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Field experience and laboratory results on the application of RTV coating on HVDC lines

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SUMMARY

The utilization of RTV pre-coated insulators is rapidly expanding worldwide thanks to the very positive laboratory and field returns.
TERNA started the installation of pre-coated glass cap and pin insulators in 2003 on AC lines up to the 380 kV voltage level and today there are more than 1 million units installed in the Italian high voltage grid. No flashover was reported through all these years of service and insulation washing was no longer needed on those line equipped with RTV insulators. Every year tests for the evaluation of both coating degradation and ageing are performed on different units removed after different years of service from the lines. The outcomes of such tests are different since they are strictly related to the environment in which the insulators are exposed. In the worst condition sensitive changes related to degradation or ageing have been pointed out, even if both laboratory tests and field experience confirm their high level of endurance.
Since 2008 TERNA decided to gradually expand the installation of pre-coated glass cap and pin insulators on HVDC lines considering the very good returns of the AC applications.
Since degradation and ageing are different in DC, specific tests were performed in laboratory to make some inference on endurance.
This paper reports different type of tests on RTV pre-coated cap and pin insulators for DC applications with the aim to characterize the behaviour on new and field returned units among which results from the multi-stress ageing test (known as 2000 hour Terna’s test), which represents a particularly significative test for the overall evaluation of the performances of the insulators. The

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results of such tests are compared with the results of tests carried out on naturally aged insulators (after 7, 8 and 9 years of installation) in order to quantify the extent of aging in operation and estimate the useful life of the RTV coating.
New insulator strings were tested in laboratory in different string configurations (“I” string, “V” string and quite horizontal string) and applying in sequence twice the 2000 h ageing test.
Test results from laboratory and field aged samples pointed out interesting information. A discussion on the comparison of such results in terms of hydrophobicity, hydrophobicity recovery and reduction of flashover performances (evaluated through the “quick flashover method”) is reported, since both hydrophobicity recovery and flashover voltage reduction are considered as operational degradation factors for ageing inference.
Both tests on laboratory aged sampled and on field returned samples highlight the high level of reliability of pre-coated glass cap and pin insulators also for DC applications.

KEYWORDS

RTV coated cap and pin insulators, ageing, glass insulators, DC

INTRODUCTION

The use of Room Temperature Vulcanized (RTV) coated insulators is rapidly increasing in transmission grids crossing harsh environments [1-8]. Widespread installations started at the beginning of the current millennium especially on overhead line applications. Terna was one of the pioneers in this field and today the number of units installed is well above 1 million [2,3]. The advantage of this technology was immediately visible with a striking reduction of outages related to pollution, a reduction of maintenance costs since insulator washing was not required anymore and easy to check procedures (e.g. the same applicable for glass insulators if the coating is applied to glass insulators), the very high level of reliability if compared with composite insulators from both mechanical and electrical point of view [2-4,7,8].

In the Italian grid with more than 1 million of installed units, TERNA has never faced a flashover in more than 15 years of field experience. Probably the secret of such success is due to a stringent specification of the coating and ad hoc tests on the final product in order to ensure the quality of the product. Thickness control, adhesion evaluation, multi-stress ageing test, Soxhlet extraction, inclined plane test, etc. altogether contribute to give important information on the reliability that a coated insulator can have in very harsh environments.

From the beginning it was striking that insulators pre-coated in the factory and in a controlled environment is essential to a high level of reliability. No field coated solutions are accepted in the Italian grid for overhead line insulators since thickness and adhesion requirements are hardly met. Furthermore, a vulcanization in a controlled chamber is essential to get the needed crosslinking homogeneity.

After a number of years of experience in the AC lines, TERNA decided to extend the application of RTV pre-coated glass cap and pin insulators on DC lines [8], starting with some trial installation more than 10 years ago. Today more than 120 km of DC overhead lines stretching along sites classified as heavy and very heavy (typically near the coast and industrial sites) are equipped with this solution. Pollution problems immediately disappeared both at the end of long dry periods at the end of the summers up to mid fall and during winter strong winds from the sea causing strong salt storms. An additional 130 km of DC overhead lines will be installed within the next 2 years with RTV coated insulators.

