DC-toughened glass insulators pre-coated with RTV silicone rubber – field returns from aged samples installed on HVDC lines

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***Abstract*—RTV silicone rubber coating on ceramic insulators has been used for at least two decades in order to solve critical problems related to pollution in harsh environments. In Italy the experience on AC 380 kV transmission lines started ten years ago; today this kind of insulators is considered as an attractive solution to solve problems of flashovers in highly polluted areas. Recently a trial installation started on HVDC Terna's lines. The first tests performed on an insulator string sampled after more than 2 years have shown that RTV pre-coated insulators seem to be a valid alternative to ceramic insulators in highly polluted environment even if further investigations are needed in order to better understand their behavior under DC stress.**

Keywords—insulators; HVDC lines; RTV coating; unified specific creepage distance; field experience

I. INTRODUCTION

The advantages of room temperature vulcanized (RTV) silicone rubber coatings to ceramic insulators on AC lines has been widely reported in different papers [1-3]. The intrinsic function of the RTV coating to prevent the development of leakage current and flashover for extended periods has increased their applications up to 380 kV AC lines crossing harsh and very harsh polluted environments (especially in coastal and industrial areas). Returns from field highlight that the RTV pre-coated insulators are an excellent solution to solve contamination flashovers [4-6]. Today, in the absence of standards, an IEEE position paper [6] has been published with the aim to provide guidance in the specification of RTV silicone rubber pre-coated porcelain or toughened glass insulators for transmission lines.

Terna started about ten years ago with the first trial installation of RTV pre-coated toughened glass insulators on a 380 kV AC line being a pioneer in this field at this voltage level [4]. Since 2003 tests are going on with periodical sampling of insulator strings. To gain the proper confidence in the performance of this solution, tests have been performed on new and field aged insulator strings. (The purpose being to better understand their ageing behavior in heavy and very heavy polluted areas) The positive results brought Terna to install in Italy about 530,000 RTV silicon rubber pre-coated insulators between 2005 and 2011.

Due to the good field experience from AC application, Terna has decided to start an in-field investigation on HVDC lines in order to assess the behavior of RTV pre-coated DC toughened glass insulators. Refurbishment of existing DC lines and future upcoming DC interties could rely on RTV pre-coating technology whereas it could be the right answer to very polluted environments limiting the creepage distance of insulator strings. Thus, the first trial installation started in 2009 on the ± 200 kV existing DC line section in Tuscany, one of the overhead line sections of the famous SACOI HVDC intertie. Since the beginning such first trial installation showed positive returns with reduction of insulation flashovers in harsh pollution conditions. The use of coating expanded rapidly and substantially with the positive field experience of the trial. Today a good part of the overhead line section in Tuscany of the SACOI intertie is equipped with RTV silicone rubber pre-coated insulators and it is continuously monitored by the line crew especially during those weather conditions that gave troubles in the past.

In this paper, the results of laboratory tests on field aged insulators are reported and discussed. In particular, the evaluation and the status of the silicone coating has been assessed through the measurement of the hydrophobicity, the measurement of the pollution level on the insulator surface, the measurement of the conductivity of the pollution layer and the control of the thickness of the silicone coating. Although, this monitoring campaign is still in an early stage and while caution is required in the interpretation it can be said that the first results seem encouraging.

II. BACKGROUND

Today in Italy more than 530,000 RTV pre-coated toughened glass insulators have been installed on HVAC lines after more than 10 years and more than 2,000 on HVDC lines after more than 4 years showing satisfying performances.

As far as the Unified Specific Creepage Distance (USCD) as defined in [7] is concerned, values ranging from 38 to 59 mm/kV have been adopted for AC lines depending upon type and amount of pollution in the relevant sites, while a value of 49 mm/kV has been used for the Tuscany section of the SACOI HVDC intertie.

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Before the installation of pre-coated toughened glass insulators, uncoated insulators used to be washed with a specific frequency dependent on the site in order to avoid flashovers due to pollution (usually with a frequency ranging between six months up to two years). Since the installation of the pre-coated toughened glass insulators no washing has been performed and no flashover occurred.

