2024 Paris Session

10313
B2 Overhead Lines
PS1 Challenges from renewables integration and influences
of energy transition on OHL

HVDC overhead line insulators: basics and performance

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SUMMARY

The increase of energy demand and the progressive deeper impact of renewable energy in the global energy mix has triggered a strong interest in building new DC lines, upgrade older lines or convert AC to DC some existing segments taking advantage of existing rights of ways. This trend is consistent worldwide with projects going through a variety of environments and therefore with the need to design or adapt the insulation of the line with the most appropriate insulators.

IEC has established a long time ago a DC standard (IEC 61325) [1] which describes the technical requirements for DC overhead line insulators made of glass or porcelain dielectrics, but standardization bodies are still struggling with polymers for which some work is ongoing in CIGRE and IEC, often describing tests which are performed under AC stress and extrapolated to DC application, which by nature can be a challenge or seem inconsistent with the expected difference of performance when a DC voltage is applied. On the other hand, IEC 60815-4 [2] is a guide providing information related to the pollution performance and string design characteristics of insulators in DC stress conditions.

Several key aspects of DC insulator design will be re explained as it appears that some of the basics have been forgotten by some line engineers over the years. Among the main considerations some particularities of the end fittings and some geometrical aspects of the dielectric itself have been overlooked while relatively well described in the past and misapplications are possible today if these aspects are not clearly understood.

From a pollution point of view IEC 60815-4 [2] should be reviewed and the paper will present actual data to be compared with the theoretical approach described in the guide. The biggest gap between the mathematical model and reality is related to the calculation method of the USCD (Unified Specific Creepage distance) for a given pollution level. Consequently, strings will end up being longer with the model than needed resulting in possible higher costs of the towers.

A particular aspect of polluted insulators in DC in harsh environments is the benefit of a hydrophobic surface. For polymer insulators the ageing and erosion of the housing is a fundamental question for which there is no test today making consensus (ongoing work in

CIGRE D1 72) [3]. For silicone coated glass or porcelain insulators the question is different given the absence of a fiberglass core which needs an absolute protection under the housing. Coating erosion and strength in DC have been evaluated especially for coated glass insulators and results will be presented.

Pollution performance in DC through artificial pollution tests with silicone coated insulators will also be discussed including the difficult aspect of producing an artificial heavy or very heavy layer. The transfer of hydrophobicity, which is the fundamental benefit of using hydrophobic surfaces for those thick layers can be a challenge in a laboratory and mostly the representativeness of the surface deposit when applied in one operation compared to the natural and progressive built up in service which will allow a progressive transfer over time.

KEYWORDS
Glass Insulators, HVDC, Pollution, Shape of Insulators, Silicone Coating, Erosion, Salt Fog, Solid Layer, Porcelain Insulators, Polymer Insulators

INTRODUCTION

The difference between AC and DC stresses on insulators has forced standards to adapt and define specific design features and testing for DC applications. While relatively well described for porcelain and glass cap and pin insulators the case of polymers continues to generate questions despite some standards which still point out questions and unsolved issues. A quick review of the key features in the design of DC insulators will be a reminder of these specificities but also point out room for improvement in IEC.

The proper selection of overhead line insulators for HVDC application implies the knowledge of the environmental conditions along the route of the project prior to construction and most definitely at the design stage when the geometrical characteristics of towers and structures are being established. IEC 60815-4 [2] is a guide providing valuable information to this respect but is inaccurate for the definition of the leakage distance in the case of porcelain or glass cap and pin insulators. This section constitutes the centre piece of this paper and should be largely discussed in the upcoming meetings for the revision of this guide. A main reason for this inaccuracy is the misunderstanding of the importance of the shape of the dielectric skirt. This paper will show how important the profile of the insulator is in HVDC for reducing the propagation of dry bands across the insulator and the consequence for the pollution performance under polluted conditions.