This paper on RTV insulators for DC applications focuses the attention on lab-aged and on field-aged insulators trying to make some comparison between the artificial and natural ageing. In particular, for lab-aged insulators two cycles of the 2000-hour ageing test has been performed and the reduction of the breakdown voltage through the quick flashover method has been analysed. For field aged insulators, two strings sampled from a DC line have been subjected to the breakdown voltage evaluation through the quick flashover method. Hydrophobicity recovery has been also taken into account considering this as another method for ageing evaluation.

TESTED INSULATORS AND TEST METHODS

The insulators artificially aged in laboratory and naturally aged in the field have the same profile and dimensions, with the same DC glass material, the same coating material and the same coating application method. The insulator profile is reported in Fig. 1 with the dimensions reported in the figure caption. This is a typical fog-type insulator used on DC line and the one selected for the DC Italian lines. The insulator strings coming from the field were installed the same day in adjacent towers in order to guarantee the same stresses over the years.

Artificial ageing tests, Quick Flashover (QFO) tests and hydrophobicity recovery tests were performed in RSE laboratory in Milan and in the Sediver Bazet laboratory.

The artificial ageing tests have been performed following the 2000-hour test procedure [9] and here briefly reported. This test is made of 12 weekly cycles in a combination of multi-stress actions consisting of: salt-fog, clean-fog, rain and dry periods (with and without UV irradiation) under test voltage with the exception of the drying periods with solar radiation to allow UV lamps to be near the insulator strings giving the prescribed radiation. A description of the week cycle is reported in Fig. 2.

During the first five days of the week each daily cycle begins with salt-fog lasting 9 hours with the strings energized. The nebulized salt solution consists of water and sodium chloride which saturates the test room. The salinity of the solution used is 40 kg/m³ while its specific flow rate is 0.133 l/m³h corresponding to 47.9 l/h with a test room volume equal to 360 m³.

Figure 1. Insulator dimensions and appearance. P = 170 mm, D = 330 mm, creepage distance = 555 mm.