III. EXPERIMENTAL

The installed insulators, a normal profile for DC application with shell diameter of 330 mm, spacing of 146 mm and creepage distance of 545 mm, were coated in factory with specific processes in order to guarantee uniform and controlled thickness of the coating and the needed adhesion. Terna, based on its previous experience in the development of RTV pre-coated insulators for AC lines [6], has developed a series of specific tests for the evaluation of the quality of manufacturing. As far as the coating characteristics are concerned, Terna requires that the particle of the alumina trihydrate (ATH) filler shall fall in the range of 10 to 20 µm

Insulator strings made of 18 units were installed in different suspension towers in Tuscany area in which the pollution can be considered harsh for the strong combination of both marine winds and the presence of industrial sites (heavy fuel power plant and steel mills). The insulator strings of the SACOI suspension towers are usually single I string and when the line crosses particular area (for example road crossing or residential areas) are double I strings.

SACOI intertie is a monopolar 3-terminal HVDC system with Line Commutated Convertor (LCC) technology connecting the three converter stations (Codrongianos, Lucciana and Suvereto) with different overhead line and cable sections and current return via both earth and sea electrodes. Each section (whether overhead line or cable line) consists of two parallel lines (two independent conductors in the same tower or two independent cables) usually operated in parallel. One of the peculiarity of LCC systems is that they need to reverse the voltage polarity when the direction of power shall be changed. Consequently, the insulator strings of both conductor in the same tower are subjected to a positive (+200 kV) DC voltage or a negative (-200 kV) DC voltage in respect of the versus of the power transfer of the intertie.

The insulator string sampled for the test reported hereafter has been subjected to the yearly stresses as illustrated in Table 1. The high value of out of service condition in 2010 was due to a cable fault. This insulator string was installed in January 2009 and removed in April 2011, about 2 years and 4 months later.

TABLE I. YEARLY PERCENT OF TIME IN WHICH THE INSULATOR STRING HAS BEEN SUBJECTED TO: POSITVE POLARITY, NEGATIVE POLARITY AND WITHOUT ELECTRICAL STRESS SINCE THE LINE WAS OUT OF SERVICE.

Period	Positive polarity	Negative polarity	Out of service
2009	23.4	66.5	10.1
2010	27.4	48.7	23.8
2011*	24.7	66.7	8.6
* such period refer to the first 4 months of 2011			

12 insulators out of 18 of the sampled string were used for the tests illustrated hereafter. In particular such 12 insulators were the 12 consecutive units on the high voltage side. In the following, the unit #1 is the first insulator on the high voltage side, while the unit #12 refer to the 12th unit from the high voltage side (or the 7th unit from the tower side).

The tests performed are the following:

- visual inspection;
- hydrophobicity evaluation;
- pollution level evaluation;
- pollution layer conductivity measurement;
- silicone coating thickness measurement;

The visual inspection has been performed with an examination with normal or corrected vision without magnification in order to reveal degradation, abrasion, scrapes, etc. of the coating or corrosion of the metal parts. The visual inspection is needed also to reveal possible tracking or erosion activities of the coating.

The hydrophobicity is evaluated through the STRI method [8] that is divided in seven classes (HC), the first named HC1 in which the surface can be deemed hydrophobic and the last named HC7 in which the surface can be deemed completely hydrophilic.

The pollution level has been evaluated with the method reported in Annex C of [7]. With this test it is possible to evaluate both the Equivalent Salt Deposit Density (ESDD) and the Non-Soluble Deposity Density (NSDD).

The conductivity of the pollution layer has been estimated through the method reported at Paragraph 16.1 of [9]. For the clean fog, deionized water was used, with a fog flow of 120 l/h, air pressure for the fog of 7 bars, a test voltage of 4 kV and a duration of the test of 4 hours.

The silicone coating thickness has been evaluated using a Terna internal procedure [10] for the qualification of pre-coated insulators with RTV silicone rubber. In particular, considering points A and B on Fig. 1 three specimens equally distant in the same circumference (each specimen is far 120 ° angular degrees to the other two specimens on the same circumference) shall be taken and the thickness of each specimen shall be evaluated with a precision of ± 5 µm. The mean value of the nine measurements on points A shall exceed 350 µm, while the mean value of the fifteen measurements on points B shall exceed 280 µm.

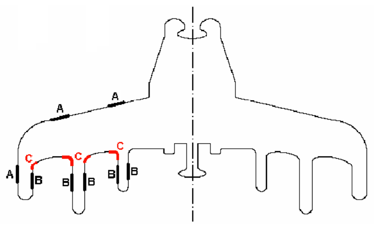

Fig. 1. Sampling points along the insulator coated surface for the coating thickness measuremnt.