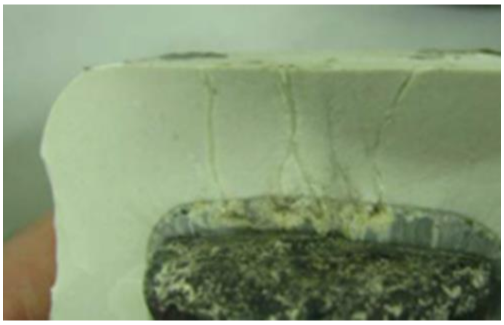
Hydrophobic surfaces can be an excellent approach for the mitigation of pollution related flashovers in heavy of very heavy pollution classes which is one of the reasons why polymer insulators can be perceived as an attractive solution. Unfortunately, under such very harsh conditions erosion can become a limiting factor of application. As an alternative to polymer insulators in these severe conditions more and more projects are considering silicone coating glass insulators for which the consequences of erosion are not as harmful. Likewise, the shape of insulators matters even when using a hydrophobic surface and an example in salt fog testing will provide interesting directions for future work.

1. BRIEF DESCRIPTION OF FUNDAMENTAL DIFFERENCES BETWEEN AC AND DC CAP AND PIN INSULATORS

This section intends to revisit some specific aspects required for HVDC cap and pin insulators but not only. Often forgotten in discussions where for DC engineers concentrate on string design under pollution, the construction of insulators for DC needs to be remembered given the specifics described below. The main difference between AC and DC insulation is the presence of an ionic and polarized environment which can destroy the dielectric though the existence of an ionic current inside the dielectric itself but also accelerate the corrosion of the end fittings.

a. Dielectric strength under DC ionic current

This phenomenon has been largely described over the years and specific tests have been introduced as those described in IEC 61325 [1] where the body resistance and resistance against thermal runaway are being tested. Not having a high resistivity dielectric will lead to either punctures for porcelain discs (figure 1) or shattering for glass. Figure 2 shows the typical resistivity levels required for HVDC.



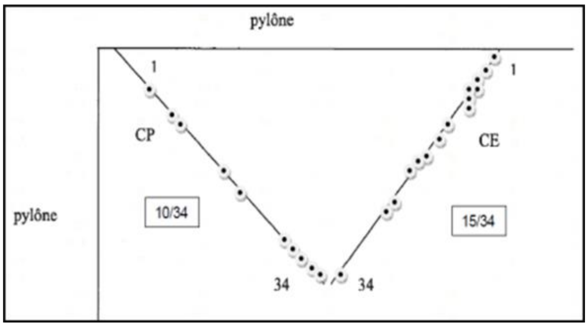


Figure 1: example of the punctures in porcelain insulators used in HVDC with a body resistance too low for the application and distribution of punctured units in a typical V string of a 500 kV DC line showing between 30% and 50% of punctured units.

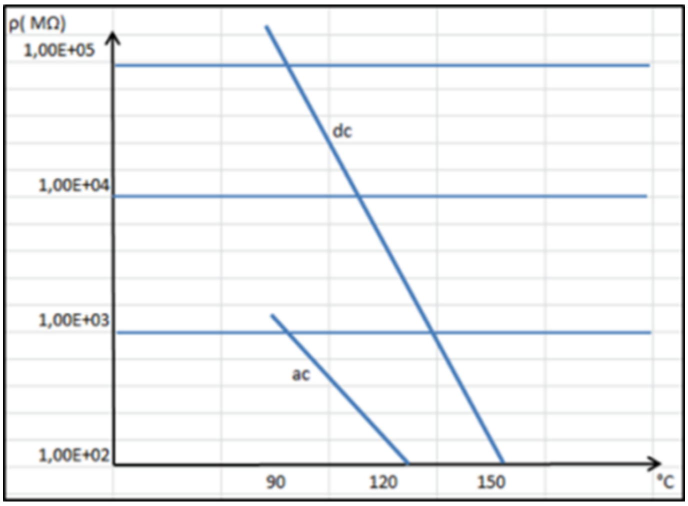


Figure 2: example of body resistance levels measured according to IEC 61325 for HVDC insulators (Sediver data) [4]

b. Protection of the end fittings

End fittings will rust faster under DC stresses compared to AC if they are not properly protected mostly because of more stable discharge activity and leakage current. IEC 61325 [1] describe how to protect the pin from electro-corrosion thanks to an adherent zinc sleeve which is an effective way to eliminate this problem as shown in figure 3.