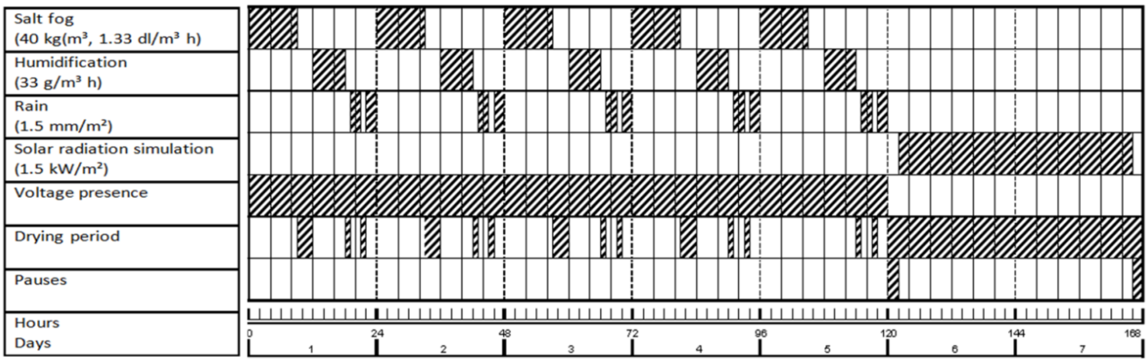

Fig. 2. The weekly cycle of the 2000-hour test

The nebulization of the saline solution is generated by a standard nebulizer, as reported in [10,11], which is mounted on a vertical column at a height of 4.2 m from the ground and oriented so as to atomize the solution not directly towards the objects being tested, but close to the strings and parallel to a wall of the pollution chamber. At the beginning of each salt-fog phase, the conductivity of the solution that feeds the nebulizer is measured in order to verify its correspondence in line with [10,11]. After this phase, a resting period lasting 3 hours is left for drying and then the clean-fog phase begins and is applied for 6 hours. The clean-fog phase is carried out by creating inside the test room an environment saturated with water vapor, generated by an industrial electric steamer. This steamer is regulated to guarantee a specific water consumption of 33 g/m³h as per [9]. The steamer pre-heats the water 1 hour and 45 minutes in advance in order to start the clean-fog phase with the required steam production (the steamer lid is removed at the beginning of this phase). As per the salt-fog, the steam (clean-fog) does not directly invest the insulators under test.
The rain phase is the last environmental phase of the first 5 daily cycle of the week and begins after one-hour break at the end of the clean-fog phase left for drying with the strings energized. It consists of two periods of 2 hours each, separated by one-hour break for drying with the strings energized. The rain is applied on the insulator under test according [9], de facto in this case in line with [12]. Water resistivity is set to 100 Ohms m and nozzle pressure is set to about 2 bar. Rain has vertical and horizontal components both falling in the range of 1 – 2 mm/min.
The last two days of the week a drying period with solar radiation is applied for 44 hours with the strings not energized. Solar radiation is performed with lamps having an emission spectrum similar to sun emission as reported in Table 1. In order to have the required irradiation of 1.5 kW/m^2 as per [9], the lamps are mounted in special stands some tens of centimetres away from the insulators under test. In the case in which the insulator surface exceeds at least in one point the temperature of 60 °C,

fans are used to avoid that this limit can be exceeded [9]. In any case the max air speed few centimetres away from the insulator under test shall not exceed 2 m/s [9]. A number of lamps are used in order to have as much as possible a uniform irradiation of the insulator string under test. The surface of the insulators under tests nearest to the lamps is also the most exposed to the horizontal component of the rain as per [9].

Table 1 – Spectral energy distribution of the lamps reproducing solar radiation [13]

Spectral region	Ultra-violet B*	Ultra-violet A		Visible		Infra-red
Bandwidth	0.28 µm 0.32 µm	0.32 µm 0.40 µm	0.40 µm 0.52 µm	0.52 µm 0.64 µm	0.64 µm 0.78 µm	0.78 µm 0.90 µm
Irradiance	5 W/m²	63 W/m²	200 W/m²	186 W/m²	174 W/m²	492 W/m²
Tolerance	± 35%	± 25%	± 10%	± 10%	± 10%	± 10%

* Radiation shorter than 0.3 µm reaching the earth surface is insignificant

For the lab-aged strings, it was decided to install three different insulator string position inside the chamber in order to have the possible configuration encountered in field, i.e. 1) vertical (I string), inclined at 54° in respect to the horizontal axis (V string) and quite horizontal at 15° in respect to the horizontal axis (tension string) (see Fig. 3 a).

After each artificial ageing test, the strings have been rinsed with tap water and left for a resting period of 1 week, then, the QFO test [14,15] has been performed. An additional further rest period lasting 1 week starting with the string rinsing is performed immediately after the QFO test. In conclusion, each lab-aged string has been tested considering the following steps:

1. 2000 h test with a stress of 54.1 mm/kV on strings of 6 unit (-61.5 kV – negative voltage polarity)
2. Rinsing with tap water and rest for 1 week
3. Quick flashover method at 80 g/l with negative voltage polarity
4. Rinsing with tap water and rest for 1 week
5. Subsequent 2000 h test with a stress of 54.1 mm/kV on strings of 6 unit (-61.5 kV - negative voltage polarity)
6. Rinsing with tap water and rest for 1 week
7. Quick flashover method at 80 g/l with negative voltage polarity

