the selection of a specific creepage distance and shape of the insulator. The latest version of IEC 60815-4 [1] is describing this aspect in detail. The main drivers are:

- In DC the arc does not necessarily follow the surface of the insulator and can bridge some leakage distance
- With the same level of pollution, the flashover of a string of insulators occurs at lower values in DC than AC.
- The non-uniformity of the pollution deposit can impact severely the performance of a sting of insulators (either distribution along the string as shown in Fig. 10 or between bottom and top surface of an insulator (this parameter is called "CUR")

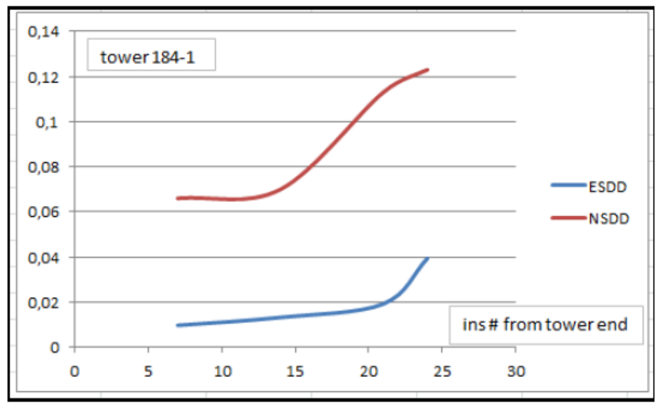


Figure 10. ESDD and NSDD measured along a string of insulators on the Pacific Intertie 500KV, USA.

The design of a DC insulator string requires an evaluation (or knowledge) of the two main parameters defining pollution:

ESDD: Equivalent Salt Deposit Density (in mg/cm²) corresponding to the amount of soluble salts contained in the deposit and responsible for an increase of the surface conductivity

NSDD: Non-Soluble Deposit Density (in mg/cm²) which is made of sand and non-soluble dust acting like a sponge during foggy or muggy periods of time.

Fig. 11 shows the IEC graph of ESDD and NSDD combined with an example of pollution measured on an AC line (blue dot) and the estimated level of pollution if this line was built as a DC line (red dot). This estimation is based on a theoretical model utilizing a set of equations described in IEC 60815-4 [1]; Among these equations, the following is interesting since it describes how to estimate the expected ESDD under DC when starting from an AC estimation (ESDDave):

$$ESDD_{dc} = ESDD_{ave} \times K_p \times K_{NSDD} \times K_{CUR} \times K_d \times K_S \, .$$

Kp is a correction factor taking into consideration the type of environment the line will go through with a qualitative approach to rain and wind events. (see in Fig. 12 the table of assumptions made for Kp by [1]).

KNSDD makes a correction to the ESDD to address the fact that the severity of the pollution is amplified by the presence of non-soluble deposits.

Kcur will make a correction to take into consideration the uneven distribution between the bottom and the top of an insulator (range expected to be between 1 and 10, the most severe case being when Kcur=1).

Kd and Ks are related to diameter of the insulator and a statistical figure to illustrate the risk for having a flashover on a long line versus a short span. More details are available in [1] and [9].

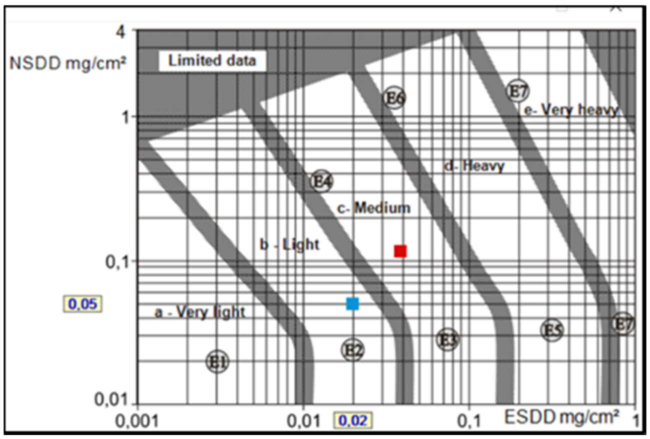


Figure 11. Pollution graph as per IEC 61815-4 [1] describing the contamination level as a relative function of ESDD/NSDD. For an environment where an AC line (blue dot) would capture a pollution of ESDD = 0.02mg/cm² and NSDD = 0.05mg/cm² a DC line would be estimated at ESDD = 0.04mg/cm² and NSDD = 0.011mg/cm² (red dot). (based on [1] and Sediver DC estimator software).

The knowledge of ESDDdc is used for defining the USCD (Unified Specified Creepage Distance) expressed in mm/KV.

According to [1] the graph for this operation is as per Fig. 13. Several indicators [3] such as laboratory tests and field experience seem to indicate that for non-hydrophobic materials (glass and porcelain) this curve is too severe. The reality seems to be closer to the line represented in orange in Fig. 13. The difference between theory and actual results can induce an overdesign of the string length of about 20% (and subsequently of the towers height and costs).