Figure 3: Benefit of a DC zinc sleeve on the pin of a DC insulator. Left without and right with a zinc sleeve after approximately 15 years in a very challenging coastal environment.

The risk of having corrosion at the base of the cap has been solved many years ago with a zinc collar fused at the base of the cap using the same criterion as for the pin. Some manufacturers of DC insulators do not follow this advice and figure 4 shows the end result after less than 10 years in service. This protection is not described currently in IEC 61325 [1] but should be added in a future revision especially for lines crossing areas where humidity is higher than 70% through extended periods of times, or near coastal areas for which the pollution class is medium or higher. Typical zinc collar protections are shown in figure 5. Polymer insulators should also take this aspect into consideration especially given the risk of having simultaneously corrosion and seal degradations as shown in figure 4.

Figure 4: rust at the base of the cap in HVDC applications for glass (left) and porcelain insulators (center). Right: seal degradation and rust on the end fitting of a polymer insulator.

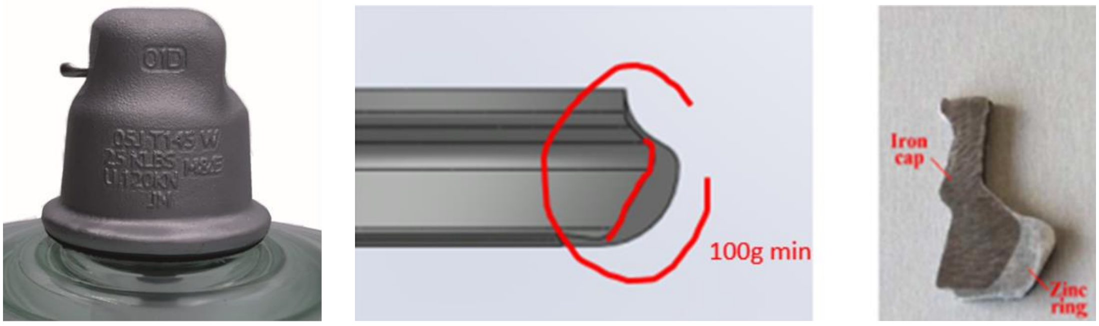


Figure 5: optimum cap design to prevent cap corrosion in HVDC applications

2. INSULATOR SHAPES FOR HVDC APPLICATIONS

IEC 60815-4 [4] gives recommendations for some geometrical particularities which are considered to fit best for DC applications. The reasons for this can be found in the development process of partial arcing along the surface of an insulator. Figure 6 describes the fact that in DC the arc will try to bridge the leakage distance between two consecutive ribs leading in some cases to much lower flashover values under critical conditions of pollution. This is one of the fundamental reasons why for example aerodynamic also called “open profiles” are not fit for a DC application since the arc would develop very quickly along a surface where there are no ribs to interfere with the development of the discharge.

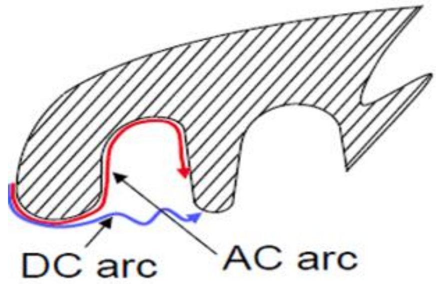


Figure 6: difference in arc development between AC and DC [2]

To illustrate this point figure 7 shows the difference in arc bridging the profile of insulators as a function of the shape. The efficiency of the leakage distance is a direct consequence of this phenomenon.