Three insulator strings were removed from the 200 kV SACOI DC line after a period of service of 7, 8 and 9 years. The insulator type is the same as the one used for the lab-aged samples as reported in Fig. 1. These field-aged samples have been submitted to the QFO test at 80 g/l using a reduced 4-unit string length instead of the 18-unit string used in that section of the SACOI line where the strings were sampled. The 18-unit string installed in that section of the SACOI line have a service specific creepage distance of 50 mm/kV. Before the QFO test the Equivalent Salt Deposit Density (ESDD) and the Non-soluble Deposit Density (NSDD) were measured in line with the procedure reported in [16] and then the strings were rinsed with tap water. The QFO tests have been performed with a 4-unit string in vertical position (I string) as reported in Fig. 3 b with negative voltage polarity. The value of ESDD and NSDD revealed on the three strings are reported in Fig. 4: this section of the SACOI line fall in a site pollution severity classified as “heavy” [16]. The differences in terms of ESDD and NSDD can be explained by the fact that the strings were sampled in different periods. In any case experience showed that these values fall in the range typically found in that section of the SACOI line.

TEST RESULTS

After the first 2000-hour test the largest erosion was revealed on the tension string, some erosion in some unit of the string reached down to the glass. The same observation was made after the second 2000-hour test outlining that the most stressed string is the tension string. In such a case, erosion traces were higher in number and deeper. Figs 5 and 6 show a view of the surface condition of an insulator taken from the tension string after 2000-hour ageing test and after 4000-hour (2000 + 2000 hours) ageing test respectively.

Table 2 reports the QFO test results of the lab-aged insulators, while Fig. 7 and Table 3 show an insulator as sampled from the line after 8 years of service and the QFO test results of the field-aged samples respectively.

a)

b)

Fig. 3. Insulator strings tested: a) 6-unit strings subjected to lab-ageing and QFO tests; b) 6-unit strings sampled from the 200 kV DC SACOI line and subjected QFO tests.

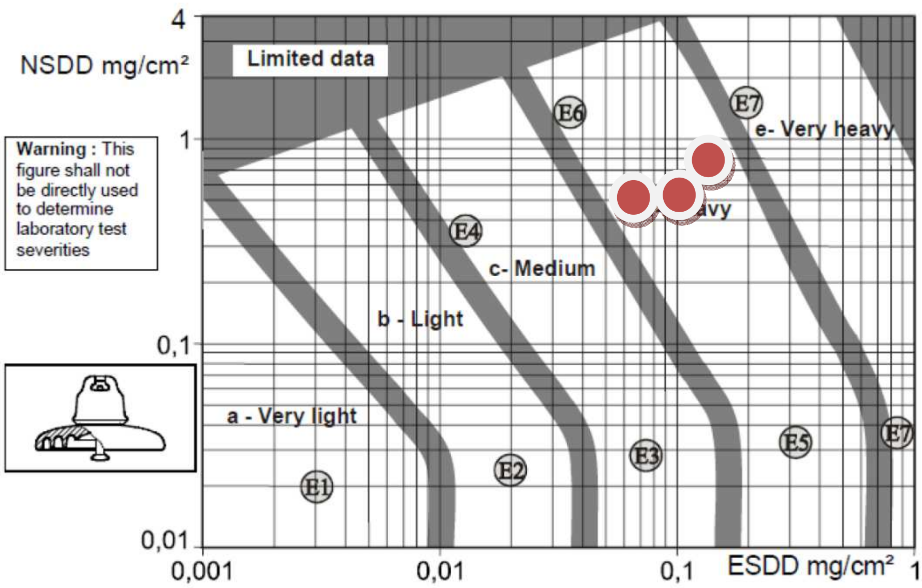

Fig. 4. Contamination levels of the three strings sampled on the 200 kV DC SACOI line.