Event Frequency	Average/Normal Wind High	Moderate	Low	Dead calm
Frequent rain	1	1	1	1
Short duration extreme events	Typical: 1.1 Range: 1 to 1.2	1.1	1.2	1.3
Build-up over months	1.3	Typical: 1.6 Range: 1.3 to 1.9	1.9	3
Build-up over years	2	2.25	Typical: 2.5 Range: 2 to 3	3
Long dry periods (< 20 mm rain/month for more than 6 months)	2.5	2.75	3	Typical: 3 Range: >3

Figure 12. Kp estimation based on [1]

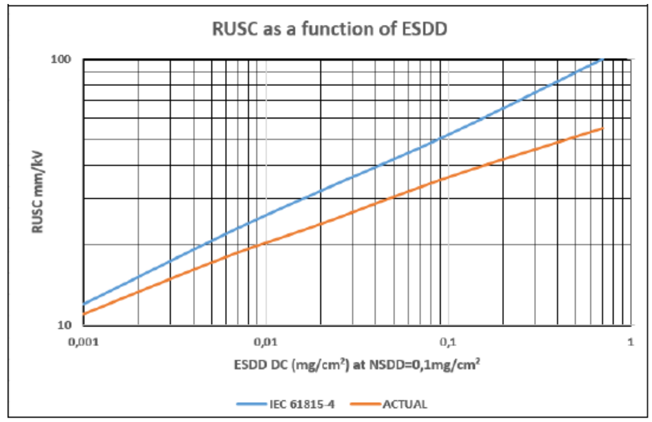
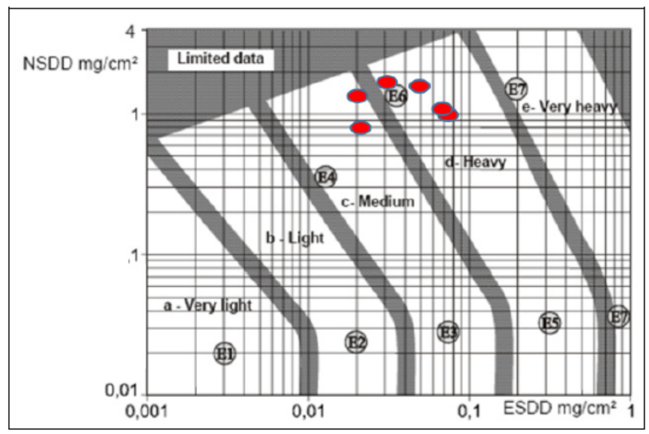


Figure 13. USCD as a function of ESDDdc as per [1] in blue and as per actual laboratory tests and field experience in orange as per [3]

As an example, the section of the Itaipu between Ibuna and Itapera, Brazil 600KVDC is interesting to study.



Location	Insulator nb. from tower	ESDD (mg/cm²)	NSDD (mg/cm²)	CUR
IBUNA	1	0,07	1,01	27,5
	14	0,02	0,89	9,67
	25	0,07	1,06	8,58
ITABERA	1	0,02	1,52	12
	14	0,03	1,77	22
	25	0,05	1,74	19,25

Figure 14. Itaipu pollution levels measured on actual insulators removed from the line. It is interesting to see in the table below the graph the CUR values often found beyond 10.

Fig. 14 shows the pollution levels measured on actual insulators from a region where there are no reports of outages linked to contamination.

The strict theoretical model would require a USCD= 47mm/kV while the line is insulated at 28.5mm/kV. This case which describes to the extreme the inconsistency in [1] is most likely the result of CUR values (ratio of ESDD between bottom and top of the insulator) beyond the normal range of application of the equations in [1].

These results, among others [3] show that savings and optimizations are possible at the string design level for DC projects. It is also a clear indication that the theoretical model described in [1] needs to be reviewed in a future revision of IEC work.

V. Silicone Coated Glass Insulators

Polymers are marginally used in DC except for China. More recently and for the first time a Chinese 800KVDC was built using factory coated silicone glass insulators instead of polymers (Fig. 15). This is a strong trend today especially when facing severe local pollution conditions.

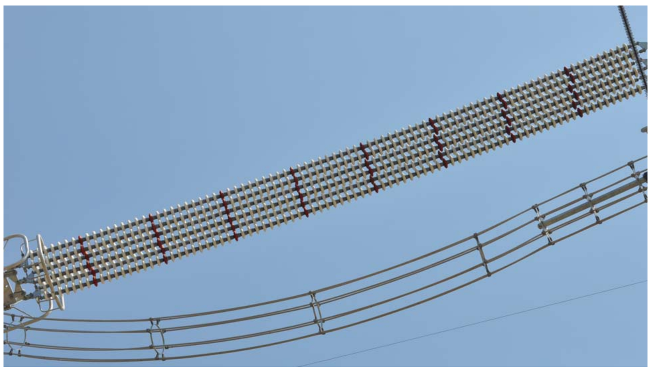


Figure 15: 800KVDC with factory coated glass insulators in China

As mentioned earlier long-term performance of polymers in DC remains questionable and field results such as ESKOM [10] demonstrate that after approximately 15 years of service ageing signs start appearing on the housing. Likewise, Fig. 9 describes the risks associated to seal erosion and degradation after a decade in service. This is consistent with the AC experience by many aspects and TERNA (the Italian TSO) after an extensive experience with coated glass insulators in AC along their coasts and extreme pollution sites has successfully decided to use silicone coated glass insulators on their 200KVDC line.

VI. Conclusion

DC overhead transmission lines need to be isolated with dedicated insulator designs. Among the key features, the body resistance needs to be increased compared to AC insulators to sustain the ionic migration effects. Likewise, the end fittings need specific protection beyond what is described in IEC [2]. The pollution management in DC is more complex than for AC and the polarization of the air surrounding the line will intensify the level of pollution. The current method described in IEC [1] is a good step forward but does not describe correctly number of parameters as can be seen from a comparison with field experience and laboratory tests. Both IEC documents should therefore be updated. An innovative approach to DC in heavy polluted areas is to use factory silicone coated glass insulators where the benefits of both technologies are combined.

References

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