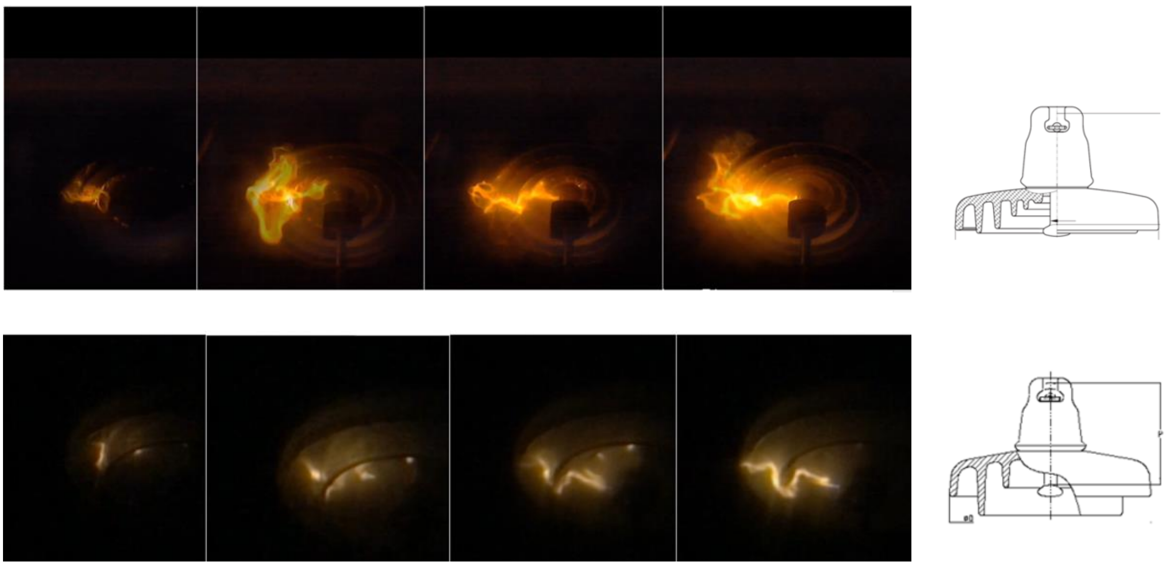
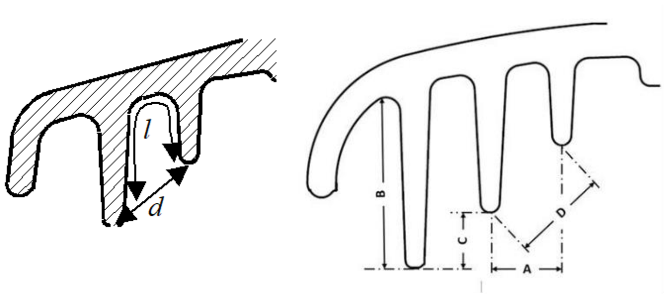


Figure 7: Top: arc development in salt fog conditions under a skirt of poorly designed insulator for a DC application. Bottom: arc development following more closely the profile for a well-designed shape adapted to DC application. (Tests performed with insulators having the same leakage distance).

IEC 60815-4 [2] explains that among the geometrical aspects of an insulator two elements are the most important such as the creepage factor CF and the ratio between partial leakage distance and distance between ribs l/d ratio (figure 8). The guide explains that DC insulators should have CF< 3 (CF=l/S where l is the leakage distance and S the arcing distance measured on a string of 5 units) and never above 3.5 and l/d <4.5. Experience shows that in addition to these two parameters other dimensions are key for an optimum performance and should be taken into consideration as shown in figure 8.



parameter	value
(D/2)/N	≥ 60
Average A	≥ 30
Average B	≥ 50
C	> 20
D	> 35

Figure 8: Left: l/d ratio below 4.5 as per IEC 60815-4. Center and right: Sediver recommendations (values in mm) based on experience and artificial pollution testing. N= nb or ribs excluding the outer rim of the skirt and the inner edge around the pin cement area.

3. MODIFICATION REQUIRED IN IEC 60815-4

IEC 60815-4 is following a method of determination of the leakage distance to be used in a DC application based on various equations and correction factors.