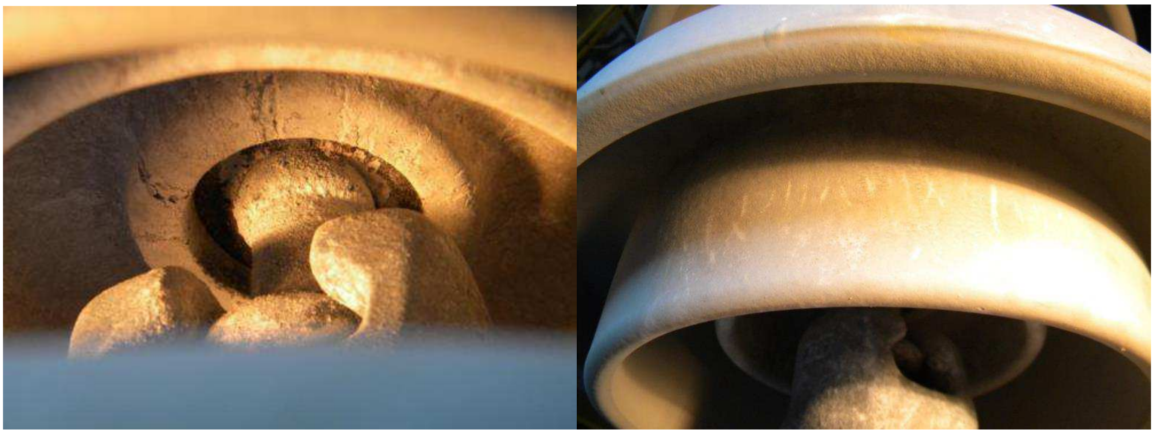

Fig. 5. Surface condition with signs of erosion near the pin and along the ribs after 2000-hour test.

Fig. 6. Surface condition with signs of erosion near the pin and between the ribs after 4000-hour test.

Fig. 7. Surface condition with slight signs of erosion near the pin and near the cap after 8 years of service. Coating damages on the outer surface are related to the transfer from the field to the lab.

Table 2. CFO values and relevant standard deviations from the QFO test performed immediately after the 2000-hour test and after additional 2000-hour test on 6-unit strings

String orientation (during ageing test)	After 2000-hour test		After 4000-hour test	
	CFO [kV]	σ [kV]	CFO [kV]	σ [kV]
I string	84.1	0.9	80.4	0.4
V string	86.2	1.7	82.1	2.5
Tension string	85.6	2.8	71.9	1.4

Table 3. CFO values and relevant standard deviations from the QFO test performed on 4-unit strings sampled in the SACOI 200 kV DC line after 7, 8 and 9 years of service

String orientation QFO test (at 80g/l)	After 7 years of service		After 8 years of service		After 9 years of service	
	CFO [kV]	σ [kV]	CFO [kV]	σ [kV]	CFO [kV]	σ [kV]
I string	51.6	1.5	49.7	1.3	71.5	2.0
HC at the beginning and at the end of the QFO test	**Before QFO test**	**After QFO test**	**Before QFO test**	**After QFO test**	**Before QFO test**	**After QFO test**
Top surface	6/7	7	6/7	7	6/7	6
Bottom surface	6	7	4/7	7	4/6	5/6
Mean HC recovery time (hours)		110		120		135

The same test procedures were applied to insulators for which only the bottom was coated with silicone. The test results are showing consistently the same pattern either after the first or the second 2000h test sequence when considering the standard deviation. Undercoated insulators showed even an unexpected marginally better flashover performance than the fully coated units, but the discussion of such results will be reported in a future paper.

The visual observation of the erosion level after the ageing test also demonstrate a very good behaviour with little damage to the coating as shown in Fig. 8.

Fig. 8. Under coated insulators before the test. Typical erosion pattern after the test with almost no change between the first and the second DC 2000h test

DISCUSSION

From the analysis of the results reported in Table 2 there is not a large difference between the different string orientations after 2000 hours of test. After the second 2000-hour test, the V string has the highest Critical Flashover (CFO) value (82.1 kV), while the I string is only 2 kV lower which is not a significative difference. Finally, the tension string shows a real difference with a value which dropped down to 71.9 kV. Considering the CFO difference between 2000 hours ageing and 4000 hours ageing, i.e. the critical flashover reduction rate, they are 13.7 kV for the tension string, 4.1 kV for the V string and 3.7 kV for the I string.