This test is performed as a sample test on new insulator units. In this study such verifications will confirm the compliance to the requirements.

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IV. Results

In Fig. 2 a picture from the top and bottom surface of insulators #12 and #1 has been reported in which it can be pointed out that in the former a scrape is evident while in the latter no significant signs of degradation can be revealed. In particular the dark signs under the external rib on Fig. 2 b) represents pollution accumulation. The scrape on the insulator coating reported in Fig. 2 a) can probably be linked to handling operations and in any case not due to any electrical activity.

a) b)

Fig. 2. Visual inspection: a) insulator #12 top surface with a lateral scrape; b) insulator #1 bottom surface with dirt under ribs andwithout interesting signs of degradation.

Similar scrapes have been noted also in some other units, but in any case due to their position on the insulator surface and the absence of any electrical activity in the surrounding, those are clearly related to handling at the time of installation, or during sampling or during transportation from the site of installation to laboratories. One very important statement here is to note that there is no degradation related to electrical activity.

Hydrophobicity of the whole string has been assessed. A reduction of hydrophobicity on the bottom surface of the first units on the high voltage side has been pointed out. On the contrary, the top surface of the same units remains hydrophobic. Fig. 3 shows the hydrophobicity class of both top and bottom surfaces for insulator units #1 and #2. It can be highlighted that the bottom surfaces are quite hydrophilic. In particular, for the examined units it has been found that for the bottom surface the hydrophobicity class falls between HC5 and HC6, while for the top surface the hydrophobicity class falls between HC1 and HC2. Hydrophobic properties are dynamic and LMW silicone species transfer remains a key characteristic. The hydrophobicity levels found on these DC insulators is practically identical to that found on AC insulators sampled after a similar period of service but installed in another site in the AC 380 kV grid of Terna. Thanks to the very positive experience on AC toughened glass RTV pre-coated insulators for more than 7 years, the interest in this trial is also focused on comparison between AC and DC hydrophobicity recovery.

Units #1 and #12 have been selected also for the evaluation of the pollution level. Such selection has been decided also to evaluate if the pollution level along the string was uniform, since especially in DC, non-uniform pollution levels along the string have been recorded and considered typical in DC applications [11,12]. The pollution level evaluation on insulator units #1 and #12 are reported in Table II. It can be highlighted that the ESDD values on both insulator units are practically the same, while a slight difference can be revealed for the NSDD, but on the top surface only: 0.05 mg/cm^2 on unit #12 and 0.08 mg/cm^2 on unit #1. Considering ESDD and NSDD couple of values and according to [7] the level of pollution falls on "very heavy" Site Pollution Severity (SPS) for the bottom surface of both units and falls on "medium" SPS for the top surface of the insulator unit #12 and #1 respectively. As far as the NSDD to ESDD ratio is concerned, it yields values lower than 5, ranging from 2.5 and 4. The ESDD bottom to top ratio for both insulator units is 9, as typically expected on HVDC lines.

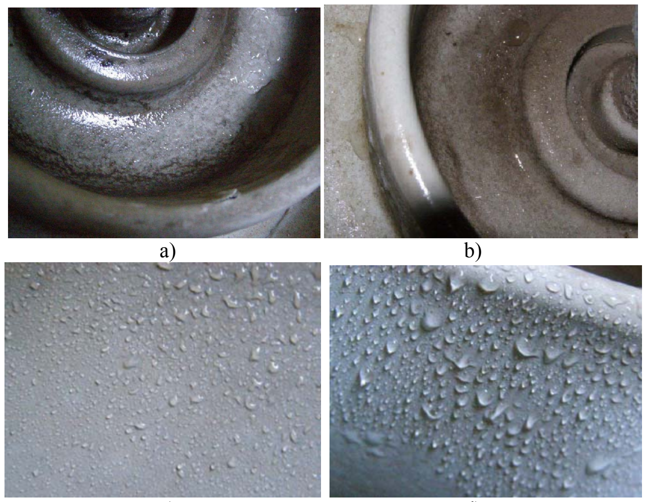

Fig. 3. Hydrophobicity evaluation: a) insulator #1 bottom surface – HC6; b) insulator #2 bottom surface – HC5; c) insulator #1 top surface – HC1; d) insulator #2 top surface – HC2;.