The determination of the appropriate leakage distance for a string of insulators in a DC application was initially made through a large test program performed in the EPRI laboratory in Lenox, USA approximately 40 years [5] ago which consisted of clean fog with solid layer artificial pollution testing of a large variety of insulators which shapes either no longer exist or, for some of them are not used or were not even designed for DC at all (figure 9 illustrate the shapes which were considered during this test).

Additionally, these tests were not performed according to IEC 61245 [8] but rather through a customized procedure aimed at comparing glass, porcelain and polymer insulators simultaneously in so called equivalent strings.

The data from EPRI and IEC were converted in kV/m of leakage distance and plotted in figure 10 with actual test data from glass strings. It is interesting to note that IEC 60815-4 is coinciding with the old tests where the EPRI data correspond to a U50 flashover curve. The same graph also shows the actual test results performed on DC glass insulators currently supplied as well as published data from porcelain.

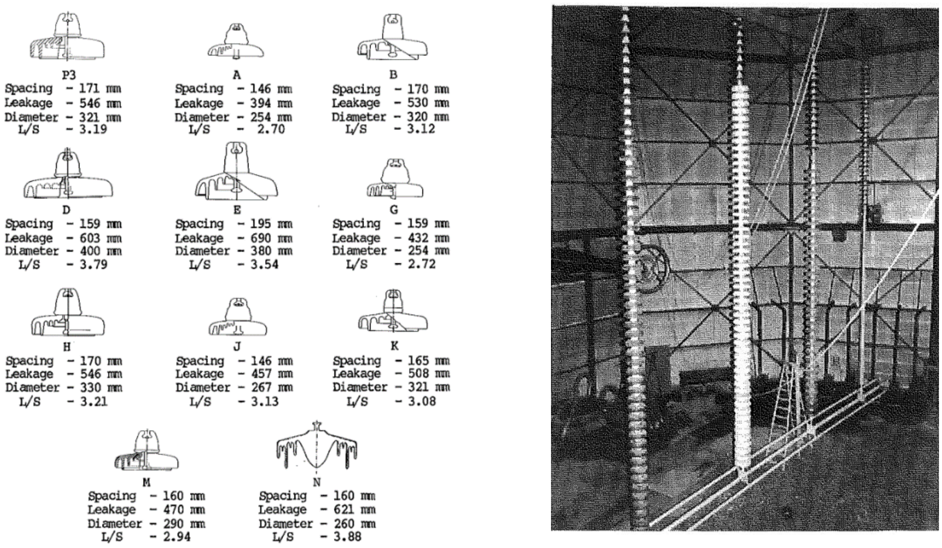


Figure 9 : Insulator types and set up of the EPRI test program [5]

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For glass insulators the shapes are optimum for DC pollution in line with section 2 of this paper and the tests were performed according to IEC 61245 [8]. Also, for glass insulators both U50 and withstand results are shown. While the withstand values are not always a max withstand value the combination of the 2 curves demonstrate good consistency of this set of data and should become the reference.