It is important to outline that the HC values 6 hours after the 4000-hour test ranged between 1 and 2 for both the top surface and the bottom surface and the hydrophobicity is completely recovered (HC 1) for both the top surface and the bottom surface no longer than 24 hours from the end of the 4000-hour test. This fact highlights that the impact on the hydrophobicity recovery of the 2000-hour and 4000-hour tests is negligible. On the other hand, such tests have an important role in the erosion process.

Unfortunately, the QFO test has not been applied on the virgin strings before the 2000-hour test started and consequently we do not have this information in our hands. With a slight difference in test procedure a test has been performed on a 5-unit I string. The procedure adopted was an up-and-down test in salt fog with a salinity level of 40 g/l. Such test was performed in the Sediver-Bazet Laboratory giving a CFO value of 128 kV.

As far as field-aged strings are concerned, it is interesting to note that the reduction of the CFO voltage is marginal from 7 to 8 years of service, while an increase appears after 9 years of service. It is important to keep in mind that each sampling made year after year includes variabilities such as weather conditions, higher rain level, extended dry season or specific events of pollution.

The Hydrophobicity Class (HC) recorded at the end of each test, as well as the hydrophobicity levels found on the units returned from the line need to be considered carefully. In fact, the insulator string with 9 years of service has a better hydrophobicity level than the ones taken earlier: HC 5/6 against HC 7 for the other two strings. This could be attributed to the statistical number of stress events encountered during service life (usually tens of events per year but not more and not systematic). Typically for the string tested after 9 years hydrophobicity and CFO value might be higher as a result of a longer quiet time lapse between the most recent and consecutive stress events, thus providing a better opportunity for a good recovery process.

As previously mentioned, the speed of hydrophobicity recovery is another approach to the evaluation of the ageing [7]. In Table 3 the time required to the bottom surface to completely recover to HC 1 for the three strings has been reported. It is important to outline that the 9-year string starts, at the end of the QFO test, with a HC equal to 5/6 against the other two strings which start from an HC equal to 7 and still it takes more time to recover. This fact outlines that the speed of recovery is independent of the initial hydrophobic condition of the surface, ageing playing a clear role in the dynamics.

With the aim to compare all the results obtained with different tests, the CFO values have been rearranged to be reported to a 18-unit string as the one used in the SACOI line section where the field-aged strings were sampled. Consequently, the CFO value obtained in a n-unit string has been multiplied simply to 18/n. Although this approach can be criticized, in any case can help to give a general view for the comparison among different tests. Furthermore, some CFO value has been further rearranged in order to consider specific conditions. In the case of the field-aged 9-year string the HC as shown above at the end of the QFO was around 5/6, in this case the QFO test was not able to reduce the HC class as per the other two strings. The HC has a not negligible influence on the CFO voltage: passing from HC 7 to HC 6 the CFO value can increase about 1.4 times (average) and passing from HC 7 to HC 5 can increase about 1.6 [17]. Considering such average values, if the QFO test was prolonged in order to reach HC 7, the CFO value would probably decrease to about 1.5 times (HC 5/6), i.e. 47.7 kV.

As a term of comparison with the results from aged strings (in lab and in field), the test results on virgin 5-unit string at 40 g/l salt-fog shall be rearranged to report the CFO value to 80 g/l. Considering that the USCD is inversely proportional to the critical flashover (assuming the same statistical distribution and the same dispersion), from [18] it can be stated that:

$$\frac{USCD_{40}}{USCD_{80}} = \frac{CFO_{80}}{CFO_{40}} = \left(\frac{40}{80}\right)^{0.25} = 0.841$$

Thus the 5-unit string having 128.0 kV of CFO with 40 g/l could correspond to 107.6 kV with 80 g/l.

Considering the I string orientation only for homogeneity with the different tests, Table 4 reports the CFO values for an equivalent 18-unit string.