TABLE II. Pollution level evaluation on Insulator Unit #1 and #12 according to [7]

Insulator	ESDD [mg/cm^2]	NSDD [mg/cm^2]	Level of pollution	NSDD/ESDD	Bottom/top ESDD ratio
#12 top surface	0.02	0.05	medium	2.5	9
#12 bottom surface	0.18	0.66	Very heavy	3.67	
#1 top surface	0.02	0.08	medium	4	9
#1 bottom surface	0.18	0.61	Very heavy	3.39	

Fig. 4 reports the leakage current with time during the measurement of the pollution layer conductivity performed on insulator units #3 and #4 connected in series. The pollution conductivity has been estimated around 0.13 μS, actually a very low value. At the end of the test both insulator units still show a good level of hydrophobicity on the top surface with areas qualified as HC3.

Silicone thickness measurements along the insulator surface performed as reported in the previous section is reported in Table III for the insulator units #9 and #11. The average values on both top surfaces and bottom surfaces are

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higher than the minimum requirements reported in [10]. The average thickness values on the top surface are 400 µm and 430 µm for insulator unit #9 and #11 respectively, above the minimum required value of 350 µm, while the average thickness values on the bottom surface are 310 µm and 355 µm for insulator unit #9 and #11 respectively, above the minimum required value of 280 µm.

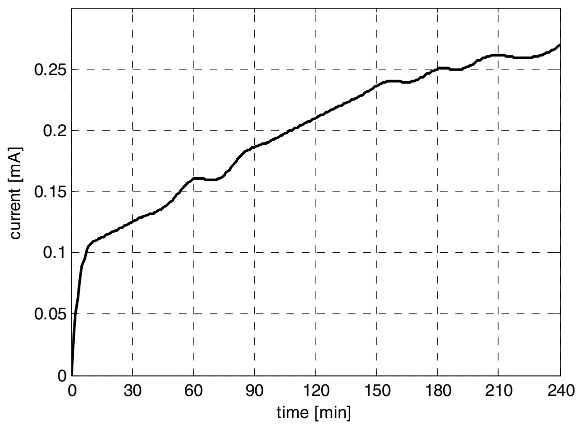

Fig. 4. Leakage current vs. test duration during the measurement of the pollution layer conductivity performed on insulators #3 and #4 connected in series.

TABLE III. SILICON COATING THICKNESS MEASUREMNT ALONG THE INSULATOR SURFACE AS REPORTED IN FIG. 1. MEASUREMENT PERFORMED ON INSULATOR UNIT #11 AND #9

Insulator #11			
Direction	**0°**	**120°**	**240°**
A [µm]	540-290-230	820-415-300	690-310-260
Average A [µm]	430		
B [µm]	240-300-390-315-500	460-180-500-400-570	360-220-360-250-300
Average B [µm]	355		
Insulator #9			
Direction	**0°**	**120°**	**240°**
A [µm]	830-380-285	525-280-250	500-300-240
Average A [µm]	400		
B [µm]	240-265-360-170-220	340-380-360-250-290	390-360-450-300-250
Average B [µm]	310		

V. CONCLUSIONS

An insulator string of toughened glass insulators for DC application pre-coated with RTV silicone rubber has been sampled from a ±200 kV DC line after 2 years and 4 months. 12 out of 18 insulators units installed on the high voltage side of the whole sampled string has been sent to SEDIVER laboratory for a series of tests in order to assess any degradation due to ageing.

Test results show that:

- the top surface of the insulators have maintained a very good level of the hydrophobicity, on the other hand a reduction of the hydrophobicity level has been noticed on the bottom insulator surface with the presence of quasi hydrophilic areas;
- no specific marks of electric activity were found. Some traces of mechanical degradation (scrapes) have been observed, but they have to be linked to various handling operation related to the purpose of the study. In any case, due to their limited number and small dimension, they have no influence on the overall performances of the insulator string;
- the pollution level can be evaluated as "medium" on the top surface and "very heavy" on the bottom surface; this strong difference can be ascribed to the differences in rain natural washing on the top and bottom surfaces; "I" string installation also worsens the rain natural washing;
- very low value of pollution layer conductivity has been recorded: 0.13 µS;
- concerning the measure of the thickness of the coating, all the values measured are above the minimum requirements.

Although it is not possible to address conclusions based only on the results reported in this paper at this early stage of field experience in DC, the reduction of flashover and washing needs are already very encouraging. Consequently further investigation through the same tests and new tests will be performed to help gaining a better understanding of the behavior and performance of silicone coating under DC stress.

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