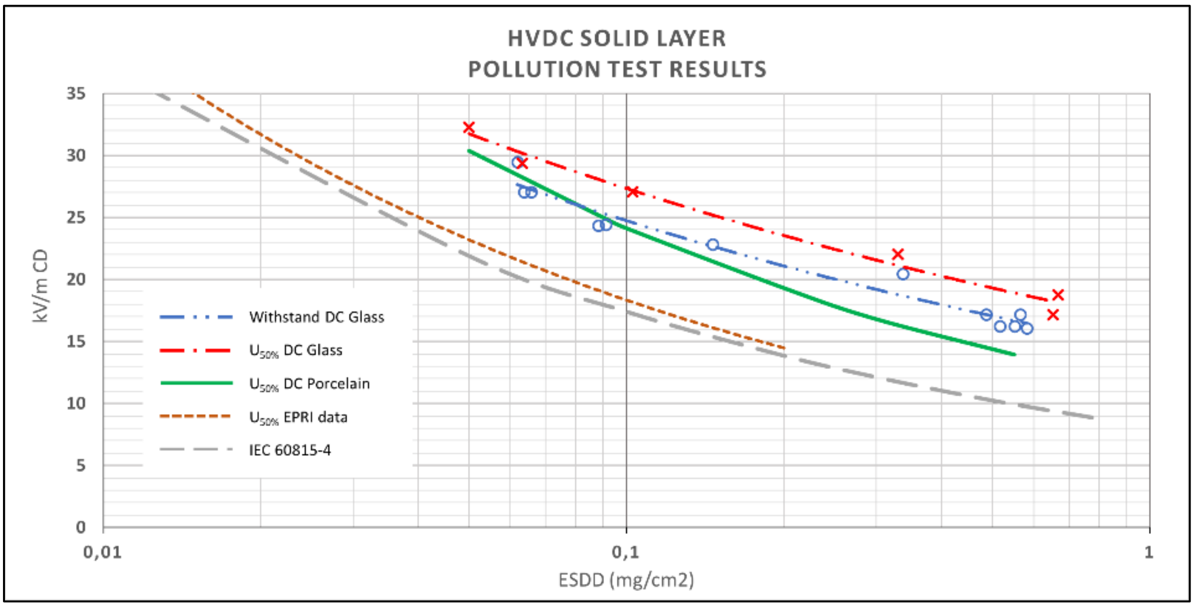

Figure 10: Comparison of performance of glass and porcelain DC insulators with respect to IEC 60815-4 [2] and old EPRI test data [5]. (Results are in kV/m of creepage distance as a function of ESDD with NSDD=0.1 mg/cm²). Tests on glass insulators performed in the Sediver CEB pollution laboratory in Bazet, France.

The results are pointing out a substantial gap between the IEC curve and reality, between 30% and 40% for DC glass insulators and is inducing misconceptions in their expected performance and subsequently generates a costly overdesign especially of the towers. A drastic review of the guide is therefore mandatory to get closer to reality and make IEC 60815-4 become credible.

Given the difference in the dynamics of the dry band arcing between AC and DC it must also be noted that converting AC test results to DC is inadequate.

4. SILICONE COATING

The use of silicone coated insulators in HVDC is increasing like it does for AC applications. Two aspects of interest are being discussed hereafter: selection of the coating material (only coatings made in the factory are being considered) and pollution performance.

4.1 Selection of the coating for DC applications

While IEC 63432 is drafting a standard for the use of coating applications the 2000h multi-stress test described in the document so far is strictly an AC test. Work was already done with a DC version of this test [6]. Such evaluations were performed also in the Sediver R&D aging laboratory in Saint-Yorre, France. Insulators used in this test are in line with the requirements of adherence and thickness of AC coatings (thickness between 300µm and 450µm). The test was performed at 40g/l with a USCD =45 mm/kV. Figure 11 shows the results on insulators having the same profile but two different chemistries and differences in aging appear clearly at the end of the process either on the hydrophobicity or the erosion of the test samples.

Type B shows superior performance compared to type A while in AC both types of coatings show similar good results. Once again it confirms that under DC conditions silicone suffers more than in AC as already shown for polymer insulators.

Figure 11: 2000 h multi stress test with a DC applied voltage. Center Type A with erosion and hydrophobicity HC5-6. Right Type B no erosion and HC1-2.

Insulators for which only the underneath side is coated are also used in some HVDC applications. An interesting example is a case located in the western part of the USA on a 500kVDC line operating at a USCD = 25mm/kV including in areas of medium class pollution and for which uncoated insulators were facing flashovers. This configuration was also tested in a 2000h DC multi stress test with very good results as shown in figure 12.