Table 4. Inference of 18-unit string CFO values in kV with the QFO test from different tests

New	2000-hour aged	4000-hour aged	7-year aged	8-year aged	9-year aged
387.4 kV	252.3	241.2	232.2	223.7	214.7

Considering such test data, it is important to highlight some specific aspect about such results. Lambeth in his milestone paper [14] shows how there's a specific relationship between the QFO test and the withstand test [10,11] and for ceramic insulators the CFO value obtained with the QFO test is representative of the withstand voltage obtained with the withstand test. As far as QFO test and polymer insulators (coated or composite insulators) is concerned it is important to consider that such law valid for ceramic insulators is no longer applicable for two main reasons [14]: the first is due to the tendency of the surface to lose hydrophobicity as long as the test goes on and secondly it is not known the HC of an insulator in field during a high stress condition. Sometimes the hydrophobicity class is not uniform on unit and either along the insulator string. For such reasons the equivalence between the CFO value of the QFO test and the withstand voltage value from a withstand test valid for ceramic insulators is no longer valid or too pessimistic for polymer insulators. Furthermore, based on TERNA experience both in DC and in AC (for the latter with a service time up to 17 years) the HC of a string immediately after sampling was never recorded as completely hydrophilic, in the worst conditions HC 7 was recorded for the top surface while the bottom surface always have shown some partial hydrophobic condition. Consequently, considering as worst HC value in service condition equal to 6 uniformly over the whole string, the CFO values of the field aged strings should be rearranged and multiplied by a factor roughly around 1.4 [17]. As a further margin, but too pessimistic, such value should be rearranged to 1.2 considering a HC 6/7 uniformly over the whole string. Table 5 shows the reprocessed CFO value of the 7, 8 and 9-year field-aged strings in order to take into account a degraded surface with an HC equal to 7, 6 and in between 6 and 7. In such a case, considering uniform HC values along the string, it is possible to resort to the equivalence between the QFO test with the withstand voltage. Table 5 and Figure 9 shows the CFO values with a best fit for the inverse power law at the three HC values. Taking into account that the lower line (HC 7) is too pessimistic for the reason above, one can consider that after a number of years of service the "most probable" line falls in between the other two. If a margin of 10% is taken on the nominal voltage of the SACOI line, 220 kV can be considered as the min withstand voltage allowed for the string, an end-of-life estimation falls between 15 and 25 years. Obviously, such estimation is valid for a string in a DC line with 50 mm/kV installed on a pollution severity site classified as "heavy" (see Fig.4).

It is important to highlight that such inference on the end-of-life shall be taken with care since field confirmations are needed considering that TERNA never recorded a flashover on RTV insulators, the hydrophobicity loss has never been recorded uniform along the string. This fact induces the Authors of the paper to esteem the end-of-life larger than 20 – 25 years.

Table 5. Inference of 18-unit string CFO values in kV with the QFO test of field-aged strings considering different worst HC class during service condition. Lines with HC 6 and HC between 6 and 7 are considered more trustworthy.

Worst HC in service	7-year aged	8-year aged	9-year aged
7	232.2	223.7	214.7
6	325.8	313.2	300.6
6/7	278.6	268.4	257.6