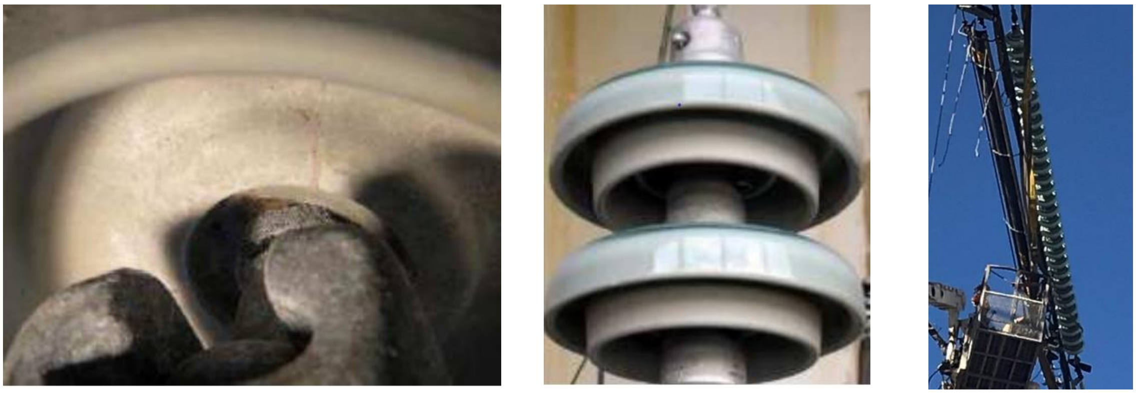

Figure12: under coated insulators after a 2000h HVDC multi stress ageing test and during installation on a 500kV line

4.2 Pollution performance of silicone coated insulators in HVDC

As a matter of fact, there is today no standard procedure for testing hydrophobic surface insulators (HTM) which is why IEC 63414 is being drafted. The complexity is the determination of the desired level of hydrophobicity prior to testing a surface which is covered with an artificial layer of contaminant.
Heavy NSDD levels in service are the result of weeks or months of airborne dust collection and the silicone surface has time to progressively produce the transfer of hydrophobicity to the surface which is not the case in an artificial pollution test where the contaminant is applied at once. For this reason, it appears unrealistic to test HTM surfaces with pollution levels where NSDD>0.1 mg/cm².

Likewise for salt fog testing the question is the preconditioning of the surface. Work done previously [7] gives some guidance and ongoing testing is showing the very good performance in DC of silicone coated insulators.

An example of such performance is shown in figure 13 where a string of silicone coated glass insulators is compared to a polymer insulator using a procedure in line with the upcoming IEC protocol. Test conditions were 20g/l with a USCD= 31mm/kV in a preconditioning test phase at -200kVDC. The polymer insulator flashed over after 1h while the coated glass string finished without any noticeable activity over the 3h sequence of preconditioning. Shape is considered as the main attribute of the glass string to outperform the polymer insulator since both strings were tested with a silicone surface of the same leakage distance and similar hydrophobicity levels.