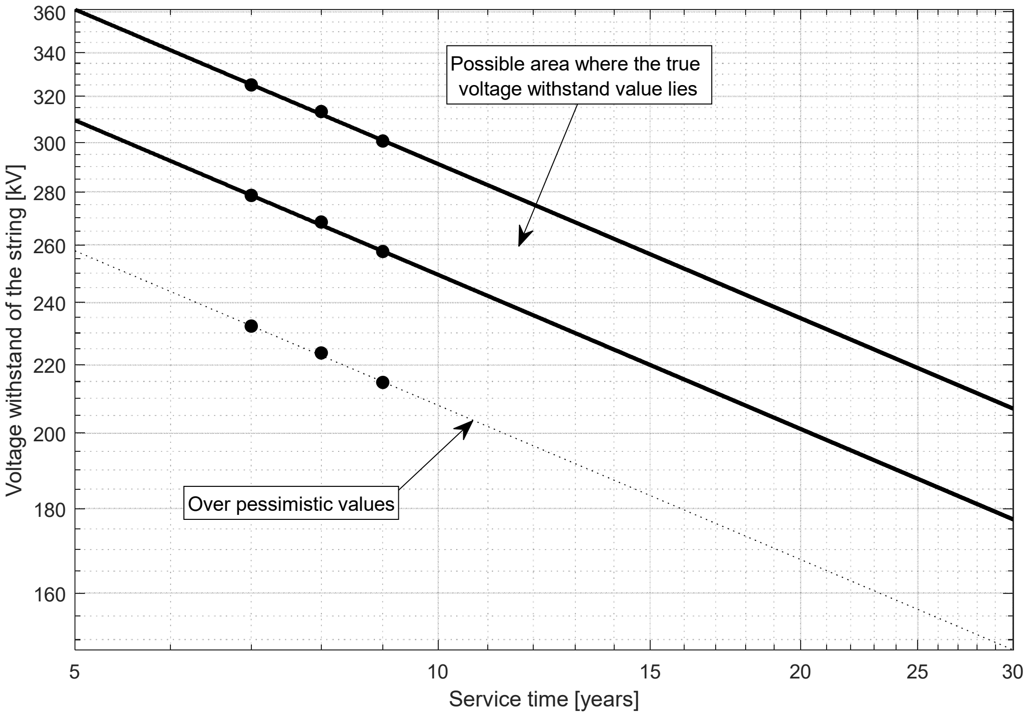

Fig.9. Inference of 18-unit string CFO values with the QFO test of field-aged strings considering different worst HC class during service condition. Dotted line considered over pessimistic (HC = 7 during service condition). Solid line more plausible results delimiting an area in which a range of withstand value can be inferenced at different service time.

CONCLUSIONS

Different field-aged and lab-aged QFO tests have been reported on RTV coated glass cap and pin insulators in DC. The following conclusions can be reported:

- 2000-hour DC ageing multi-stress test give important information about the ability of the coating to withstand erosion activities. String orientation has an important impact in the erosion activities, tension string suffering more than I strings or V string. Erosion is concentrated around the pin and in some case the erosion depth is enough to reach the glass surface in limited spots. The CFO values from the QFO test performed after the 2000-hour test have substantially the same values.
- 4000-hour test give further important information about the ability of the coating to withstand erosion activities. As for the first 2000-hour test, string orientation has an important impact confirming that the string with the deepest signs of ageing is the tension string and in sequence I string and V string. Erosion is mostly concentrated around the pin mild signs can be revealed along the ribs. In some cases, the erosion which had reached spots of the underneath glass in the first 2000h test have expanded. No signs of erosion were found on the top surface. The CFO values from the QFO test performed after the 4000-hour test highlights a drop in the CFO value on the tension string with respect to the CFO value recorded after 2000-hour test. I and V strings have substantially the same values with a slight reduction compared to the CFO values after the first 2000-hour test.
- Virgin insulator string shows a CFO value about 1.5 and 1.6 times higher than the CFO value after 2000-hour test and 4000-hour test respectively performed at 54.1 mm/kV.
- Virgin insulator string shows a CFO value about 1.65, 1.73 and 1.8 times larger than the CFO value after 7, 8 and 9 years of service respectively with a service creepage distance of 50 mm/kV and a site pollution severity classified as “heavy”.
- CFO values of field aged strings are influenced by the value of HC before and after the QFO test. The time lapse between stress events in the field plays a clear role on QFO test results.

- 7, 8 and 9 field-aged strings recover to HC in 100 – 130 hours, while lab-aged strings with both 2000-hour and 4000-hour tests in no more than 24 hours.
- Very light signs of erosion around the pin have been revealed in field aged strings at 50 mm/kV on a site pollution severity classified as “heavy”

Considering the test results reported in this paper and the field returns, the end-of-life of a DC string with a service specific creepage distance of 50 mm/kV in a “heavy” pollution severity class can be considered larger than 20 – 25 years. Further tests combined with more field returns will help on refining such inference.

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