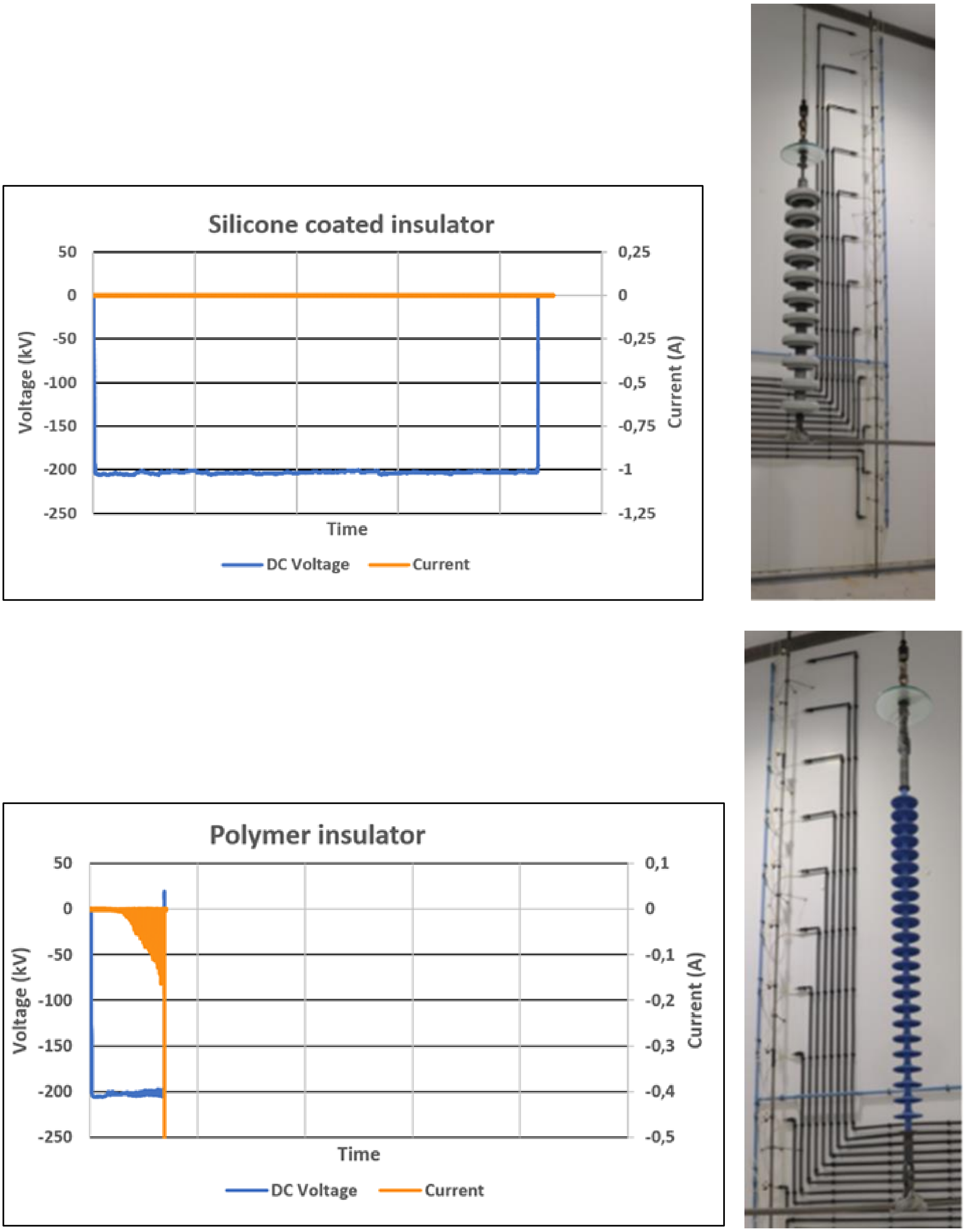

Figure 13: Silicone coated glass string (top) with no activity and equivalent polymer insulator (bottom) during a salt fog preconditioning test at -200kVDC at 20g/l with dry band activity leading to flashover of the polymer insulator after approximately 1h.

CONCLUSION

Specific aspects of DC cap and pin insulators need to be taken into consideration since there are particularities often forgotten by engineers. IEC 61325 [1] is the reference document describing well the different aspects to remember. An evolution of this standard should describe more precisely the precautions to take into consideration for the protection of the cap from early corrosion which was already implemented decades ago by major insulator manufacturers.

Pollution characteristics of insulators in DC have been presented with a focus on the shape of the skirt. The efficiency of the leakage distance of the insulator has been presented and only specific DC shapes should be used for a DC application. Previous work [5] which was done and used in IEC 60815-4 [2] cannot be used as a reference given the type of insulators which were tested, and the test procedure used at that time. These results are largely underestimating the performance of DC cap and pin insulators. A summary of actual pollution test results in DC presented in this paper clearly demonstrate the need for a reevaluation of the IEC relevant document.

Silicone coating applied to cap and pin insulators is an extremely effective approach in the mitigation of severe pollution of DC lines. An adapted version to DC of the 2000h AC multi stress test on coated insulators can be very helpful in the selection of the most appropriate coating. The pollution performance of silicone coated glass insulators appears to be capable to outperform polymer insulators.

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